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MACHINING AND GRINDING OF NICKEL- AND COBALT-BASE ALLOYS

By C. T. Olofson, J. A. Gurklis, and F. W. Boulger

Prepared Under the Supervision of the
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MACHINING AND GRINDING OF NICKEL- AND COBALT-BASE ALLOYS

By

C. T. Olofson, J. A. Gurklis, and F. W. Boulger*

ABSTRACT

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This report covers the state of the art of metal-removal operations for nickel- and cobalt-base alloys. It describes the methods currently employed for conventional machining, grinding, electrolytic, and chemical-machining processes. The precautions that should be taken to avoid troubles resulting from the characteristics typical of these alloys are pointed out. Nine machining, two grinding, two cutting, and two unconventional metal-removal operations are discussed separately. Other sections discuss the classification of these alloys and their general response to machining variables.

*Principal Investigators, Battelle Memorial Institute, Contract No. DA-01-021-AMC-11651(Z)

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PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report on practices used for removing metal from nickel- and cobalt-base alloys is intended to provide information useful to designers and fabricators. The detailed recommendations are considered to be reliable guides for selecting conditions, tools, and equipment suitable for specific operations. The causes of common problems are identified and precautions for avoiding them are mentioned.

The report summarizes information collected from manufacturers' handbooks, technical books and publications, reports on Government contracts, and by personal contacts with engineers associated with specialized companies. A total of 74 references, most of them covering the period since 1960, are cited. Detailed data available prior to 1961, mostly on superalloys, were covered by DMIC Memorandum 134 issued by the organization known as the Defense Metals Information Center. A large part of the more recent information on nickel alloys originated from a systematic search of Government reports and technical papers.

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MACHINING AND GRINDING OF NICKEL- AND COBALT-BASE ALLOYS

SUMMARY

Problems in machining nickel- and cobalt-base alloys originate from their relatively high strengths and their marked propensity to work harden. The harder chips produced are abrasive to tools, and hence accelerate tool wear.

Nickel- and cobalt-base alloys also exhibit poor thermal diffusivities; therefore, tool-chip interface temperatures are higher than they would be when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided. Excessive temperatures also lead to welding and tool buildup which in turn increases friction and produces poor surface finishes.

These difficulties can be minimized by following recommendations given in this report. The use of the relatively low cutting speeds along with the suggested cutting fluids will reduce buildup, friction, and tool-chip temperatures. Work hardening is minimized by using sharp tools of approved geometries. Furthermore, tools should cut, not push metal, and they should never dwell or rub in the cut. When proper techniques are employed, machining nickel- and cobalt-base alloys is usually successful.

INTRODUCTION

Nickel- and cobalt-base alloys are versatile materials exhibiting useful properties of corrosion resistance and high strength at elevated temperatures. Many of these alloys, and particularly those in the superalloy category, are difficult to machine compared with metals like aluminum, brass, or mild steel. Exacting precautions are often necessary for machining superalloys, a general class which includes materials used for high-temperature service under severe stress and where oxidation resistance is frequently required. Troubles stem from the relatively high strengths of some nickel- and cobalt-base alloys and their marked propensity to work harden when machined in the annealed or solution-heat-treated condition.

Successful, economical machining of nickel- and cobalt-base alloys requires the careful selection and use of suitable tool materials and cutter designs. Rigid machining setups, relatively low cutting speeds and feeds, and chemically active cutting fluids are used to minimize glazing of the machined surfaces and welding of chips to the tool. This report describes the general machining behavior of nickel- and cobalt-base alloys and arranges the various alloys into seven major machinability groups based on composition and machinability ratings. It also describes the setup conditions needed for each group for specific machining operations. The cutting conditions suggested are intended to serve as guides or starting points for subsequent adjustment to existing plant conditions, available machine tools, and the machining requirements for the parts involved.

GENERAL INFORMATION

Nickel, cobalt, and iron alloy with each other over wide ranges in composition (Ref. 1). When alloyed with chromium, these elements form the basis for most of the superalloys so important in various applications to defense and aerospace systems.

Unalloyed nickel is used mainly for electronic components and corrosion-resistant parts (Ref. 2). A considerable amount of nickel is used in the commercially important nickel-copper alloys known by the trademark Monel (Ref. 3). This family of alloys includes a more-or-less continuous series of 11 work-hardenable and two age-hardenable alloys designed for different applications.

Cobalt is rarely used in the pure state except as a binder for cemented carbides. Cast alloys of cobalt and chromium with tungsten or molybdenum, or both, are used for wear resistance. The materials of major interest for this report, however, are the cobalt-rich superalloys (Refs. 4,5). They exhibit unusually high strengths at elevated temperatures and are resistant to oxidation. Figure 1 compares the temperature ranges over which cobalt-base and other superalloys operate (Ref. 6).

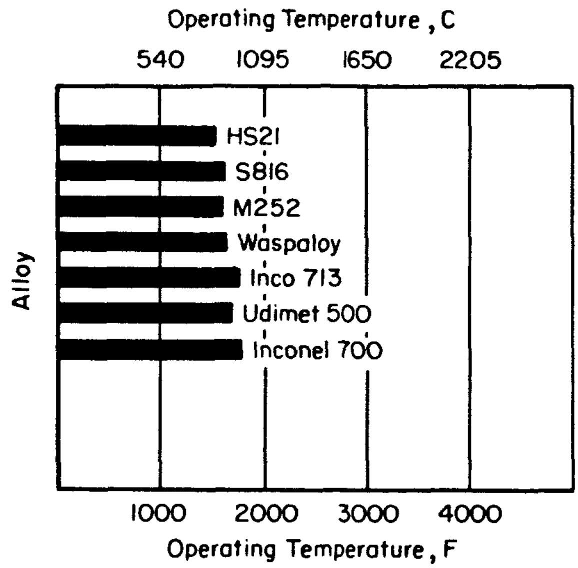


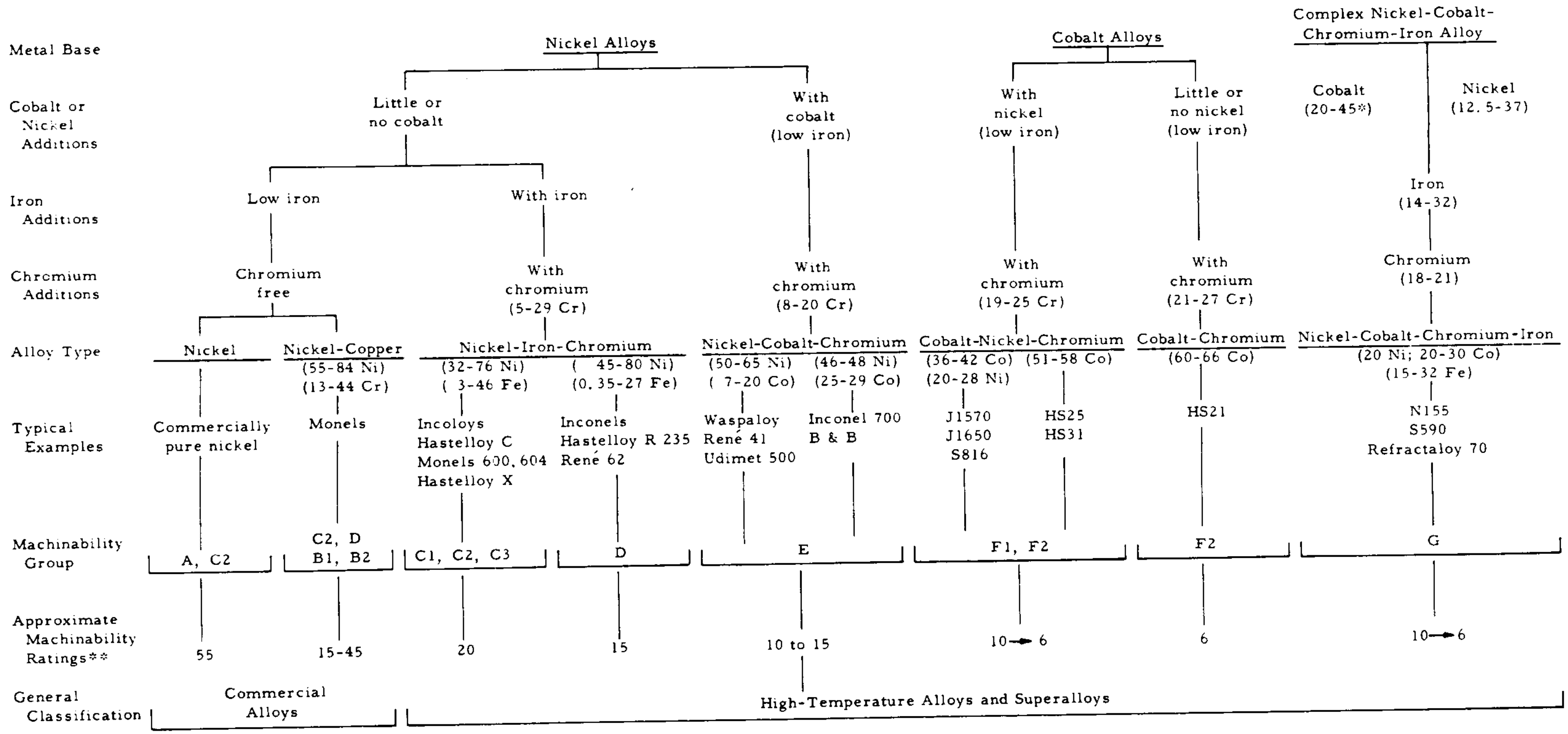
FIGURE 1. OPERATING RANGES FOR SOME SUPERALLOYS (REF. 6)

CLASSIFICATION OF ALLOYS

The nickel- and cobalt-base alloys described in this report include 16 commercially pure nickels, 13 Monel alloys, and 78 high-temperature or superalloys. These alloys are organized and arranged, approximately, by composition and machinability groups as shown in Figure 2. Their compositions and properties are listed in Tables I through VII inclusive (Refs. 2,3,7-13).

Many of these alloys have similar compositions and properties and so are expected to machine similarly. Consequently, these alloys are classified together and identified by a group letter for machining purposes. These codes are used throughout this report in various machining tables of data supplied for each machining operation.

Some of the superalloys listed are no longer used, while others are so new that little machining experience has been obtained. All alloys, however, are listed for completeness.



*All alloy measurements given in per cent.
**Based on AISI B1112 steel as 100.

FIGURE 2. GENERAL CLASSIFICATION AND REPRESENTATIVE ALLOYS OF VARIOUS TYPES OF NICKEL- AND COBALT-BASE ALLOYS

TABLE I. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF NICKEL AND ALLOYS OF NICKEL

Machinability Classifications — A, C2

Alloy(a)	Type(b)	Nominal Chemical Composition, per cent										Usual Form(c)	Room Temperature Properties				
		Ni	Co	Fe	Mg	Mn	Cu	W	Ti	C	Si		Condition(d)	Strength, ksi Tensile	Strength, ksi Yield	Elongation, per cent	Machinability Class(e)
Nickel 270	WH	99.97	--	--	--	--	--	--	--	--	--	W	Ann	52	*	55	C2
Nickel 200	WH	99.5	--	--	--	--	--	--	--	0.06	--	W	Ann	55-80	15-30	55-40	A
													CD	65-110	40-100	35-10	
Nickel 201	WH	99.5	--	--	--	--	--	--	--	0.01	--	W	Ann	56	21	45	A
													CD	60-100	35-90	35-10	
Nickel 205	WH	99.5	--	--	0.04	--	--	--	0.02	0.06	--	W	Ann	55-80	15-30	55-40	A
													CD	65-110	40-100	35-10	
Nickel 220 and 225	WH	99.5	--	--	0.04	--	--	--	0.02	0.06	--	W	Ann	60-70	18-22	47	A
													CD	65-110	40-100	35-10	
Nickel 230	WH	99.5	--	--	0.06	--	--	--	0.003	0.09	--	W	Ann	60-70	18-22	47	A
													CD	65-110	40-100	35-10	
Nickel 233	WH	99.5	--	--	0.07	--	--	--	0.003	0.09	--	W	Ann	60-70	18-22	47	A
													CD	65-110	40-100	35-10	
Nickel 212	WH	98	--	--	--	2	--	--	--	0.10	--	W	Ann	76	28	43	A
TD Nickel	WH	98	--	(With 2 per cent thoria by volume)						--	--	W	CD	62-90	50-80	25-23	A
Nickel 202	WH	95.5	--	--	0.03	--	--	3.8	--	0.03	--	W	*	*	*	*	A
Nickel 204	WH	95.2	4.5	--	--	--	--	--	--	0.03	--	W	*	*	*	*	A
Nickel 211	WH	95	--	--	--	4.75	--	--	--	0.10	--	W	Ann	86	34	40	A
Nickel 210	NH	95.6	--	0.5	--	0.9	0.5	--	--	0.8	1.6	C	AC	45-60	20-30	30-15	A
Nickel 213	NH	95	--	0.5	--	0.8	0.5	--	--	1.5	1.6	C	AC	*	*	*	A
Nickel 305	NH	91.5	--	0.5	--	0.9	0.5	--	--	0.8	6	C	AC	*	*	*	C2

*Asterisks denote the data are unavailable.

(a) Designations of Huntington Alloy Products Division, International Nickel Company (all wrought alloys work hardenable).
(b) WH = hardenable by cold working only
NH = not usually hardened by heat treatment.
(c) W = wrought products
C = castings.
(d) Ann = annealed
CD = cold drawn
AC = as cast.
(e) The various machinability classes are described on pages 3 and 4.

TABLE II. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF NICKEL-COPPER ALLOYS (MONELS)

Machinability Classifications — B1, B2, C2, D

Alloy(a)	Type(b)	Nominal Chemical Composition, per cent: Ni	Cu	Si	C	Others	Usual Form(c)	Room Temperature Properties: Condition(d)	Strength, ksi: Tensile	Yield	Elongation, per cent	Machinability Class(e)
Monel Alloy 406	WH	84	13	--	0.12	--	W	*	*	*	*	B1
Monel Alloy R405	WH	66	31.5	--	0.18	--	W	Ann	70-85	25-40	50-35	B1
								CD	85-115	50-100	35-15	
Monel Alloy 400	WH	66	31.5	--	0.12	--	W	Ann	70-85	25-40	50-35	B1
								CD	84-120	55-100	35-22	
Monel Alloy K500	AH	65	29.5	--	0.15	Ti 0.6 - Al 3.0	W	Ann	90-110	40-60	45-25	C2
								STA	160	111	24	D
Monel Alloy 501	AH	65	29.5	--	0.23	Ti 0.6 - Al 3.0	W	Ann	90-110	40-60	45-25	C2
								STA	160	111	24	D
Monel Alloy 410	NH	66	30.5	1.6	0.2	--	C	AC	65-90	32-40	45-25	B2
Monel Alloy 505	NH	64	29	4	--	--	C	AC	110-145	80-115	45-25	B2
Monel Alloy 506	NH	64	30	3.2	0.10	--	C	AC	100-130	60-80	25-10	B2
Monel Alloy 507	NH	64	30.5	2.7	0.55	--	C	AC	90-115	60-80	20-10	B2
Monel Alloy 411	NH	62	32.5	1.6	0.2	Cb 1.3	C	*	*	*	*	B2
Monel Alloy 402	WH	58	40	--	0.12	--	W	Ann	60-85	23-40	50-35	B1
								CD	75-120	45-100	35-15	
Monel Alloy 403	WH	57.5	40	--	0.12	Mn 1.8	W	Ann	60-85	23-40	50-35	B1
								CD	75-120	45-100	35-15	
Monel Alloy 404	WH	55	44	--	0.06	--	W	Ann	67	25	47	B1
								CD	78	63	28	

*Asterisks denote that data are unavailable.

(a) Designations of Huntington Alloy Products Division, International Nickel Company (all wrought alloys work hardenable).

(b) WH = hardenable by cold working only
NH = not usually hardened by heat treatment
AH = age hardenable by heat treatment.

(c) W = wrought products
C = castings.

(d) Ann = annealed
CD = cold drawn
STA = solution treated and aged by heat treatment
AC = as cast.

(e) The various machinability classes are described on pages 3 and 4.

TABLE III. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF NICKEL-IRON-CHROMIUM ALLOYS

Machinability Classification - C1, C2, C3

Alloy[(a)]	Type[(b)]	Nominal Chemical Composition, per cent											Room-Temperature Properties					Machinability Class[(f)]
		Ni	Co	Fe	Cr	Mo	W	Ta	Cb	Ti	Al	C	Usual Form[(c)]	Condition[(d)]	Strength, ksi Tensile[(e)]	Strength, ksi Yield	Elongation, per cent	
Incoloy Alloy 800	WH	32	--	46	21	--	--	--	--	--	--	0.04	W	Ann	75-100	30-50	50-30	C1
														CD	100-150	75-125	30-10	
Incoloy Alloy 805	WH	36	--	55	8	0.5	--	--	--	--	--	0.12	W	*	*	*	*	C1
Incoloy Alloy 810	NH	32	--	46	21	--	--	--	--	--	--	0.25	C	*	*	*	*	C1
Incoloy Alloy 801	AH	32	--	45	21	--	--	--	--	1	--	0.04	W	Ann	90	40	36	C1
Incoloy Alloy 901	AH	43	--	34	14	6	--	--	--	2.5	0.25	0.05	W	STA	166s	107	23	C1
															175b	130	--	
Incoloy Alloy 825	AH	43	--	30	22	3	--	--	--	1	0.15	0.03	W	Ann	85-105	35-65	50-30	C1
Incoloy Alloy 804	AH	44	--	26	29	--	--	--	--	0.4	0.25	0.06	W	*	*	*	*	C1
Hastelloy X	WH	48	--	19	22	9	1	--	--	--	--	0.15	W	Ann	104p	49	46	C3
															108b	51	50	
															102s	47	45	
Hastelloy F	WH	48	--	16	22	7	1	0.5	2	--	--	0.05	W	Ann	108-116b	48-53	40-46	C3
NA-22H	NH	48	--	18	27	--	6	--	--	--	--	0.5	C	AC	65	--	3.5	C3
Hastelloy C	NH	55	--	6	16	17	4	--	--	--	--	0.08	W	ST	129	54	37	C2
													C	AC	81	51	10	
Inconel Alloy 625	WH	61	--	3	22	9	--	--	4	--	--	0.05	W	CD	142	85	42	C2
Inconel Alloy 604	WH	74	--	7	16	--	--	--	2	--	--	0.04	W	Ann	80-100	25-50	55-35	C2
														CD	105-150	80-125	30-10	
Inconel Alloy 600	WH	76	--	7	16	--	--	--	--	--	--	0.04	W	Ann	80-100	25-50	55-35	C2
														CD	105-150	80-125	30-10	

* Asterisks denote that data are unavailable.

(a) The Incoloys and Inconels are designations of the Huntington Alloy Products Division, International Nickel Company
The Hastelloys are designations of the Haynes Stellite Division, Union Carbide Corporation (all wrought alloys are work hardenable).

(b) WH = hardenable by cold working only
NH = not usually hardened by heat treatment
AH = age hardenable by heat treatment.

(c) W = wrought products
C = castings.

(d) Ann = annealed
CD = cold drawn
STA = solution treated and aged by heat treatment
ST = solution treated by heat treatment
AC = as cast.

(e) s = sheet; b = bar; p = plate.

(f) The various machinability classes are described on pages 3 and 4.

TABLE IV. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF NICKEL-IRON-CHROMIUM ALLOYS (SUPERALLOYS)

Machinability Classification - D

Alloy[a]	Type[b]	Nominal Chemical Composition, per cent												Usual Form[c]	Room-Temperature Properties			
																Strength, ksi		
		Ni	Co	Fe	Cr	Mo	W	Ta	Cb	Ti	Al	B	C		Condition[d]	Tensile[e]	Yield	Elongation, per cent
D979	AH	45	--	27	15	4	4	--	--	3	1	0.01	0.05	W	STA	204b	146	15
																195f	134	14
René 62	AH	48	--	22	15	9	--	--	2.3	2.5	1.2	0.01	0.08	W	STA	205	160	7
	AH	50	--	18	17	3	3	--	6.2	1.1	0.6	--	0.02	W	STA	--	180	--
Alloy 718	AH	53	--	18	19	3	--	--	5.2	0.8	0.6	--	0.04	W	STA	190	150	25
														C	STA	145	120	10
DCM	AH	60	--	12	14	5.3	--	--	--	3.4	4.3	0.08	0.05	C	STA	140	115	5
Hastelloy R-235	AH	63	--	10	16	5.5	--	--	--	2.5	2.0	--	0.16	W	STA	166b	100	32
GMR 235	AH	63	--	10	16	5.3	--	--	--	2	3	0.07	0.15	C	AC	108	96	3
Nimonic 80 A	AH	70	--	5	20	--	--	--	--	2.3	1.3	--	0.10	W	STA	155	87	39
Inconel Alloy 721	AH	72	--	7.2	16	--	--	--	--	3	--		0.04	W	Ann	115	50	50
												--			STA	180	120	25
Inconel Alloy 751	AH	73	--	6.8	15	--	--	--	1	2.5	1.2	--	0.04	W	*	*	*	*
Niomonic 75	AH	73	--	5	20	--	--	--	--	0.4	--	--	0.15	W	ST	96-103	60	50
Inconel Alloy X750	AH	73	--	6.8	15	--	--	--	0.85	2.5	0.8	--	0.04	W	ST	160	92	22
															STA	188	138	18
Inconel Alloy X722	AH	74	--	7	15	--	--	--	--	2.4	0.6	--	0.04	W	STA	165b	99	31
Alloy 713 C	AH	74	--	1	11	4.5	--	--	2	0.7	6	--	0.12	C	AC	117	102	5
Inconel Alloy 702	AH	80	--	0.4	15	--	--	--	--	0.7	3.4	--	0.04	W	STA	145	85	38
NASA TaZ8	AH	69	--	--	6	4	4	8	V 2	Zr 1	6	--	0.12	C	AC	136	--	2

* Asterisks denote that data are unavailable.

(a) Alloy designations normally used for identification are shown. Licensees may use somewhat similar designations (all wrought alloys are work hardenable).
(b) AH = age hardenable by heat treatment.
(c) W = wrought products
C = castings.
(d) Ann = annealed
STA = solution treated and aged by heat treatment
ST = solution treated by heat treatment
AC = as cast.
(e) b = bar; f = forging.

TABLE V. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF NICKEL-COBALT-CHROMIUM ALLOYS

Machinability Classification — E

Alloy[(a)]	Type[(b)]	Nominal Chemical Compoisition, per cent													Usual	Room Temperature Properties			
		Ni	Co	Fe	Cr	Mo	W	Ta	Cb	Zr	Ti	Al	B	C	Form[(c)]	Condition[(d)]	Strength, psi Tensile[(e)]	Strength, psi Yield	Elongation, per cent
B1900	AH	64	10	--	8	6	--	4	--	0.08	1	6	0.02	0.11	C	AC	125	110	5
MarM211	AH	63	10	--	9	2.5	5.5	--	2.7	0.05	2	5	0.02	0.15	C	AC	140	122	--
TRW-1900	AH	62	10	--	10	--	9	--	1.5	0.10	1	6.3	0.03	0.11	C	AC	130	118	6
Nichrotung 1	AH	61	10	--	12	--	8	--	--	--	4	4	0.05	0.10	C	AC	130	120	5
MarM246	AH	60	10	--	9	2.5	10	1.5	--	0.05	1.5	5.5	0.02	0.15	C	AC	147	125	6
MarM200	AH	60	10	--	9	--	12.5	--	1	0.05	2	5	0.02	0.15	C	AC	135	120	7
IN-100	AH	60	15	--	10	3	--	--	V 1	0.05	5	5.7	0.02	0.18	C	AC	140	122	--
Nimonic 100	AH	57	20	--	11	5	--	--	--	--	1.5	5	--	0.02	W	STA	181	--	--
Nimonic 90	AH	58	18	--	20	--	--	--	--	--	1.4	1.4	--	0.10	W	STA	166	101	39
Waspaloy	AH	56	14	1	19	4.3	--	--	--	--	3	1.3	0.01	0.05	W	STA	180	115	28
Astroloy	AH	56	15	--	15	5.8	--	--	--	--	3.5	4.4	0.03	0.10	W	STA	180-205	145-155	5-15
J1500	AH	55	10	—	20	10	--	--	--	--	3	1	--	0.15	W	STA	179s	110	20
																	180b	122	16
René	AH	55	10	1	19	10	--	--	--	--	3.2	1.7	0.01	0.10	W	STA	185s	148	9
																	206b	154	14
M252	AH	55	10	2	19	10	--	--	--	--	2.5	0.8	--	0.15	W	STA	180	122	20
Unitemp 1753	AH	53	7	9	16	1.6	8.4	--	--	--	3	1.9	--	0.22	W	ST	123	61	55
																STA	195	135	20
Udimet 700	AH	52	18	0.8	15	5.1	--	--	--	--	3.5	4.3	1.1	0.12	W	STA	204	140	17
Udimet 500	AH	50	19	2	19	4	--	--	--	--	2.9	2.9	0.01	0.12	W	STA	190	130	18
Nimonic 95	AH	49	20	5	20	--	--	--	--	--	3.1	1.9	--	0.15	W	STA	181	--	--
B & B	AH	48	25	--	15	6	--	--	--	--	2.7	3.2	0.5	0.05	W	*	*	*	*
S.E.L. No. 1	AH	48	27	--	15	4	--	--	--	--	2	4	--	0.13	W	*	*	*	*
Inconel 700	AH	46	29	0.7	15	3.8	--	--	--	--	2	3	--	0.12	W	STA	171	104	25

*Asterisks denote that data are unavailable.

(a) Alloy designations normally used for identification are shown. Licensees may use somewhat similar designations (all wrought alloys are work hardenable).
(b) AH = age hardenable by heat treatment.
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TABLE VI. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF COBALT-NICKEL-CHROMIUM AND COBALT-CHROMIUM ALLOYS

Machinability Classification — F1, F2

Alloy[a]	Type[b]	Nominal Chemical Composition, per cent													Usual Form[c]	Room Temperature Properties				Machinability Class[f]
		Co	Ni	Fe	Cr	Mo	W	Ta	Cb	Zr	Ti	Al	B	C		Condition[d]	Strength, psi Tensile[e]	Strength, psi Yield	Elongation, per cent	
J1570	AH	39	28	2	20	--	6	--	--	--	4	--	--	0.2	W	STA	145b	88	16	F1
J1650	AH	36	27	--	19	--	12	2	--	--	3.8	--	0.02	0.2	W	STA	174	116	9	F1
M203	AH	36	25	1.5	20	--	12	--	1.5	--	2.2	0.8	--	0.07	W	*	*	*	*	F1
M205	AH	37	26	1.5	19	--	12	--	1.2	--	--	2.8	0.22	0.15	C	*	*	*	*	F1
M204	AH	41	25	1.5	19	--	12	--	1.2	--	--	--	0.22	0.07	C	*	*	*	*	F1
X50	NH	42	20	2.5	23	12	--	--	--	--	--	--	--	0.76	C	*	*	*	*	F1
V36	NH	43	20	3	25	4	2	--	2	--	--	--	--	0.3	W	ST	146	83	19.5	F1
S816	NH	43	20	3	20	4	4	--	4	--	--	Mn 1.2	--	0.4	W	ST	140	67	35	F1
Haynes Alloy 25	NH	51	10	3	20	--	15	--	--	--	--	--	--	0.15	W	ST	140p	67	58	F2
																	150b	70	65	
HS30	AH	53	16	--	24	6	--	--	--	--	--	--	--	0.4	C	AC	97	81	10	F2
																Aged	120	95	3	
HS36	AH	55	10	--	19	--	15	--	--	--	--	--	--	0.4	C	AC	90-115	85-105	3-8	F2
																Aged	115-135	100-115	0.5-3	
HS31	AH	56	10	--	25	--	8	--	--	--	--	--	--	0.5	C	AC	113	80	8	F2
																Aged	128	112	2	
MarM509		57	10	--	21	--	7	3.5	--	0.5	--	--	0.1	0.6	C	AC	112	85	3	F2
X63		58	10	—	23	6	--	--	--	--	--	1.25	--	0.4	C	AC	100	48	5	F2
HS-6		58	3	3	29	1.5	4	--	--	--	--	--	--	1.0	C	--	121	120	1.5	F2
MarM302		58	--	--	21	--	10	9	--	0.3	--	--	--	0.9	C	Aged	140	100	2	F2
ML1700		59	--	--	25	--	15	--	--	--	--	--	0.4	0.2	C	*	*	*	*	F2
MarM322		61	--	--	22	--	9	4.5	--	2	--	--	--	1.0	C	AC	121	91	3.2	F2
HS21		62	3	--	27	5	--	--	--	--	--	--	0.01	0.25	C	AC	101	82	8	F2
																Aged	124	110	2	
W1-52		65	--	--	21	--	11	--	2	--	--	--	--	0.45	C	AC	119	89	--	F2
HS23		66	2	--	24	--	6	--	--	--	--	--	--	0.4	C	AC	111	86	9	F2
																Aged	132	121	3	

*Asterisks denote that data are unavailable.

(a) Alloy designations normally used for identification are shown. Licensees may use somewhat similar designations (all wrought alloys are work hardenable).

(b) AH = age hardenable by heat treatment
NH = not usually hardened by heat treatment but can be in these cases.

(c) W = wrought products
C = castings.

(d) STA = solution treated and aged by heat treatment
ST = solution treated by heat treatment
AC = as cast.

(e) b = bar; p = plate.

(f) The various machinability classes are described on pages 3 and 4.

TABLE VII. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF COBALT-NICKEL-IRON-CHROMIUM ALLOYS

Machinability Classification — G

Alloy(a)	Type(b)	Nominal Chemical Composition, per cent													Usual	Room Temperature Properties			
																	Strength, ksi		Elongation,
		Co	Ni	Fe	Cr	Mo	W	Ta	Cb	Ti	Al	Mn	Be	C	Form(c)	Condition(d)	Tensile	Yield	per cent
Refractaloy 26	AH	20	37	18	18	3	--	--	--	2.9	0.2	--	--	0.05	W	STA	170	100	18
N155	NH	20	20	32	21	3	2.5	--	1	--	--	--	--	0.15	W	ST	117f	71	30
																	111b	54	57
S590	NH	20	20	27	20	4	4	--	4	--	--	--	--	0.43	W	*	*	*	*
Refractaloy 80	NH	30	20	14	20	10	5	--	--	--	--	--	--	0.10	W	Ann	100	84	3
															C	Ann	83	57	8
Refractaloy 70	NH	30	20	15	20	8	4	--	--	--	--	--	--	0.05	W	Ann	132	87	3
Elgiloy	WH/AH	40	15	16	20	7	--	--	--	--	--	2	0.04	0.15	W	CD (20%)	160 est	--	--
																CD (20% and aged)	185	129	17

*Asterisks denote that data are unavailable.

(a) Alloy designations normally used for identification are shown. Licensees may use somewhat similar designations (all wrought alloys are work hardenable).

(b) AH = age hardenable by heat treatment
WH = hardenable by cold working
NH = not usually hardened by heat treatment.

(c) W = wrought products
C = castings.

(d) STA = solution treated and aged by heat treatment
ST = solution treated by heat treatment
Ann = annealed
CD = cold drawn.

(e) f = forging; b = bar.

MACHINING BEHAVIOR

Table VIII indicates in a general way the relative difficulty of machining nickel- and cobalt-base alloys compared with that of machining other constructional materials. The values are based on the SAE ratings which use resulfurized B1112 steel as the standard of comparison. The listing indicates that metal-removal rates comparable with those for low-alloy and heat-treatable stainless steel (e.g., Type 410) are practical for the commercially pure nickels. The permissible cutting speeds are lower for most of the Monels and Inconels and comparable with those for austenitic stainless steel (e.g., Type 302). The superalloys are far more difficult to machine. The nickel-base and cobalt-rich alloys generally rate about the same except that the cast alloys from each group seem to be more abrasive to the

TABLE VIII. TYPICAL MACHINABILITY RATINGS OF NICKEL- AND COBALT-BASE ALLOYS (REFS. 18, 19, 20)

Alloy	Type	Condition[(a)]	Rating[(b)]
Aluminum	2017	T4	300
Resulfurized Steel	B1112	HR	100
Carbon Steel	1020	CD	70
Alloy Steel	A4130	A, CD	70
Stainless Steel	410	Ann	55
Nickel	Commercially pure	Ann	55
Alloy Steel	A4340	A, CD	50
Monel Alloy	501	Ann	45
Monel Alloy	K500	Ann	35
Stainless Steel	302	Ann	35
Hastelloy Alloy	C	Ann	20
Inconel Alloy	X750 and 718	STA	15
Haynes Alloy	HS25	Ann	10
Udimet Alloy	500 and 700	STA	9
Inconel Alloy	700	STA	9
René	41	ST	9
Co-Ni-Cr Alloy	J1570, J1650	STA	8
Haynes Alloy	HS31, HS21	Cast	6
René	41	STA	6

(a) T4 = solution heat treated and artifically aged
HR = hot rolled
Ann = annealed
STA = solution treated and aged
CD = cold drawn.

(b) Based on AISI B1112 steel as 100.

cutting tool (Refs. 14,15). These alloys have ratings and limiting cutting speeds ranging from one-half to one-sixth those of austenitic stainless steels (Refs. 16,17,18).

There are several reasons for the poor machinability of many of the nickel-base and cobalt-rich alloys. First, they are harder and stronger than other materials, as indicated in Table IX. Second, they are strain hardened more during machining by the plastic deformation that occurs in the chips and surface layer of the workpiece. Figure 3 compares the effects of deformation on the hardness of several metals differing in composition and initial hardness. Harder chips are more abrasive and accelerate tool wear. The original properties of the workpiece and those developed during machining control the cutting forces on the tool. Heat-treated nickel and cobalt-rich alloys require up to 2 hp for each cubic inch of metal removed per minute in contrast to about 0.8 hp for each cubic inch of metal removed per minute for carbon and low-alloy steels (Refs. 16,21,22).

TABLE IX. MECHANICAL PROPERTIES AND MACHINABILITY RATINGS FOR CERTAIN STEELS AND HIGH-TEMPERATURE ALLOYS

Alloy	Condition[(a)]	Strength, ksi		Elongation per cent	Machinability Rating
		Tensile	Yield		
2014 Aluminum	T4	62	42	20	300
B1112 Steel	HR	56	33	25	100
1020 Steel	CD	61	51	15	70
Monel Alloy K500	Ann	100	50	35	35
	STA	160	111	24	15
Inconel Alloy X750	STA	188	138	18	15
Haynes Alloy 25	Ann	150	70	65	10

(a) T4 = solution heat treated and artifically aged
HR = hot rolled
Ann = annealed
STA = solution treated and aged
CD = cold drawn.

About 95 per cent of the energy expended in machining is converted into heat. Other factors being equal, the increase in temperature at the cutting zone is related to cutting forces and energy requirements. However, the temperatures at the tool point depend on the rate at which heat is removed by the chip, the cutting fluid, and by conduction through the tool.

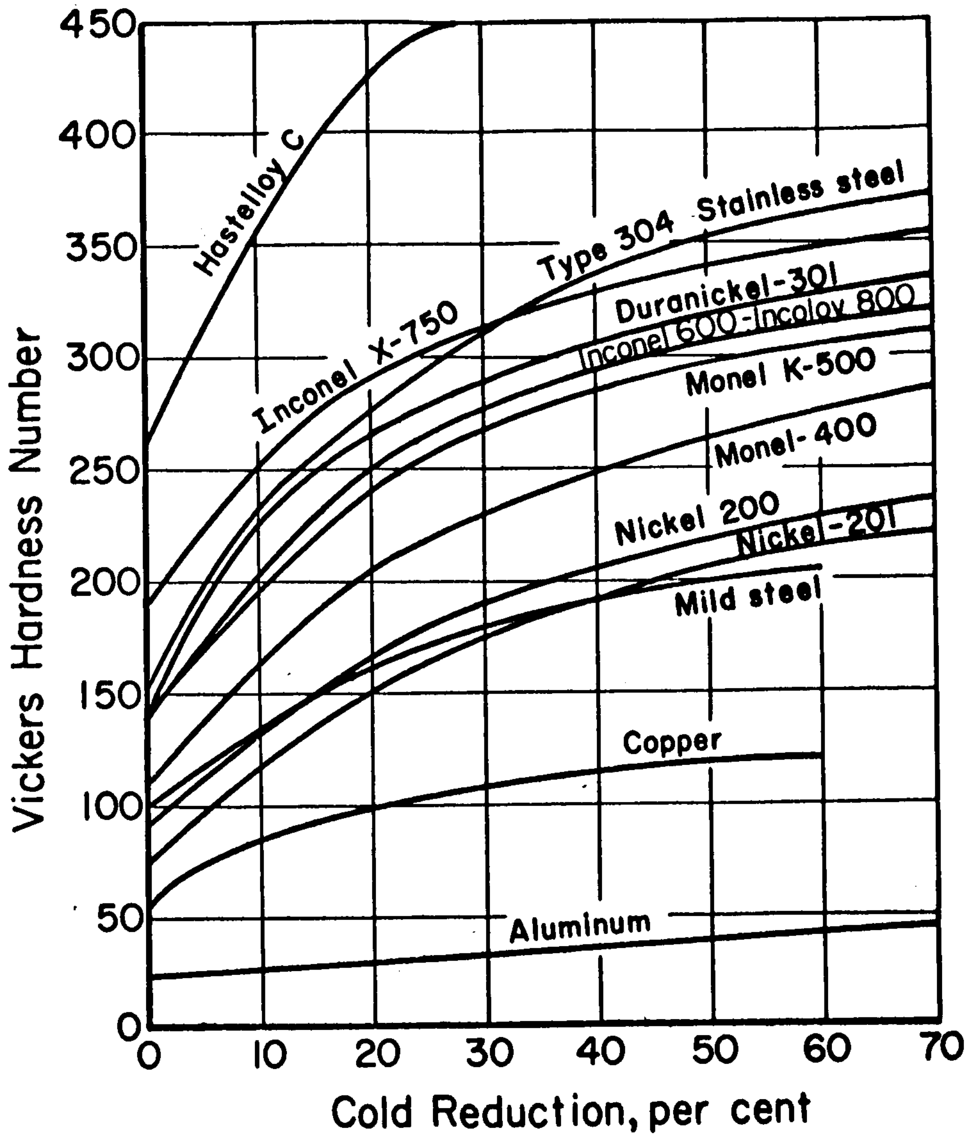


FIGURE 3. THE EFFECT OF COLD REDUCTION ON HARDNESS INDICATING WORK-HARDENING CAPABILITY

The heat-transfer characteristics of a material depend on thermal diffusivity, a function of density, specific heat, and thermal conductivity. Since nickel- and cobalt-base alloys exhibit poor thermal diffusivities, as indicated in Table X, tool-chip interface temperatures are higher than those realized when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided by suitable cutting fluids (Refs. 16,23,24).

TABLE X. PHYSICAL PROPERTIES AND RELATIVE HEAT-TRANSFER PROPERTIES OF NICKEL-BASE ALLOYS, 7075 ALUMINUM ALLOY, AND AISI 1020 STEEL (REF. 25)

Property	Monel	Hastelloy X	7075 Age-Hardened Aluminum Alloy	AISI 1020 Steel
Density, ρ, lb/in.^{3}	0.319	0.297	0.101	0.290
Thermal Conductivity, k, Btu/ft^2(hr)(F)(in.)	188	83.5	845	390
Specific Heat C, Btu/lb/F	0.110	0.105	0.21	0.117
Volume Specific Heat ρC, Btu/in.^{3}/F	0.035	0.031	0.021	0.031
Thermal Diffusivity, $\frac{k}{\rho C}$	5380	2690	39,800	11,500

The tendency to develop higher cutting temperatures during machining of difficult nickel-base and cobalt-rich alloys has several effects. It accelerates tool wear by lowering the strength of cutting tools (Refs. 14,16,23) and promotes chemical reactions and seizing which increase friction and cause chips to form a built-up edge on the tool and to adhere to the workpiece to give a poor surface finish. The use of slower cutting speeds and better cutting fluids will reduce energy requirements and tool-chip temperatures. Expedients that minimize deformation effects during machining are also desirable.

Work hardening can be minimized by using short, polished tools; larger (positive) rake angles to promote cutting instead of flow; and larger relief angles to prevent rubbing. Tools should not be allowed to dwell in the cut or to produce glazed or burnished surfaces (Refs. 19,23). Unusually light feeds and cut depths should be avoided. Some investigators recommend machining the heat-treatable alloys in the aged or partially-aged conditions to avoid work-hardening effects (Refs. 19,23). For the same reason, cold-drawn and stress-relieved stock is often preferred in alloys that are not hardenable by heat treatment.

GENERAL MACHINING REQUIREMENTS

The difficulties inherent in machining nickel- and cobalt-base alloys can be minimized considerably by providing the proper cutting environment. The basic requirements include rugged machine tools in good condition; vibration-free, rigid setups; high-quality cutting tools; and suitable speeds, feeds, and cutting fluids (Refs. 18,21,24, 26-29).

Machine Tools. Machine tools used for cutting nickel- and cobalt-base alloys need certain characteristics to insure rigid, vibration-free operation (Ref. 30). They are:

- Dynamic balance of rotating elements
- True running spindle
- Snug bearings
- Rigid frames
- Wide speed/feed ranges
- Ample power to maintain speed
- Easy accessibility for maintenance.

Milling machines and lathes should also possess backlash-elimination devices, and snug, clean, correctly lubricated gibs and slides (Ref. 21).

Vibration Effects. Vibration-free operation is favored by eliminating excessive play in power transmissions, slides, and screws of machine tools (Ref. 30). Undersized or underpowered machines should be avoided. Locating machines near or adjacent to heavy traffic can also induce undesirable vibration and chatter during machining. Last, but not least, insufficient cutter rigidity and improper tool geometry can contribute to vibration and chatter (Refs. 14,29,30).

Rigidity Considerations. Rigidity is a prime requirement since it can mean the difference between success and failure with highly work-hardenable nickel- and cobalt-base alloys (Ref. 22). It is achieved by using stiff tool-toolholder systems, and adequate clamps or fixtures to minimize deflection of the workpiece and tool during machining.

In milling operations, large-diameter arbors with double arm supports, short strong tools, rigid holding fixtures, frequent clamping, and adequate support of thin walls and delicate workpieces are desirable (Ref. 29).

Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, using a short tool overhang, and providing steady or follow rests for slender parts (Ref. 30).

Drilling, tapping, and reaming require short tools, positive clamping, and backup plates on through holes (Refs. 29,30).

Cutting-Tool Requirements. High-quality cutting tools are needed for all machining operations. They should be properly ground and finished. The face of the tool should be smooth, and the cutting edges sharp and free of burrs (Ref. 29). Sharp tools help to assure a positive cut and to lessen the work-hardening response (Ref. 14).

Cutting edges should combine the proper balance of toughness, hot strength, and abrasion resistance required for the alloy being machined. Since the shear strengths of most nickel- and cobalt-base alloys are about twice those of plain carbon steels, the edge strength must be sufficient to support the cutting loads involved. Toughness of a tool is usually balanced against the hardness requirements, although high hot hardness is usually needed to retain abrasion resistance at metal cutting temperatures (Ref. 15).

Milling cutters, drills, and taps should be mounted to run true. Lathe tools usually should cut on dead center. In a multiple-tooth cutter like a mill or a drill, all teeth should cut the same amount of metal (Ref. 18).

Tool Materials. One of the critical decisions in a metal-cutting system is the choice of cutting-tool materials (Ref. 31). Tool materials adequate for machining conventional constructional materials like steel are not necessarily satisfactory for nickel and cobalt alloys.

At the risk of oversimplification, tool materials of high-speed steel, cast alloy, and carbide are all alike to the extent that they contain hard, brittle, refractory carbide particles held in a lower-melting metallic matrix. The major difference lies in the amount of carbide present, since the matrix phase of the various materials has similar melting points and, in general, is quite strong and relatively tough. High-speed steels with the lowest carbide volume are the toughest but also the least wear resistant. The cemented carbides, with high abrasion resistance but reduced toughness, lie at the opposite end of the scale. The cast cobalt alloys occupy an intermediate position (Ref. 32).

Carbide, cast-alloy, or high-speed-steel cutting tools can be used when machining cobalt- and nickel-base alloys. The choice depends on seven basic factors including:

(1) The condition of the machine tool

(2) The rigidity of the system

(3) The type of cut

(4) The surface condition of the workpiece

(5) The amount of metal to be removed

(6) The metal removal rate

(7) Tool life desired.

Carbide cutting tools are used for high-production items, extensive metal-removal operations, and scale removal. The so-called nonferrous or cast-iron grades of carbides are normally preferred. These have been identified as CISC Grades C-1 through C-4, inclusive, by the Carbide Industry Standardization Committee. A partial list of companies producing these grades of carbide cutting tools is given in Table XI.

Competitive brands of cutting tools classified as belonging to the same grade are similar but not identical. Variations in tool life should be expected from tools produced by different manufacturers and between lots made by the same producer. For this reason, some aircraft companies specify their own lists of interchangeable carbide tools made by approved manufacturers.

Carbide tools require heavy-duty, amply powered machine tools and vibration-free tool-work setups to prevent chipping. If these basic conditions cannot be met then high-speed steel tools give better results.

TABLE XI. TOOL MATERIAL GUIDE FOR CARBIDES

CISC[b] Grade	Partial List of Carbides[a] Made by Various Manufacturers												
	Adamas	Carmet	Carboloy	Firth Loach	Firthite	Kenna-metal	Newcomer	Sandvik Coromant	Talide	Tungsten Alloy	Valenite	VR/Wesson	Willey
C-1	B	CA3	44A	FA5	H	K1	N10	H20	C89	9	VC1	2A68, VR54	E8, E13
C-2	A	CA4	883, 860	FA6	HA	K6	N20	H1P	C91	9H	VC2	2A5, VR54	E6
C-3	AA	CA7	905	FA7	HE	K8	N30	H1P	C93	9C	VC3	2A7	E5
C-4	AAA	CA8	999	FA8	HF	K11	N40	H05	C95	9B	VC4	2A7	E3
C-5	DD	CA51	78C	FT3	TQA	KM	N50	S6	S88	11T	VC5	EE, VR77	945
C-5A	43A	CA610	370	FT41, FT5	TXH	K21	--	S1P	S88X	9S	VC125	VR77, VR75	8A
C-6	D	CA609	78B	FT4	TXH, TA	K2S	N60	--	S90	10T	VC6	VR75	710
C-7	C	CA608	78	FT6	TXL	K5H	N70	S1P	S92	8T	VC7	E, VR73	606
C-7A	548	CA606	350	FT61	T16, TAL	K4H	--	--	S92X	5S	--	VR73	6A
C-8	CC	CA605	330	FT7	T31, WF	K7H	N80	F02	S94	5S	VC8	EH	509, 4A

(a) For the same CISC grade, there seem to be no truly equivalent carbides of different brands. Where two carbide grades from the same manufacturer are shown for the same CISC grade, the first is sometimes recommended.

(b) Carbide Industry Standardization Committee.

Notes: (1) The following chip-removal applications have been used for the CISC grade indicated. It will be noted that some grades specify the type of metal removal for which they are best suited.

C-1 Roughing Cuts – cast iron and nonferrous materials
C-2 General Purpose – cast iron and nonferrous materials
C-3 Light Finishing – cast iron and nonferrous materials
C-4 Precision Boring – cast iron and nonferrous materials
C-5 Roughing Cuts – steel
C-5A Roughing Cuts and Heavy Feeds – steel
C-6 General Purpose – steel
C-7 Finishing Cuts – heavy feeds – steel
C-7A Finishing Cuts – line feeds – steel
C-8 Precision Boring – steel

(2) This chart can function only as a guide. The so-called "best grade" may differ for each specific job even if the material being machined is the same. The final selection can be made only by trial and error. Instructions regarding the specific use and application of any competitive grade should be obtained directly from the manufacturer.

High-speed-steel tools can be employed at lower production rates. Tool life is low by conventional standards.

Both the tungsten and molybdenum types of high-speed steel are used. The high hot hardness of tungsten high-speed steels results from the resistance to softening of tempered martensite by precipitation and coalescence of tungsten carbides at elevated temperatures. Molybdenum carbides, as found in molybdenum high-speed steel, dissolve more readily in austenite than do tungsten carbides but show somewhat greater tendencies to precipitate at tempering temperatures. Most molybdenum high-speed steels utilize both tungsten and molybdenum in suitable ratios to obtain the advantages of both elements.

Cobalt is often added to both tungsten and molybdenum high-speed steels to increase their hardness at temperatures above 1000 F. Ordinary high-speed steels become too soft to cut effectively much in excess of this temperature. Figure 4 shows this loss in hardness as temperature rises. It also shows that the cobalt grades exhibit the best hot-hardness values at temperatures above 850 F.

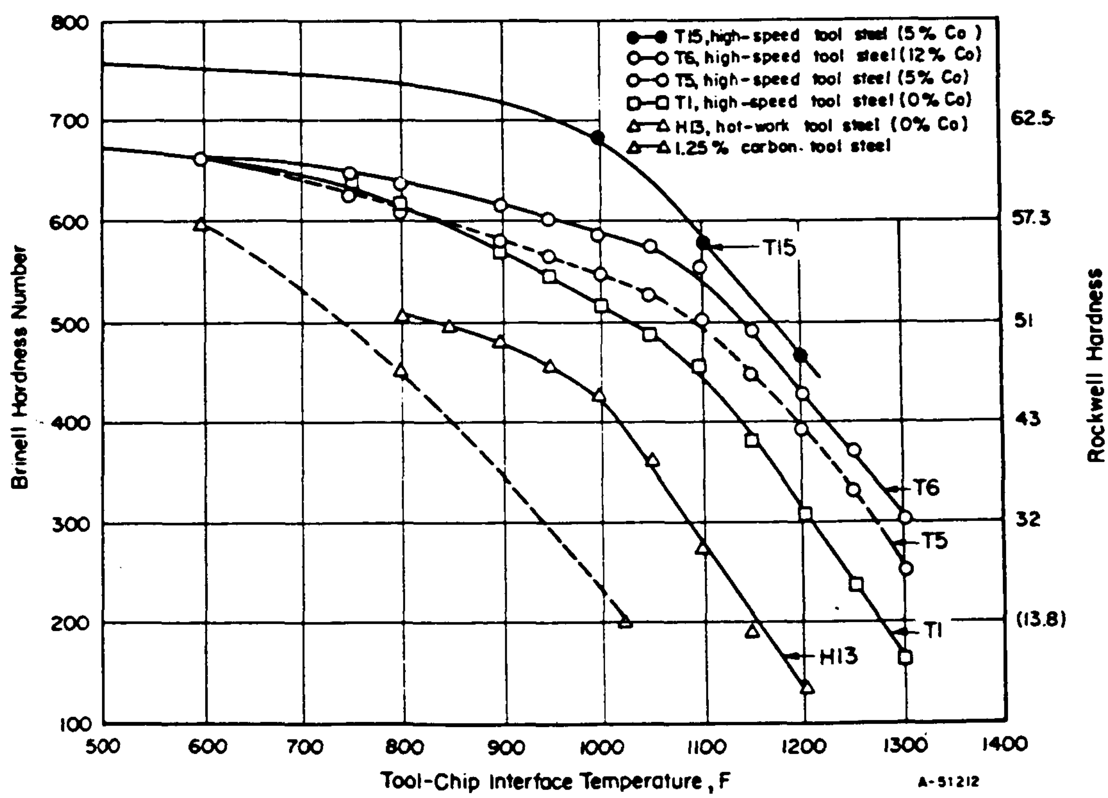


FIGURE 4. EFFECT OF TEMPERATURE ON THE HARDNESS OF VARIOUS TYPES OF TOOL STEEL

The high-vanadium high-speed steels are also effective above 850 F. These steels contain much more carbon than do the conventional grades. The use of higher carbon levels is made possible by increasing the vanadium content to maintain a specific ratio. This results in fine carbides that greatly increase wear resistance with little loss in toughness (Ref. 33). The high-vanadium T15 grade and the ultrahard high-speed steels of R_C 70 (AISI M41 to M44) are reputed to be harder than the tough grade of cemented carbide (Ref. 33).

Certain precautions must be observed, however, when the cobalt grades, high-vanadium grades, or the ultrahard high-speed steels are used. They are sensitive to checking and cracking from abrupt temperature changes such as might occur during grinding. These steels should be ground like carbides, and steps should be taken to prevent localized overheating, sudden heating, or cooling. They are more brittle than conventional high-speed steels, and hence are not usually suitable for razor-edged tools. In addition, precautions must be taken to protect cobalt high-speed steels from excessive shock and vibration in service.

While the ultrahards can be hardened to 68 to 70 R_C, only a relative handful of applications, mostly in turning and continuous cutting operations, have required these hardness levels (Ref. 34). Some of the ultrahigh-hardness high-speed steels perform better in milling cutters while others are better suited for special drills. The choice depends on details of specific operations. Unless a sound engineering approach is followed, indiscriminate use of any tool material is a sure way to increase tool costs and degrade performance (Ref. 34).

Table XII shows the wide choice of compositions of high-speed steels available to the tool engineer. There is little difference between the properties of conventional molybdenum and tungsten types of high-speed steel. Although each group has its supporters, extensive laboratory and production comparisons of comparable grades of the two types have not consistently established any outstanding superiority for either group. Of the conventional high-speed steels shown, recent production figures indicate that the M2 grade constitutes about 40 percent of the total production, the M1 grade about 25 percent, the M10 grade about 15 percent, and the T1 grade about 10 percent. This leaves only about 10 percent for the remaining high-speed steels, including the premium grades (Ref. 33).

From the standpoint of cutting ability, gains of one or two points of hardness in the 65 to 70 R_C hardness range are much more

TABLE XII. TOOL-MATERIAL GUIDE FOR HIGH-SPEED STEELS[(a)]

Group	AISI Code[(b)]	Composition, weight per cent				
		Tungsten	Chromium	Vanadium	Cobalt	Molybdenum
Tungsten	T-1	18	4	1	--	--
	T-4	18	4	1	5	--
	T-5	18.5	4	1.75	8	--
	T-6	20	4	2	12	--
	T-8	14	4	2	5	--
	T-15	14	4	5	5	--
Molybdenum	M-1	1.5	4	1	--	8
	M-2	6	4	2	--	5
	M-10	--	4	2	--	8
	M-3	6	4	2.75	--	5
	M-3, Type 1	6.25	4	2.50	--	5.70
	M-3, Type 2	5.6	4	3.3	--	5.50
	M-4	5.50	4	4	--	4.50
	M-6	4	4	1.5	12	5
	M-7	1.75	3.75	2	--	8.75
	M-30	2	4	1.25	5	8
	M-33	1.75	3.75	1	8.25	9.25
	M-15	6.5	4	5	5	3.5
	M-34	2	4	2	8	8
	M-35	6	4	2	5	5
	M-36	6	4	2	8	5
	M-41	6.25	4.25	2	5	3.75
	M-42	1.5	3.75	1.15	8	9.5
	M-43	1.75	3.75	2	8.25	8.75
	M-44	5.25	4.25	2.25	12	6.25

(a) Data from Metals Handbook, Eighth Edition, American Society for Metals (1961), p 672. For commercial listings, reference can be made to "A Guide to Tool Steels and Carbides", Steel (April 21, 1958), Cleveland 13, Ohio; or to "Directory of Tool, Die Steels, and Sintered Carbides", Twenty-Seventh Edition (1959), The Iron Age, Philadelphia 39, Pennsylvania.

(b) When greater than average red hardness is needed, cobalt-containing grades are recommended. So-called parallel grades in the molybdenum and tungsten groups are not necessarily comparable. For example, special-purpose steels such as T-6, T-8, T-15, and M-6, M-35, and M-36 seem to have no close counterparts in the opposite group. The unique compositions and properties of these steels often suit them to certain applications without competition.

significant than equivalent differences at lower hardness levels. Thus the ultrahard high-speed steels could become very useful for machining nickel and cobalt alloys. They also could provide an alternate material for carbides where cutting speeds are too low for optimum carbide performance, or where carbides fail because of shock or low strength in thin sections (Refs. 34,35).

As stated earlier in this section, cast cobalt-chromium-tungsten alloys are useful when machining metals at speeds intermediate between carbide and high-speed steel. Different grades are marketed, some of which are listed in Table XIII.

Cutting Speed. Cutting speed is the most critical variable affecting tool life and metal removal rates. Tool life decreases exponentially with increases in speed. The relationship between removal rates and speed is linear and direct. Excessive speeds cause high tool-chip interface temperatures and uneconomically short tool lives. Speeds between 10 and 170 fpm are used when turning nickel-base and cobalt-rich alloys with high-speed steel tools. Higher speeds are possible with carbide tools in similar machining situations. Specific recommendations are given in the sections devoted to particular operations.

Feed. All machining operations on these alloys require a positive, uniform feed to prevent glazing, burnishing, or work hardening the surface (Ref. 14). The cutting tool should never dwell or ride in the cut without removing metal (Ref. 15). As an added precaution, all cutters should be retracted when they are returned across the work (Ref. 29).

Acceptable feed rates fall into a narrower bracket than those commonly used on steels. The higher cutting pressures produced by cobalt and nickel alloys require that the feed be lowered to prevent deflection. On the other hand, excessively light feeds result in continuous cutting in the hardest portion of the work-hardened layer (Ref. 22).

Cutting Fluids. The use of cutting fluids is desirable in machining operations on nickel-base and cobalt-rich alloys. However, the flow should be forceful and continuous. Erratic or interrupted flow on a working cutting edge will do more harm than good, particularly on carbides (Ref. 15).

TABLE XIII. TOOL-MATERIAL GUIDE FOR CAST ALLOYS

	Composition, weight per cent									Hardness, R_C
	Cobalt	Chromium	Tungsten	Carbon	Nitrogen	Iron	Tantalum	Boron	Others	
Stellite 19[(a)]	50.6	31	10.5	1.9	--	3.0 max	--	--	3.0	55
Stellite 3[(b)]	46.5	30.5	12.5	2.45	3.0 max	3.0 max	--	--	2.0	60
Tantung G[(c)]	46	28	16	2.0	--	2.0	5	0.2	2.0	--
Stellite Star-J[(d)]	40.5	32	17	2.5	2.5 max	3.0 max	--	--	2.5	61
Stellite 98M2[(e)]	37.5	30	18.5	2	3.5	2.5 max	--	--	6	63

(a) Possesses the highest resistance to shock loading or intermittent-cutting effect, but the lowest red hardness of the alloys listed.

(b) Possesses higher hardness, but lower impact strength than Stellite 19. If Stellite 3 can handle the shock conditions of cutting, it is preferable to Stellite 19.

(c) A good compromise of hardness and shock resistance.

(d) Among the materials, the hardness of Star-J is second only to 98M2. It should machine metal faster than Stellites 3 and 19 under moderate impact conditions. Stellite Star-J is suitable for milling cast iron.

(e) Possesses the highest hardness of the materials listed, but only fair impact strength.

Highly active cutting fluids are widely used in machining nickel- and cobalt-base alloys. These fluids promote formation of adsorbed films on freshly cut metal. For example, a sulfur-containing additive reacts with the freshly cut metal to form a metal-sulfide film. This film is more easily sheared than the parent metal and also keeps the chips and tool apart. This protects the tool face from pressure welding. The film, being an excellent lubricant, also reduces chip friction.

Nickel- and cobalt-base alloys respond well to highly active cutting fluids like ordinary sulfurized or sulfochlorinated mineral oil (Refs. 23,36). As stated above, sulfur imparts improved lubricity and antiweld properties and also provides better chip action by embrittling the metal surface layer on the chip (Ref. 24).

If the oil temperature and the workpiece temperature become too high during machining, brown sulfur staining can occur on nickel alloys. This stain can be removed readily with a proprietary cleaning solution of the sodium cyanide or chromic-sulfuric acid type. This should be done prior to any thermal treatment since this stain can cause intergranular attack upon further exposure to elevated temperatures. Prolonged exposure to some acid solutions will cause severe intergranular corrosion, therefore, parts should be immersed in cleaning solutions no longer than necessary (Ref. 23).

When using high-sulfur oils with carbide tools in high-speed cutting operations, early breakdown of the cutting edges may result from attack on the nickel or cobalt binder because of the high cutting temperatures involved. Flooding the cutting area with fluid will generally cool the tool bit sufficiently to avoid this trouble (Refs. 23,36). Addition of 10 to 25 per cent kerosene is sometimes recommended to minimize this type of attack (Ref. 36).

Water-base coolants are preferred in high-speed operations such as turning, milling, and grinding because of their greater cooling effect. These fluids can be soluble oils or proprietary chemical mixtures. The chemical activity desired is generally provided by chlorine compounds (Refs. 23,36). A chemical coolant may consist of a synthetic base with added wetting agents, water conditioners, germicides, rust inhibitors, and a nonferrous deactivator. It is diluted 30:1 and is usually flood applied.

Sometimes paste-type lubricants, like lithopone paste, are used in very low-speed operations like tapping.

All lubricants must be removed completely from machined parts, particularly if they are to be subjected to high temperatures, either during subsequent fabrication or in service (Ref. 36).

The following tabulation classifies the cutting fluids mentioned and gives the symbols used in subsequent tables of this report.

Symbol	Cutting Fluid
I	Water-base coolant, soluble-oil type, or chemical type
IIa	Sulfurized oil
IIb	Sulfurized oil + 10 to 25 per cent kerosene
IIIa	Chlorinated oil
IIIb	Highly chlorinated oil
IV	Sulfochlorinated oil

MILLING-TYPE OPERATIONS

Introduction. Milling is an intermittent cutting operation, which can be difficult to control because of the large number of variables involved. Galling, edge chipping, and subsequent tool failure are the basic problems for nickel- and cobalt-base alloys. Additional problems include heat, deflection, abrasion, and distortion (Ref. 21).

The amount of metal smeared on cutter edges by galling is proportional to the thickness of the chip as it leaves the cut. The smeared metal and a small part of the underlying edge of the tool later chips off when the tooth re-enters the cut. This starts the wearland. Galling and chipping continue to cause gradual wear until the tool fails suddenly (Ref. 29). As the tool wears, the surface finish deteriorates, and it eventually becomes difficult to control dimensions.

The attritionous tool wear just described can be minimized by climb milling, a cutting situation where the direction of cutter rotation and table movement is the same. This process gives a shorter tool path and a thinner chip when the tooth leaves the workpiece. Both factors reduce the amount of metal adhering to the cutting edge, and wear from that source. Some problems result from the deflection of thin parts, or slender end mills or slotting cutters (Refs. 28,29), and from the distortion of workpieces accompanying the mechanical relief of residual stresses. In the latter case, thermal stress-relieving treatments in fixtures prior to machining is desirable.

Basic Milling Operations. Milling operations can employ either the face or peripheral milling approach. Face-milling operations employ the combined action of cutting edges located on both the periphery and face of the cutter. The milled surface is generally at right angles to the cutter axis, and is flat except when milling a shoulder. Face mills and end mills represent the tools used in this operation.

In peripheral or arbor milling the cutting teeth are located on the perimeter of the cutter body. The types of arbor-mounted cutters used include plain mills, helical mills, slab mills, side mills, and slotting cutters.

Face mills produce flat surfaces more efficiently and accurately than plain-milling cutters do (Refs. 36,37,38,39). Faster feed rates are also possible with face mills because they are more rugged. In addition, the complicated supports usually required for arbor-mounted cutters are unnecessary when face mills are used. Face milling is done with relative ease and is preferred whenever practical, because it minimizes work hardening and chattering (Refs. 23,28).

Machine Tool Requirements. Horizontal or vertical knee-and-column milling machines, as well as fixed-bed milling machines are used on various face- and end-milling operations. Numerically controlled or tracer-controlled milling machines could be used for profile and pocket-milling operations.

Generally speaking, 10 to 15 horsepower is usually sufficient for milling difficult materials. This means, for example, a Number 3 heavy-duty or a Number 4 standard knee-and-column milling machine. However, the machines needed to accommodate large parts may have as much as 25 to 50 horsepower available (Refs. 21,28).

Milling Cutters. The choice of the milling cutter depends on the type of machining to be done. Face mills, plain-milling cutters, and slab mills are usually selected for milling plane surfaces. End mills are suitable for light operations such as profiling and slotting (Ref. 37). Form cutters and gang-milling cutters are used for shaped cuts. Helical cutters are preferred because they promote a smoother cutting action. The use of the smallest diameter cutter with the largest number of teeth without sacrificing necessary chip space minimizes chatter and deflection (Ref. 39). All cutters, however, need adequate body and tooth sections to withstand the cutting loads developed in the particular machining operation.

Cutter Design. Tool angles of a milling cutter should be chosen to facilitate chip flow and immediate ejection of the chip. The controlling angles are the axial rake, radial rake, and corner angles.

Milling cutters generally use large enough helix angles (axial rake) to provide a good shearing action, and both rake angles are usually made positive to promote this action (Refs. 23, 29). Since welding and subsequent tool chipping is a problem for carbide cutters, a negative rake cutter (Tool Design H; see Figure 6 on page 34) has been used to minimize this possibility (Ref. 24).

The axial-radial rake-angle combination should be balanced with the corner angle to produce a positive angle of inclination. Positive-inclination angles lift the chip up and away from the machined surface and thus prevent scratching (Ref. 38). Angles of inclination, as well as true rake, can be determined from the intersection of an axial-rake/radial-rake line with a given corner angle on the nomographs shown in Figure 5. The angles involved are 0-degree axial rake, -10-degree radial rake, and a 30-degree corner angle.

The use of a corner angle not only encourages positive angles of inclination but it also provides a longer cutting edge to distribute cutting forces over a greater area. This results in lower cutting pressures and temperatures and less smearing. A 30 to 45-degree chamfer also produces a longer cutting edge and a wider thinner chip. However, a corner angle is usually more effective than a chamfer.

Conventional relief angles should be satisfactory when milling nickel- and cobalt-base alloys (Ref. 28). However, relief angles less than 1-1/2 degrees may lead to excessive smearing along the tool flank, while angles greater than 10 degrees weaken the tool and encourage "digging in" and chipping of the cutting edge (Ref. 39). Relief angles between 5 and 10 degrees are being used for most milling applications.

Tools. All cutters should be ground to run absolutely true in order to make the best use of the relatively light feeds used in milling these alloys, and to make certain that all teeth are cutting the

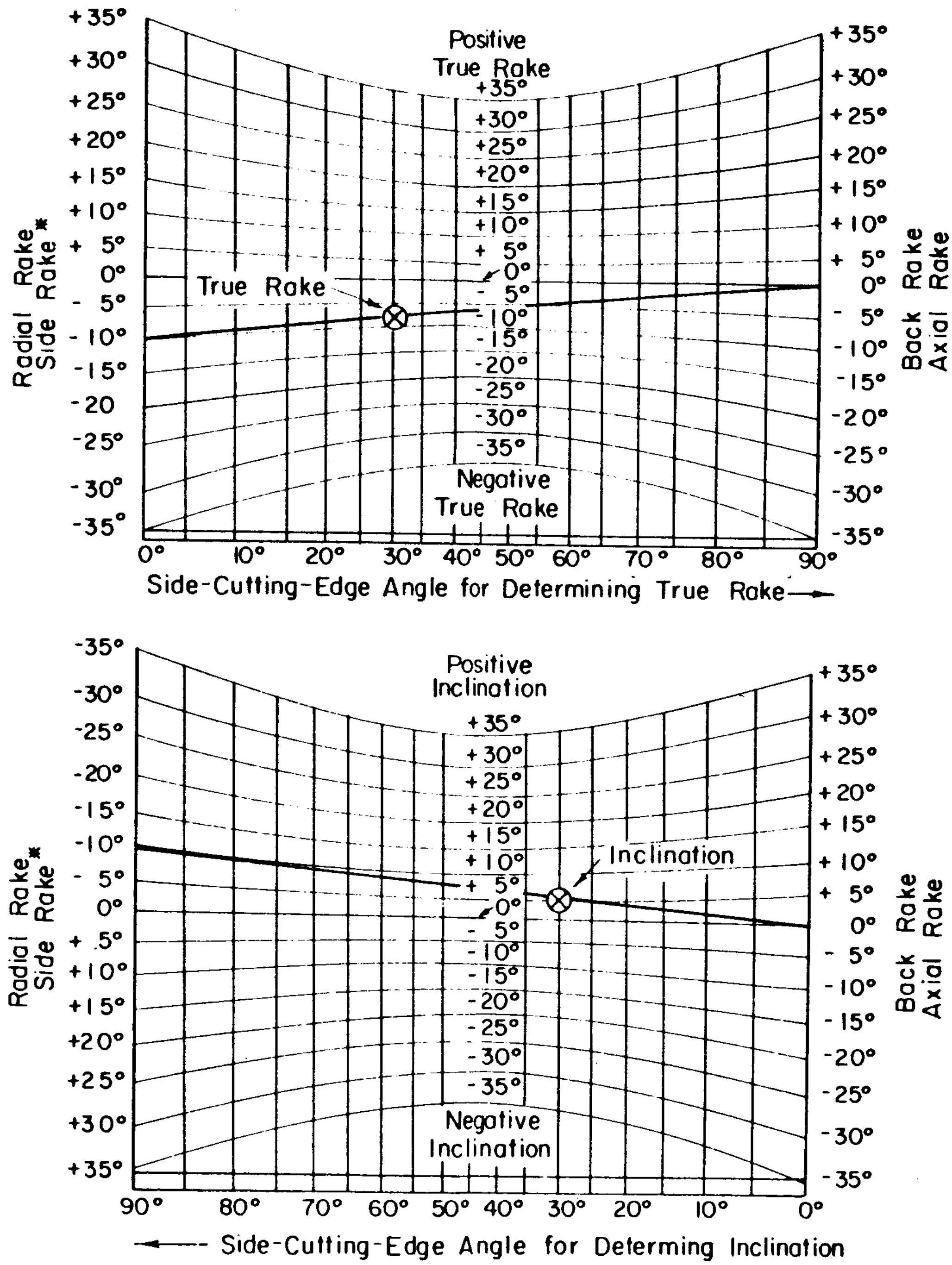


FIGURE 5. NOMOGRAPHS FOR DETERMINING TRUE RAKE AND INCLINATION ANGLES FOR MILLING CUTTERS (REF. 37)

*Turning tool nomenclature.

same amount of material. The total run-out should not exceed 0.001-inch total indicator reading (TIR) (Ref. 39).

The choice of the proper tool material is not a simple matter in milling and depends on the various factors already described. Carbide milling is not usually recommended because tools fail prematurely from chipping and localized breakdown (Refs. 21,22,24,40). Carbide cutters should not be used if the machine tool is not in good condition or if a setup cannot be made rigid enough.

High-speed-steel cutters are more reliable than carbide cutters and are popular because of their ready availability (Refs. 21,22,40, 41). The T5, T6, and T15 cobalt grades are used for maximum tool life (Refs. 24,39), whereas the regular Ml, M2, and M10 grades are suitable for low production milling (Refs. 23,28). High-speed steel can be used under conditions of insufficient rigidity, as well as for slots and formed cuts.

Some differences in the performance of high-speed-steel cutters may exist between cutters of the same type and geometry supplied by different manufacturers. This difference can be attributed to the geometry, composition, and/or heat treatment of the tool. Hence, purchasing specifications should cover both the grade and the heat treatment of the steel.

Setup Conditions. Fixtures should hold and support the workpiece as close to the machine table as possible. The solid part of the fixture rather than the clamps should absorb the cutting forces (Ref. 30). Fixtures should be rugged enough to minimize distortion and vibration.

The selection of speeds, feeds, and depth of cut in any setup should take into account the rigidity of the setup, the optimum metal removal rate/tool life values, and the surface finish and tolerances needed on the finished part.

Cutting Speed. When starting a new job, it is advisable to select a depth of cut for the job and then start in the lower portion of speed ranges suggested in pertinent tables of data (Ref. 39). Sufficient flywheel-assisted spindle power should be available to prevent loss in cutting speed as the cutter takes the cutting load (Ref. 30).

Feed. Feed rates for milling nickel- and cobalt-base alloys are necessarily limited to avoid overloading the cutters, fixtures, and milling machine. Lighter feeds reduce the tool/chip contact area, thereby reducing the incidence of welding and premature chipping. Delicate types of cutters and flimsy workpieces also require lighter feeds. However, too light a feed may produce a rubbing rather than a cutting action, thereby inducing a serious work-hardened layer on the part (Refs. 23,27). Hence, if deflection is a problem, it is better to reduce the depth of cut rather than lowering the feed below 0.002 ipt (Ref. 39).

It is important to maintain a positive feed since cutters must not idle or stop in the cut (Refs. 27,39). Climb milling is preferred to up milling for carbide tools because rubbing is avoided at the beginning of the cut (Refs. 22,24,28,39,40,41). Also, the downward motion assists rigidity and diminishes the tendency to chatter (Ref. 23). The disadvantage of climb milling is the necessity for positive control of backlash in the table drive (Ref. 23).

Depth of Cut. The selection of cut depth depends on setup rigidity, part rigidity, the dimensions and tolerances required, and the type of milling operation undertaken. Depths of cut up to 0.25 inch can be used if sufficient power is available. When forging scale is present, the nose of each tooth must be kept below the hard skin to avoid rapid tool wear.

Cutting Fluids. Sulfurized mineral oils and highly chlorinated oils are used extensively and are usually flood applied (Refs. 22,41). Water-base fluids are also used.

Good tool life can be obtained by using the spray-mist technique for all water-base coolants. The mist should be applied ahead of a peripheral-milling cutter (climb cutting), and at both the entrance and exit of a face-milling-type cutter. Pressurizing the fluid in an aspirator system permits better penetration to the tool-chip area, better cooling, and better chip removal (Ref. 27). There are a number of proprietary fluids that are producing excellent results.

General Supervision. All milling operations require reasonably close supervision. The supervisor should check new milling setups before operations begin. Thereafter, he should spot check for nicks and scratches to prevent potentially defective parts from being processed too far.

Milling cutters should be kept sharp (Refs. 29,39); therefore, they should be examined for buildup and early indications of dulling.

Some people advocate that the cutting faces should be honed between cuts to remove buildup, so that the cutter teeth will not be damaged (Ref. 39). Others recommend having at least two cutters available in case replacement is necessary for a given operation. Minimum downtime usually occurs when the entire cutter is replaced by a new one. In any case, cutters should be removed before too much wear develops.

The normal criterion of wear for replacing a cutter is considered to be a wearland of 0.010 inch for a carbide cutter and 0.015 inch for a high-speed steel cutter (Ref. 28).

Cutters should be carefully ground and lapped (preferably liquid honed) to exact dimensions before use. These tools usually have an average life of three times that of equivalent tools used in the as-received condition. Additional costs for this extra care in preparing cutters are more than made up in reduced cost per inch of cut as a result of reducing downtime, tripling cutter life, and producing higher quality work (Ref. 27).

Face Milling. Face mills are used for milling relatively wide, flat surfaces usually wider than 5 inches (Ref. 37). Typical designs include those of "Futurmill", "Ingersoll", and styles of other manufacturers. Special face mills are also used and include the rotating insert and conical types.

Diameters of face mills are important. They should be as wide but not appreciably wider than the width of the cut. If a smaller diameter cutter can perform a given operation and still overhang the cut by 10 per cent, then a larger cutter should not be used. Conversely, it is not good practice to bury the cutter in the work (Ref. 39).

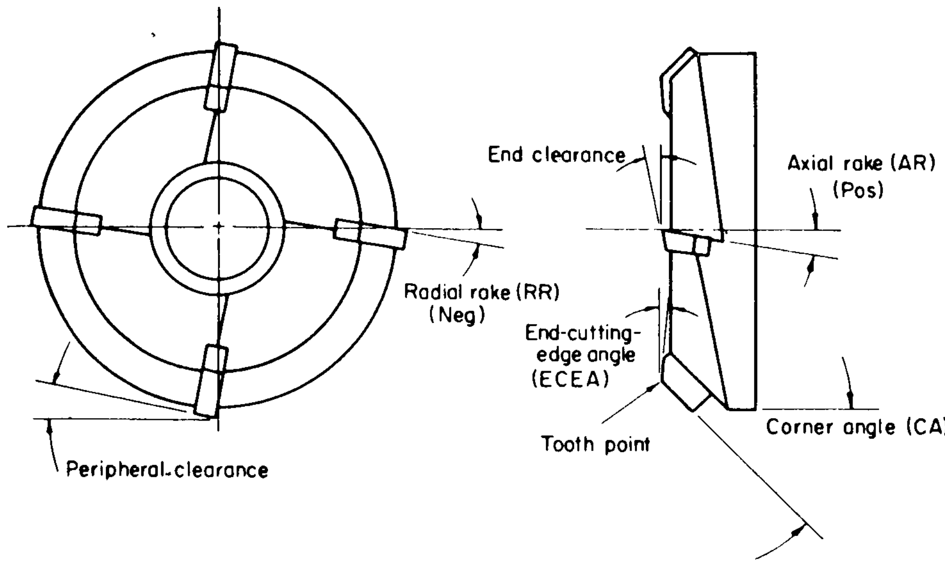
Face mills and shell end mills range from 1 to 6 inches in diameter. Face mills are also available in diameters greater than 6 inches. A good surface finish and freedom from distortion are desirable qualities when machining a wide surface. Surface finish, in the case of milling, improves significantly with decreasing feed, but only slightly with increasing speed.

Table XIV contains typical data on feeds, speeds, depths of cut, and tool design. Figure 6 explains the tool angle nomenclature and the tool designs used.

TABLE XIV. FACE MILLING NICKEL- AND COBALT-BASE ALLOYS WITH HELICAL FACE MILLS
(REFS. 9, 10, 18, 19, 21, 23, 24, 27, 28, 36, 39-41, 43, 44)

Alloy			Carbide						High-Speed Steel					
			Tool						Tool					
Group	Group Representatives	Alloy Condition(a)	Grade(b)	Design(c)	Depth of Cut, inch	Feed, ipt	Cutting Speed(d), fpm	Cutting Fluid(e)	Grade(b)	Design(c)	Depth of Cut, inch	Feed, ipt	Cutting Speed(d), fpm	Cutting Fluid(e)
A	Nickel, wrought	CD	--	--	--	--	--	--	M2, M10	A	*	0.004	80-100	I
			C-2, C-3	E	0.05-0.25	0.006-0.008	325-400	I	M3, T5	F	0.05-0.25	0.004-0.006	95-125	I
B1	Monels, wrought	CD	--	--	--	--	--	--	M2, M10	A	*	0.008	60-180	I
			C-2, C-3	E	0.05-0.25	0.006-0.008	325-400	I	M3, T5	F	0.05-0.25	0.004-0.006	95-125	I
B2	Monels, cast	AC	C-2	E	0.05-0.25	0.006-0.008	220-275	I	T5, M3	F	0.05-0.25	0.004-0.006	75-105	I, IIa
C1	Hastelloy B and C	ST	C-2, C-3	E	0.05-0.25	0.004-0.006	150-220	I	T15	F	0.05-0.25	0.003-0.005	50-70	IIa, III, IV
C2	Incoloys	Ann	--	--	--	--	--	--	M2, M10	A	*	0.003-0.006	30-40	IIa
C3	Hastelloy X	ST	--	--	--	--	--	--	T5, T15	*	0.10-0.20	0.002-0.006	15-25	IIa
			--	--	--	--	--	--	T5, T15	G	0.015-0.10	0.006-0.020	35-50	IIa
D	Inconels	ST	C-2, C-3	E	0.05-0.25	0.003-0.005	50-70	I	T15	F, D	0.05-0.25	0.002-0.003	15-25	IIa, III, IV
			C-1	H	0.125-0.25	0.006-0.010	40-70	I	T15	G	0.03-0.125	0.003-0.006	25-35	IIa, IIb
			--	--	--	--	--	--	M2, M10	A	*	0.004	10-20	IIa
		STA	C-2, C-3	E	0.05-0.25	0.004-0.006	50-70	I	T15	F	0.05-0.25	0.002-0.003	20-25	IIa, III, IV
			G-2	H	0.03-0.125	0.003-0.006	40-90	--	T15	G	0.03-0.125	0.003-0.006	15-30	IIa, IIb
					--	--	--	--	M2, M10	A	*	0.004	5-15	IIa
	Nimonic 80A	ST	--	--	--	--	--	--	T5, T15	G	0.03-0.125	0.003-0.006	25-35	IIa, IIb
	Nimonic 90	STA	--	--	--	--	--	--	T5, T15	G	0.03-0.125	0.003-0.006	15-30	IIa, IIb
E	Rene 41	ST	C-2, C-3	H	0.125-0.25	0.006-0.010	40-60	IIa, I	T15	C	0.05-0.10	0.006-0.011	22-35	I, IIIb
			C-2, C-3	H	0.05-0.25	0.003-0.006	50-70	I, IIIb	T15	E	0.05-0.25	0.002-0.003	20-25	IIa, IIIa, IV
			C-2, C-3	H	--	--	--	--	M2	*	*	0.004	20	I
		STA	C-2, C-3	H	0.03-0.125	0.003-0.006	60-100	IIa, I	T15	C, F	0.060-0.25	To 0.011	20-25	IIa, IIIa, IIIb, IV
			C-2, C-3	H	0.060-0.25	0.004-0.0065	50-70	IIIb, I	T15	G	0.03-0.060	To 0.006	25-35	I
									M3	J	0.010	0.002-0.006	15-20	IIa
	Udimet 500	ST	C-1, C-2	H	0.125-0.25	0.006-0.010	50-75	IIa, I	T15	F	0.05-0.25	0.002-0.003	20-25	IIa, IIIa, IV
			C-1, C-2	E	0.05-0.25	0.003-0.005	50-70	I	--	--	--	--	--	--
		STA	C-1, C-2	H	0.03-0.125	0.003-0.006	60	IIa, I	T15	I	0.060	0.005	25	I
			C-1, C-2	E	0.05-0.25	0.004-0.006	50-70	I	T15	F	0.05-0.25	0.002-0.003	20-25	IIa, IIIa, IV
	Inconel 700	ST	C-1, C-3	E	0.05-0.25	0.003-0.005	50-70	I	T15	F	0.05-0.25	0.002-0.003	20-25	IIa, IIIa, IV
		STA	C-2, C-3	E	--	--	--	--	T15	I	0.060	0.005	25	I
			C-2, C-3	E	0.05-0.25	0.004-0.006	50-70	I	T15	F	0.05-0.25	0.002-0.003	20-25	IIa, IIIa, IV
F	J1570	ST	C-1, C-2	H	0.125-0.25	0.006-0.010	40-60	IIa, I	T15	F	0.05-0.25	0.003-0.005	25-35	IIa, IIIa, IV
	S816		C-1, C-2	E	0.05-0.25	0.004-0.006	90-120	I	--	--	--	--	--	--
		STA	C-1, C-2	H	0.03-0.125	0.003-0.006	60-100	IIa, I	T15	F	0.05-0.25	0.003-0.005	25-35	IIa, IIIa, IV
			C-2, C-3	E	0.05-0.25	0.004-0.006	90-120	I	--	--	--	--	--	--
	HS25	ST	C-2, C-3	K	0.06-0.08	0.005-0.01	50	IIb	T15	F, J	0.05-0.25	0.003-0.006	20-35	IIa, IIIa, IV
	L605		C-2, C-3	E	0.05-0.25	0.004-0.006	90-120	I	M2	*	0.1-0.2	0.002-0.006	15-17	IV
	HS21	STA	C-2, C-3	E	0.05-0.25	0.004-0.006	90-120	I	T15	F	0.05-0.25	0.003-0.005	25-35	IIa, IIIa,

* Asterisks denote that data are unavailable.
(a) CD = cold drawn; Ann = annealed; ST = solution treated; STA = solution treated and aged; AC = as cast.
(b) CISC designation for carbides; AISI designations for high-speed steels.
(c) See Figure 6 for tool angles involved.
(d) The lower speed in each range is used for the heavier feeds and depths of cut.
(e) See page 34 for specific types.



	Tool Design Symbols										
	A	B	C	D	E	F	G	H	I	J	K
Tool Angles, degrees											
Axial rake	7	0	0	7	5 to 10	0 to +5	15	15	+10	0	0
Radial rake	15	7	30	15	0 to -5	0 to 5	10	-10	10	10	0
End relief	7 to 8	10	10	4	5 to 7	5 to 7	2 to 4	5	10	5	7
Peripheral relief	7 to 8	10	10	5	6 to 10	6 to 10	2 to 4	5	10	5	7
End-cutting edge		5	5	5	4 to 7	4 to 7	1 to 3	5	5	5	15
Corner		45	45	45	45	45	45	65	45	45	15
Tool material	--	Carbide	High-speed steel	--	Carbide	High-speed steel	High-speed steel	Carbide	High-speed steel	High-speed steel	--

FIGURE 6. TOOL GEOMETRY FOR FACE MILLS

End Milling. End milling, a type of face-milling operation, utilizes the cutting action of teeth on the circumferential surface and one end of a solid-type cutter (Ref. 37). End-milling cutters are used for facing, profiling, and end-milling operations and include the standard end mills and two-lip end or slotting mills (Ref. 37). Chip crowding, chip disposal, and tool deflection are possible problems in some end-milling operations. Another problem is the production of nonperpendicular sides or grooves. Sometimes the high cutting pressure needed to machine strong alloys causes cutter deflection. The problem is minimized by using a four-flute end mill and then taking cuts in proportion to the rigidity of the cutter (Ref. 39).

Due to this inherent lack of rigidity, end mills should be as short as practical (Refs. 29,39), and their shank diameter should equal their cutting diameters. The proper combinations of hand of helix and hand of cut should be considered to avoid deflection of the cutter in the direction of an increasing depth of cut (Ref. 37).

When milling slots where the end of the cutter is in contact with the work, the hand of the helix and the hand of the cut should be the same. This means a right-hand helix for a right-hand cut, or a left-hand helix for a left-hand cut (Refs. 36,37,39).

When profile milling, where the periphery of the cutter is doing the cutting, the opposite is true, i.e., left-hand helix for a right-hand cut and vice versa (Refs. 36,37).

Cutter diameter in profile or pocket milling depends on the radius needed on the pockets.

High-speed-steel cutters are normally used for end milling and profile-milling operations. Helical-style cutters give better performance than the straight-tooth designs do. The shank of end mills should be somewhat softer than the cutter flutes to avoid breakage between shank and flutes.

Tables XV and XVI provide machining data for profile milling and slotting operations. Figure 7 illustrates the tool nomenclature used.

Slab Milling. Slab milling is used to improve the tolerances and surface finish on extrusions. The operation is usually done on a heavy duty, fixed bed mill like the Sundstrand "Rigid Mill".

Rigid setups are necessary. Arbor-mounted cutters require arbors of the largest possible diameter (Ref. 29). The arbor should

TABLE XV. PROFILING NICKEL- AND COBALT-BASE ALLOYS WITH HELICAL END MILLS (REFS. 23, 36, 44)

Alloy			Carbide							High-Speed Steel					
			Tool				Feed, ipt[e]		Tool				Feed, ipt[e]	
Group	Group Representatives	Alloy Condition[a]	Grade[b]	Design[c]	Depth of Cut, inch	Cutting Speed[d], fpm	3/8-In. Dia	3/4-In. Dia	Grade[b]	Design[c]	Depth of Cut, inch	Cutting Speed[d], fpm	3/8-In. Dia	3/4-In. Dia
A	Nickel, wrought	CD	C-2	A	0.015-0.05	275-325	0.001	0.002-0.003	M1, M2, M10, M15	A	0.015-0.05	100	0.001	0.002
B1	Monels, wrought	CD	C-2	A	0.015-0.05	275-325	0.001	0.002-0.003	Ditto	A	Ditto	80	0.001	0.002
B2	Monels, cast	AC	C-2	A	0.015-0.05	190-240	0.002	0.002-0.003	"	A	"	65	0.001	0.003
C1	Haselloy B and C	ST	--	--	--	--	--	--	--	--	--	--	--	--
C2	Incoloys	Ann	--	--	--	--	--	--	"	A	"	30-40	0.001	0.003
C3	Hastelloy X	ST	--	--	--	--	--	--	--	--	--	--	--	--
D	Inconels	ST	C-2	A	0.015-0.05	35-55	0.002	0.002-0.003	"	A, B	"	20-35	0.001	0.002-0.003
		STA	--	--	0.015-0.05	65-70	0.003	0.003-0.004	"	A, B	"	15-30	0.001	0.002-0.003
E	Nimonics 80A	ST	--	--	--	--	--	--	"	A, B	"	20-35	0.001	0.003
	Nimonics 90	STA	--	--	--	--	--	--	"	A, B	"	15-30	0.001	0.003
	René 41	ST	C-2	A	0.015-0.05	35-50	0.002	0.002-0.003	T15	A	0.015-0.05	15-20	0.001	0.002
	Udimet 500													
	Inconel 700	STA	C-2	A	0.015-0.005	65-70	0.003	0.003-0.004	T15	A	0.015-0.05	15-30	0.001	0.002
F	J1570	ST	C-2	A	0.015-0.005	80-110	0.002	0.002-0.003	T15	A	0.015-0.05	25-35	0.001	0.002
	S816													
	HS25	STA	C-2	A	0.015-0.005	80-100	0.002	0.002-0.003	T15	A	0.015-0.05	25-35	0.001	0.002
	L605													
	HS21													

Cutting Fluids: For nickel and Monels use water-base coolants, soluble oil type, or chemical type. For all other alloys use sulfurized oil, chlorinated oil, or sulfochlorinated oil.

(a) CD = cold drawn; Ann = annealed; ST = solution treated; STA = solution treated and aged; AC = as cast.

(b) CISC designation for carbides; AISI designations for high-speed steels.

(c) See Figure 7 for tool angles.

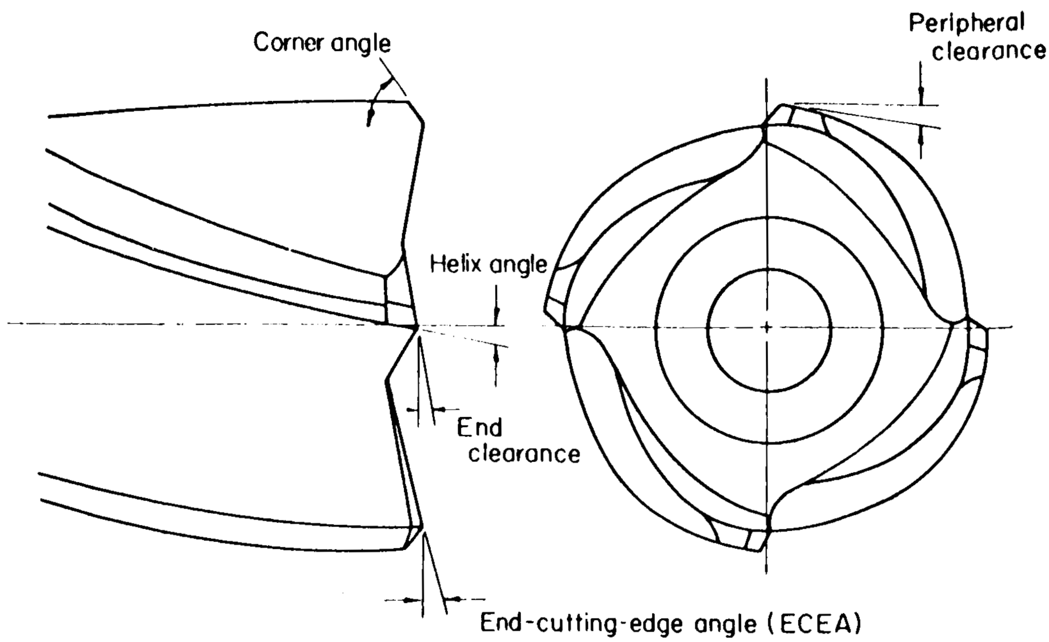
(d) The lower speed in each range is used for the lighter feeds and heavier depths of cut, and vice versa.

(e) Feeds are for 3/8 and 3/4-inch-diameter end mills. Lower feeds are needed for 1/8-inch end mills, and feeds up to 0.004 and 0.005 ipt are used for 1 or 2-inch end mills.

TABLE XVI. SLOTTING NICKEL- AND COBALT-BASE ALLOYS WITH PERIPHERAL AND END MILLS (REF. 24, 36)

Alloy			Carbide Peripheral Mills					High-Speed-Steel End Mills					
Group	Group Representatives	Alloy Condition[a]	Tool Grade[b]	Tool Design[c]	Depth of Cut, inch	Cutting Speed fpm	Feed, ipt	Tool Grade[c]	Tool Design[d]	Depth of Cut, inch	Cutting Speed, fpm	Feed, ipt 3/8 Dia	Feed, ipt 3/4 Dia
D	Inconels	ST						M2	B		25-35	0.002	0.004
		STA		--	--	--	--	T15	B		15-30	0.002	0.004
E	René 41	ST	C-2	C	0.125	95	0.003	M2	B	0.25	22	0.001	0.002
		STA	C-2	C	0.125	60	0.003	T15	B	0.25	18	0.001	0.002
F	Udimet 500	STA	C-2	C	0.125	100	0.005		C	0.25	30	0.001	0.002
	Inconel 700												

(a) ST = solution treated; STA = solution treated and aged.
(b) CISC designation for carbides; AISI designations for high-speed steels.
(c) See Figure 7 for tool angles.



	Tool Design Symbols		
Tool Angles, degrees	A	B	C
Helix	25	30 to 45 RH	35 RH
Radial Rake	5	10	
End clearance	2	2	
Peripheral clearance	6	10	12
End-cutting edge	3	3	
Corner		45 x 0.060	45 x 0.030

FIGURE 7. TOOL GEOMETRY FOR END MILLS

have just the proper length required for the number of cutters mounted and the arbor support employed (Ref. 37). Arbor overhang beyond the outer support should be avoided since it is conducive to chatter and vibration (Ref. 37).

Cutters should be mounted as close to the column face of the milling machine as the work will permit. The cutters of opposite hand to the cut should be used so that the cutting forces will be absorbed by the spindle of the machine (Ref. 37). This is accomplished by using cutters with a left-hand helix for a right-hand cut, and vice versa. The effective force involved will press the cutter and arbor against the spindle, holding them in position, thus providing a more rigid setup. When two milling cutters are used end to end on the arbor, both right-hand and left-hand helices should be used. This setup neutralizes the cutting forces that tend to push the cutters away from the work (Refs. 36, 37).

Carbide cutters are preferred for spar milling because of the higher production rates attainable. Helical-style cutters are recommended since they provide wider and thinner chips than do the corresponding straight-tooth types.

Table XVII gives machining data used for various slab-milling operations. Figure 8 provides the tool angles used for these data.

TURNING AND BORING

Introduction. Turning, facing, and boring operations are essentially the same and constitute one of the lesser machining problem areas (Ref. 28). They give less trouble than milling, especially when cutting is continuous rather than intermittent. The speeds used for turning can be used for boring and facing cuts. However, the depths of cut and feeds usually have to be reduced for boring, because of an inherent lack of rigidity of the operation.

Machine-Tool Requirements. In addition to the machine-tool requirements set forth earlier, it is very important that the proper cutting-speed ranges for nickel- and cobalt-base alloys are available at the machine. In general, the over-all range of spindle speeds available on many of the existing lathes is not broad enough to cover some of the lower speeds needed for these alloys.

Modern lathes should have either a variable-speed drive for the spindle; or the spindle gear train should have a geometric progression

TABLE XVII. SLAB MILLING NICKEL- AND COBALT-BASE ALLOYS WITH PLAIN HELICAL MILLS (REFS. 23, 44)

Alloy Group	Alloy Group Representatives	Alloy Condition(a)	Carbide Tool Grade(b)	Carbide Tool Design(c)	Carbide Depth of Cut, inch	Carbide Feed, ipt	Carbide Cutting Speed(d), fpm	Carbide Cutting Fluid(e)	High-Speed Steel Tool Grade(b)	High-Speed Steel Tool Design(c)	High-Speed Steel Depth of Cut, inch	High-Speed Steel Feed, ipt	High-Speed Steel Cutting Speed(d), fpm	High-Speed Steel Cutting Fluid(e)
A	Nickel,	CD							M2, M10	A, B	*	0.003	80-100	
			C-6, C-7		0.05-0.25	0.006-0.008	300-370	I	T15	F	0.05-0.25	0.005-0.007	85-110	I
B1	Monels, wrought	CD							M2, M10		*	0.007	60-80	I
			C-6, C-7		0.05-0.25	0.006-0.008	300-370	I	T15	F	0.05-0.25	0.005-0.007	85-110	I
B2	Monels, cast	AC			0.05-0.25	0.007-0.009	200-260	I	T15	F	0.05-0.25	0.006-0.008	70-105	I
C1	Hastelloy B and C	ST	C-2, C-3		0.05-0.25	0.005-0.007	130-190		T5, M15	F	0.05-0.25	0.004-0.006	30-45	IIa, IIIa, IV
C2	Incoloys								M2, M10			0.005	30-40	
C3	Hastelloy X		--		--	--	--							
D	Inconels	ST	C-2, C-3		0.05-0.25	0.004-0.006	40-55	IIa, IIIa, IV	T15	F	0.05-0.25	0.003-0.005	20-25	IIa, IIIa, IV
												To 0.006	25-35	
									M2, M10			0.003	10-20	
		STA							T15			0.003-0.005	20-25	IIa, IIIa, IV
									M2, M10			0.003	5-15	
	Nimonic 80A	ST			--	--	--	--				To 0.006	25-35	
	" 90	STA										To 0.006	15-30	
E	René 41	ST												
	Udimet 500		C-2, C-3	E	0.05-0.25	0.004-0.006	40-55	IIa, IIIa, IV	T15	F	0.05-0.25	0.003-0.005	18-25	IIa, IIIa, IV
	Inconel 700	STA												
F	J1570													
	S816	ST	C-2											
	HS25		C-3	E	0.05-0.25	0.005-0.007	85-105	IIa, IIIa, IV	T15	F	0.05-0.25	0.004-0.006	25-35	IIa, IIIa, IV
	L605	Ann												
	HS21													

* Asterisks denote that data are unavailable.

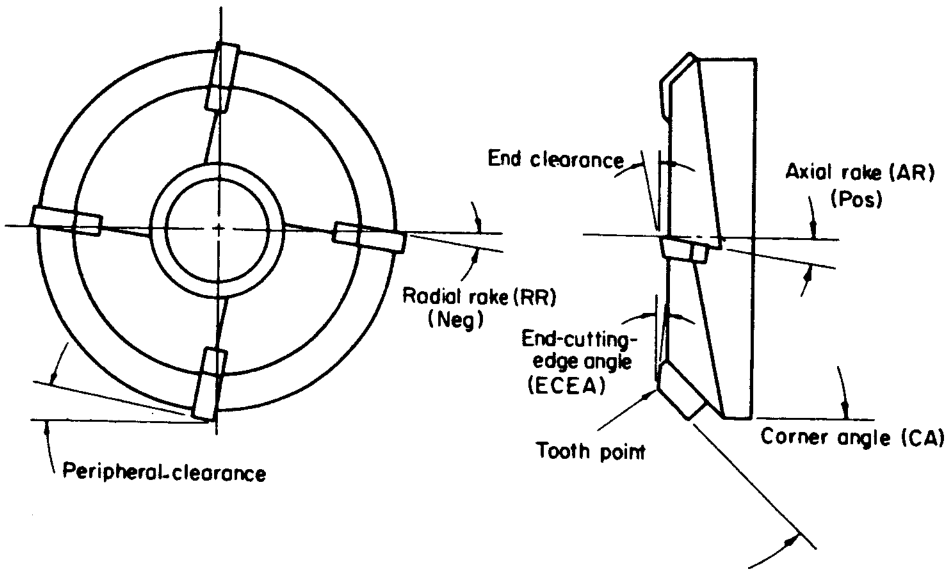
(a) CD = cold drawn; AC = as cast; ST = solution treated; STA = solution treated and aged; Ann = annealed.

(b) CISC designations for carbides; AISI designations for high-speed steels.

(c) See Figure 8 for tool angles.

(d) The lower speed in each range is used for the lighter feeds and heavier depths of cut, and vice versa.

(e) See page 34 for specific types.



	Tool Design Symbols		
	A	B	C
Tool Angles, degrees			
Axial rake	45	52 to 65	-5 binegative
Radial rake	+12	+15	+5
End relief	7 to 8	7 to 8	10
Peripheral relief	7 to 8	7 to 8	10
End-cutting edge			1
Corner			45 x 0.030

FIGURE 8. TOOL GEOMETRY FOR PERIPHERAL-MILLING CUTTERS

of 1.2 or less in order to provide speed steps of 20 per cent or less for more precise speed selections (Ref. 21).

The trend in new lathes is toward variable-speed drives. Rigidity, dimensional accuracy, rapid indexing of tools, and flexibility are additional features that are being emphasized (Ref. 21).

The application of numerically controlled machines for turning is rapidly spreading. On lathes equipped with tracer or numerical control, variable speed and feed features are being added so that the speed and feed can be optimized during contouring operations (Ref. 21).

Lathes with 10-horsepower ratings should be ample for most turning operations. Workpieces ranging between 1 inch and 10 inches in diameter can be turned on a standard or heavy duty 1610 engine lathe. The 1610 is the lathe-industry designation on 16-inch swing over bed and 10-inch swing over cross slide. These lathes have a range of spindle speeds that almost meet the requirements previously described (Ref. 21).

A modern lathe in good condition provides production rates of five to ten times the rates possible with older machines. Vibration and lack of rigidity are common problems in older equipment.

Cutting Tools. Standard cutting tools are used for turning nickel- and cobalt-base alloys. These are available in a variety of shapes, sizes, tool angles, and tool materials. High-speed steel, carbide, and cast-alloy tools can be used. In all cases, a minimum of overhang is needed to avoid tool deflection.

Tool Angles. Cutting tools should be designed to provide proper chip flow, minimum tool wear and tool forces, and maximum heat dissipation. The factors contributing to these desirable qualities include the nose radii and the rake, side-cutting edge, and relief angles (Ref. 42).

Positive, zero, and sometimes negative rake angles can be used depending on the properties of the workpiece, the tool material, and the type of machining operation. Positive rakes are usually recommended for these alloys because they reduce cutting forces, and produce better surface finishes (Refs. 16,17,21,43-45). Although positive-rake tools cut more freely than negative-rake tools, their cutting edges are weaker. Consequently, negative-rake tools are more effective in roughing cuts or other applications where the additional edge strength is needed.

The side-cutting-edge angle is the next important angle. A large angle lowers the cutting temperature by increasing the tool-chip contact area available for heat dissipation, and by reducing cutting pressures.

A side-cutting-edge angle of 40 degrees or possibly larger is recommended for turning operations that do not require form tools or machining against a shoulder (Refs. 15-17,24). The larger side-cutting-edge angles and their longer cutting edges reduce cutting temperatures and pressures. These reductions often permit greater feeds and speeds for equivalent tool life. Furthermore, thin chips are produced, and the depth-of-cut notch is reduced or eliminated. Excessive angles, however, can cause chatter (Ref. 16).

The side and end-relief angles provide clearance between the tool flank and the work, and the values selected usually represent a compromise between two extremes. Insufficient relief will cause tool rubbing against the workpiece as soon as a little tool wear has occurred. Excessive relief weakens the support of the cutting edge. The same situation applies to the end-cutting-edge angle. This angle supports the nose of the cutting tool by resisting the forces of tool feed. Relief angles between 5 and 12 degrees can be used on nickel- and cobalt-base alloys, but these angles should have values no greater than those just sufficient to prevent drag between the tool and workpiece (Refs. 24,36).

The long, tough, stringy chip obtained when turning nickel- and cobalt-base alloys is difficult to remove from the lathe and to keep clear of the work. Hence, the use of a chip breaker is recommended for good chip control, particularly on all boring and finishing cuts (Ref. 36).

Finally, the tool nose radius must be considered. This element of tool geometry joins the side and end-cutting edges of the tool. The scalloped effect produced by a tool with a nose radius provides better surface finishes, shallower scratches, and a stronger workpiece than the notched effect produced by a sharp-pointed tool. Oversized radii, however, interfere with cutting action, causing tool vibrations that tend to work harden the machined surface and reduce tool life (Refs. 16,17,23,45,46). A small nose radius, usually considered to be less than one-half the depth of cut, reduces work hardening and chatter, and generates less heat. However, tool life is somewhat lower due to the reduced strength of a small radius. A nose radius one-half the depth of cut, or somewhat larger, thins the chip which in turn tends to increase tool life. It also presents a much stronger cutting edge.

When turning nickel- and cobalt-base alloys, use the smallest nose radius that proves serviceable. For general usage, a 1/32-inch nose radius should be satisfactory (Ref. 16).

Tool Preparation. To minimize work hardening, cutting tools should be carefully ground and finished before use (Ref. 46). The direction of finishing scratches on the chip-bearing surfaces should correspond to the intended direction of chip flow. A rough surface can cause a properly designed tool to deteriorate rapidly.

The life of a carbide tool also can be extended if the sharp cutting edge is slightly relieved by honing; especially, tools used in heavy roughing cuts. Since all tools must be sharp, only a slight hone is recommended to give the added strength to the cutting edge and to reduce chipping. Tools for light, precision boring require either no honing or only a very slight removal of the feather edge. On finish cuts, where feeds of 0.003 ipr or less are required, it is desirable to lap the cutting edge rather than hone it (Refs. 15-17).

Tool Materials. High-speed-steel, cast-alloy, and cemented-carbide cutting tools are suitable for lathe-turning tools. This operation seems to be the only one where the latter can be used to advantage. Cobalt high-speed steels seem to perform best in boring operations (Refs. 28,46). Ceramic tools are not recommended since they do not have the edge strength necessary to cut superalloys (Ref. 15). The selection of a tool material for a given job depends on the factors described in the section on milling and on pages 17 to 23 inclusive.

Experience indicates that high-speed-steel cutters are best suited for form cuts, heavy plunge cuts, and interrupted cutting. Nonferrous-cast-alloy tools can be used for severe plunge cuts, machining to dead center, and cutting narrow grooves. Carbide cutting tools are recommended for continuous cuts, high production items, extensive metal-removal operations, and scale removal. Carbide cutting tools are the most sensitive to chipping, and therefore require "over-powered", vibration-free lathes, as well as more rigid-tool-work setups. If these conditions cannot be met, then high-speed steels must be used.

High-speed-steel and cast-alloy tools should be ground on a tool grinder rather than by hand. The same is true for carbide tools; however, off-the-shelf brazed and "throwaway" carbide tools often conveniently fit the rake-, lead-, and relief-angle requirements.

Carbide cutters are available as brazed, clamped, and throwaway tooling. Brazed tools may be purchased in standard sizes and styles as shown in Table XVIII, or they can be made in the shop. The performance of mechanically clamped inserts is at least as good as that of brazed tools, and they are often recommended because of their lower cost per cutting edge.

TABLE XVIII. TOOL GEOMETRIES OF BRAZED-CARBIDE TOOLS

	Design Symbols				
	A	B	C	D	E
Tool Angles, degrees					
Back rake	0	0	0	0	0
Side rake	7	7	0	0	0
End relief	7	7	7	7	7
Side relief	7	7	7	7	7
End-cutting edge (ECEA)	8	15	--	50	60
Side-cutting edge (SCEA)	0	15	--	40	30

Throwaway carbide inserts are designed to be held mechanically in either positive- or negative-rake tool holders of various styles and shank sizes. The general coding system for mechanical tool holders is explained in Table XIX. The tool geometries available for solid-base tool holders and suitable for nickel- and cobalt-base alloys are shown in Table XX.

A word of caution, however, is in order regarding tool holders. Abnormal failure of carbide inserts can be caused by tool holders operating beyond replacement age. Worn and damaged tool holders do not provide optimum insert support or registry. They make the carbide inserts prone to early failure (Ref. 15).

Substantial reductions in costs are claimed by users of throwaway tooling. Factors contributing to this saving are:

- Reduced tool-grinding costs
- Reduced tool-changing costs
- Reduced scrap

TABLE XIX. EXPLANATION OF GENERAL CODING SYSTEM FOR MECHANICAL TOOL HOLDERS

Company Identification	Shape of Insert	Lead Angle	Rake Angle	Type Cut
(+)	T	B	(•)	R or L
(+)	R	A	(•)	R or L
(+)	P	A	(•)	R or L
(+)	S	B	(•)	R or L
(+)	L	B	(•)	R or L

Shape of Insert	Lead Angle or Tool Style	Type Cut
T = triangle	A = 0-degree turning	R = right hand
R = round	B = 15-degree lead	L = left hand
P = parallelogram	D = 30-degree lead	N = neutral
S = square	E = 45-degree lead	
L = rectangle	F = facing	
	G = 0-degree offset turning	

(+) Some producers place a letter here for company identification.

(•) Some companies use the letter "T" for negative rake, "P" for positive rake, and sometimes add "S" to indicate "solid-base" holders. For example, a TATR designation denotes a tool holder for a triangular insert mounted in such a way to give a 0-degree lead angle, and a 5-degree negative rake. The "R" denotes a right-hand cut. As shown in Table XX, 5-degree rakes are usually supplied; hence rake-angle values are not included in the tool-holder designation.

TABLE XX. TOOL GEOMETRIES OF SOLID-BASE TOOL HOLDERS FOR THROWAWAY INSERTS

Negative Rake Tools				Positive Rake Tools			
Tool Angle, degrees							
Back rake, -5 Side rake, -5 End relief, 5 Side relief, 5				Back rake, 0 Side rake, +5 End relief, 5 Side relief, 5			
Tool Holder Style[a]	Type Insert[a]	ECEA, degrees[b]	SCEA, degrees[c]	Tool Holder Style[a]	Type Insert[a]	ECEA, degrees[b]	SCEA, degrees[c]
A	T	5	0	A	T	3	0
A	T	3	0	A	T	5	0
A	R	8	0	--	--	--	--
B	T	23	15	B	T	23	15
B	T	18	15	B	S	15	15
B	S	15	15	B	T	20	15
B	T	20	15	--	--	--	--
D	T	35	30	D	T	35	30
E	S	45	45	--	--	--	--
F	T	0	0	F	T	0	0
F	S	15	0	F	S	15	0
G	T	3	0	G	T	3	0

(a) See Table XIX for explanations.
(b) End-cutting-edge angle.
(c) Side-cutting-edge angle.

- Increased use of harder carbides for longer tool life or increased metal-removal rates

- Savings through tool standardization.

Setup Conditions. Turning operations should be conducted on a standard or heavy duty lathe in good condition. The work should be firmly chucked in the collet of the spindle and supported by the tail stock using a live center. Machining should be done as close as possible to the spindle for minimum work overhang. A steady or follow rest should be used to add rigidity to slender parts.

The cutting tool should be held firmly in a flat-base holder with minimum overhang to avoid tool deflection; it should cut on dead center.

Cutting Speeds. High speeds are not recommended for nickel- and cobalt-base alloys; instead, relatively low cutting speeds must be used to obtain reasonable tool life.

Feed. Turning operations for nickel- and cobalt-base alloys require constant, positive feeds throughout machining (Ref. 46). Dwelling, stopping, or deliberately slowing up in the cut must be avoided (Ref. 15).

Feeds must be carefully chosen for these alloys (Ref. 21), and they should be as heavy as consistent with the desired finish (Ref. 28). However, the high strengths of these alloys will not allow feeds above 0.020 ipr, even where optimum tool geometry is used. This limit is imposed principally by the strength limit of tungsten-carbide cutting edges (Ref. 15). On the other hand, very light feeds should not be used unless the tool demands it (Ref. 15). Feeds of 0.005 ipr or higher are usually recommended (Refs. 16,46), with average feeds ranging between 0.005 and 0.010 ipr (Ref. 15).

Depth of Cut. The choice of cut depth will depend on the amount of metal to be removed, the metal-removal rate desired, and the turning operation undertaken. In removing scale, the tool should get under the scale and cut at least 0.020-inch deeper than the tool radius. For second cuts, the nose of the tool should get below any work-hardened surface remaining from previous processing operations, although second cuts will notch the tool at the depth-of-cut line (Ref. 15). In finish turning, light cuts, but not less than 1/64 inch, should be used for the best finish and the closest tolerances (Refs. 28, 46). Cut depths up to 1/4 inch are suggested.

Cutting Fluids. Cutting fluids are most always used during turning and boring operations to cool the tool and to aid in chip disposal. Dry cutting is done in some instances with carbides, and usually where chip contamination is objectionable. It is not recommended for semifinishing and finishing operations.

Water-base coolants are the most satisfactory cutting fluids to use, and are usually more effective than the highly active cutting oils (Ref. 21). Synthetic chemical coolants in water give the best results, although a 1:20 soluble oil-in-water emulsion is almost as good. Soluble oils with high dilution ratios increase heat extraction (Ref. 46). Sulfurized oils and sulfochlorinated oils are still preferred by some machinists, particularly where tool buildup is a problem (Ref. 46).

A full, steady flow of cutting fluid should be maintained at the cutting site for maximum effect, particularly for carbides. Intermittent cooling, in this case, does more harm than good (Ref. 15).

General Supervision. Setup conditions such as feeds, speeds, and depths of cut are given in Table XXI. Figure 9 shows the tool designs used in these setups.

The supervisor should be satisfied that the proper conditions have been selected before operations begin. During machining he should be assured that chips are being expelled from the cutting site as promptly as possible, particularly during boring operations. Chips lying on the surface tend to produce chatter and poor surface finishes.

The tool should be examined frequently for nicks and worn flanks. These defects promote galling, increase cutting temperature, accelerate tool wear, and increase residual stresses in the machined surface.

Arbitrary tool-changing schedules are often used to insure sharp tools. This usually means replacing carbide tools after a 0.015-inch wearland in rough turning and after a 0.010-inch wearland in finish turning. High-speed-steel tools are usually replaced after a wearland of 0.030 inch has developed.

If periodic interruptions are made in a machining operation before these maximum wearlands occur, any smeared metal, nicks, or crevices found on the cutting edge should be removed by honing before machining is resumed.

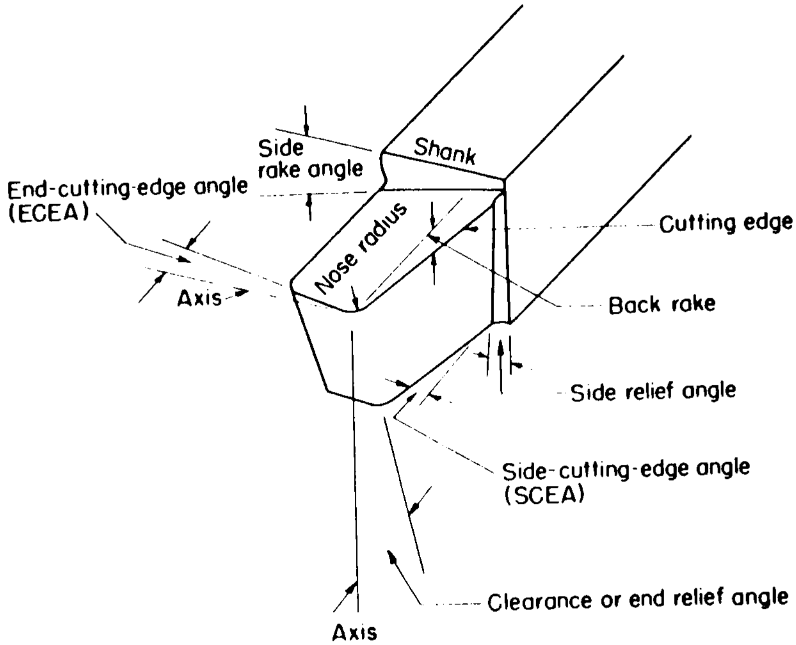
TABLE XXI. TURNING OF NICKEL- AND COBALT-BASE ALLOYS (REFS. 9, 10, 16, 18, 19, 21, 23, 24, 28, 36, 39, 41, 43, 44)

Alloy		Alloy	Carbide							High-Speed Steel					
			Tool				Cutting Speed, fpm			Tool					
Group	Representative Alloy	Condition(a)	Grade(b)	Design(c)	Depth of Cut, inch	Feed, ipr	Braced	Throwaway	Cutting Fluid(c)	Grade(b)	Design(c)	Depth of Cut, inch	Feed, ipr	Cutting Speed, fpm	Cutting Fluid(d)
A	Nickel, wrought	CD	C6	H,B	0.25	0.015	260	320	I	T5,T15	D,I	0.25	0.015-0.030	50-75	I,IV
			C7	H,B	0.05	0.008	320	450		M36,T15	D,I	0.05	0.008	100-170	
B1	Monels, wrought	CD	C6	D,H,B	0.25	0.015-0.020	250-300	275-325	I	T5,T15	D,I	0.25	0.015-0.030	60-75	I,IV
			C7	D,H,B	0.05	0.008	300-350	350-450		T15,M36	D,I	0.05	0.008-0.010	90-100	
B2	Monels, cast	AC	C6	H,B	0.25	0.015	175	325	I	T15	I	0.25	0.015	60	I,IV
			C7	H,B	0.05	0.008	225	300		T15	I	0.05	0.008	90	
C1	Incoloys	Ann	C2	D	0.25	0.020	150-200	175-225	I	T5	D	0.25	0.030	25-35	I,IV
			C6	D	0.05	0.008	325-375	325-345		M36	D	0.05	0.010	50-60	
C2	Hastelloy B,C	ST	C2	D	0.04-0.060	0.008-0.015	35	--	I	--	--		--	--	I
			C3	D	0.01-0.015	0.005-0.008	50	--		--	--		--	--	
C3	Hastelloy X	ST	C2	A	0.10	0.015	65	--	I	T15	A	0.10	0.008-0.004	30-40	IIIa
			C5	A	0.015	0.006	75	--		T15	A	0.008-0.01	0.003-0.008	35-45	IV
D	Inconels	ST	C2	H,B,D	0.25	0.010-0.015	30-45	40-50	I	T5	I,D	0.25	0.01-0.015	12-25	I,IV
	Inconel X-750		C3	H,B,D	0.05	0.008-0.010	40-60	60-70		M36	I,D	0.05	0.008-0.010	18-35	IIb
	Nimonics														
		STA	C2	H,B,D	0.25	0.008-0.015	35-50	50-60	I	T15	I,D	0.25	0.01-0.015	10	I,IV
			C3	H,B,D	0.05-0.05	0.008	50	70-100		T5	I,D	0.25	0.008-0.01	15	IIb
			C6	E	0.05-0.05	0.005-0.010	60-90	--		M36	I,D	0.05	0.008	20	
E	Rene 41	ST	C2	H,B	0.25	0.010	35	--		T15	I,A	0.25	0.010	12	I,IIa
			C2	H,B	0.25	0.015-0.020	--	30-40	I						
			C3	H,B	0.25	0.010	--	50							IIIa
			C3	H,B,A	0.05-0.10	0.008-0.009	40-50	70		T15	I,A	0.05-0.10	0.008	20	IV
			C3	H,B,A	0.02-0.05	0.003-0.006	50-60	--			I,A	0.02-0.05	0.003-0.006	25-35	
		STA	C2	H,B	0.25	0.010	40	--	I	T15	I	0.25	0.010	12	IIIb
			C2	H,B	0.13-0.25	0.010-0.015	--	35-60							
			C3	H,B	0.05	0.008	50	70		T15	I	0.05	0.008	20	
			C3	H,B	0.02-0.05	0.005	--	100							
E	Udimet 500	ST	C2	H,B	0.25	0.015	35	50	I	T15	I	0.25	0.010	15	I, IIa
			C3	H,B	0.05	0.008	50	75		T15	I	0.05	0.008	20	IIIa,IV
		STA	C2	H,B	0.25	0.015	40	60	I	T15	I	0.25	0.010	15	I
			C2	H,B	0.06-0.13	0.008-0.010	--	70-80							
			C3	H,B	0.05	0.008	50	--		T15	I	0.05	0.008	20	IIIb
			C3		0.02-0.05	0.005-0.008	--	80-100							
E	Inconel 700	ST	C2	H,B	0.25	0.013	35	50	I	T15	I	0.25	0.010	15	I,IIa
			C3	H,B	0.05	0.008	50	70		T15	I	0.05	0.008	20	IIIa,IV
		STA	C2		0.125-0.25	0.01-0.015	40	60	I	T15	I	0.25	0.010	15	I
			C3		0.05	0.008	--	70		T15	I	0.05	0.008	20	IIIb
			C3		0.02-0.05	0.008	50-80	--							

TABLE XXI. (Continued)

Group	Alloy: Representative Alloy	Alloy Condition[a]	Carbide: Tool Grade[b]	Carbide: Tool Design[c]	Carbide: Depth of Cut, inch	Carbide: Feed, ipr	Carbide: Cutting Speed, fpm: Brazed	Carbide: Cutting Speed, fpm: Throw-away	Carbide: Cutting Fluid[c]	High-Speed Steel: Tool Grade[b]	High-Speed Steel: Tool Design[c]	High-Speed Steel: Depth of Cut, inch	High-Speed Steel: Feed, ipr	High-Speed Steel: Cutting Speed, fpm	High-Speed Steel: Cutting Fluid[d]
E	J1570	ST	C2	H,B	0.25	0.010	75	125	I	T15	I	0.25	0.010	20	I
			C3	H,B	0.05	0.008	100	150		T15	I	0.05	0.008	30	
		STA	C3	H,B	0.05-0.125	0.010-0.015	40-75	125	I	T15	I	0.25	0.010	20	I
			C3	H,B	0.02-0.05	0.005-0.010	75-100	150		T15	I	0.05	0.008	30	
F	S816	ST	C2	H,B	0.25	0.015	75	125	I	T15	I	0.25	0.010	20	I
			C3	H,B	0.05	0.008	100	150		T15	I	0.05	0.008	30	
		STA	C2	H,B	0.25	0.010	75	125	I	T15	I	0.25	0.010	20	I
			C3	H,B	0.05	0.008-0.010	60-100	150		T15	I	0.05	0.008	30	
F	HS25 (L605)	ST	C2	H,B,A	0.10	0.015	45	--	I	T15	I,A	0.25	0.010	20	I,IIIa
			C2	H,B	0.25	0.010	75	125		T15	I,A	0.05	0.008	30	IV
			C3	H,B	0.05	0.008	100	150							
F	HS21	ST or	C2	H,B	0.25	0.009-0.012	40-75	125	I	T15	I	0.25	0.010	20	I
		STA	C3	H,B	0.05	0.005-0.008	65-100	150		T15	I	0.05	0.008	30	IIIa,IV
G	N155	STA	C2		0.05-0.10	0.008-0.013	50-72	--	I	T15	I	0.035	0.007-0.011	18	I
			C3		0.015	0.006-0.009	68-90	--		T15	I	0.010	0.003-0.008	20	IIIa,IV

(a) Ann = annealed; ST = solution treated; STA = solution treated and aged; AC = as cast; CD = cold drawn
(b) CISC designations used for carbides; AISI designations for high-speed steels.
(c) See Figure 9 for tool angles involved.
(d) See page 26 for types of cutting fluid recommended.



	Tool Design Symbols								
	A	B	C	D	E	F	G	H	I
Tool Angles, degrees									
Back rake	+	0	0	0 to +8	8	8	6	0	8
Side rake	+	+5	+15	5 to 15	8 to 15	10	12	6	10
End relief	Normal	5	5	6 to 8	5 to 7	5	5	5	12
Side relief	"	5	5	6 to 8	5 to 7	5	5	5	12
End-cutting edge	"	15	5	6 to 60	10	10	5	5	6
Side-cutting edge (lead)	Large	15	0	up to 45	15 to 25	20	20	15	15
Nose Radius, inch	Small	1/32	1/32	1/32	1/32	031	032	3/64	1/32
Chip Breaker Length	--	--	--	--	4 x feed	4 x feed	--	--	--
Groove Length, inch	--	--	--	--	--	0.015	--	--	--
Tool Material	Carbide high-speed steel	Carbide	High-speed steel	Carbide high-speed steel	Carbide	High-speed steel	Carbide	Carbide	High-speed steel

FIGURE 9. TOOL GEOMETRIES USED FOR TURNING NICKEL- AND COBALT-BASE ALLOYS

They are specified as the distance from the supporting column to the center line of the chuck. The horsepower rating is that usually needed to drill cast iron with the maximum drill diameter (Ref. 47). Suitable sizes of machines for drilling nickel- and cobalt-base alloys include:

- Upright Drill No. 3 or No. 4
- Upright Drill, Production: 21-inch Heavy Duty, 5 hp
- Upright Drill, Production: 24-inch Heavy Duty, 7-1/2 hp
- Upright Drill, Production: 10 hp.

Industry also has requirements for drilling parts at assembly locations. These needs are fulfilled by portable power-feed, air drilling machines. Modern units incorporate positive mechanical-feed mechanisms, depth control, and automatic return (Ref. 48). Some are self-supporting and self-indexing. Slow-speed, high-torque drill motors are needed. Spindle speeds between 230 and 550 rpm at 90-psi air pressure seem appropriate for high-speed drills. Thrust between 320 and 1000 pounds are available on some portable drilling machines.

Portable drill units include the Keller K-Matic, the Keller Airfeedrill, the Winslow Spacematic, and the Quackenbush designs (Refs. 48,49,50). The Keller K-Matic incorporates a positive, mechanical feed mechanism, a depth-control device, and an automatic-return provision. The Keller Airfeedrill utilizes a variable pneumatic feed. The Winslow Spacematic is a self-supporting, self-indexing unit capable of drilling and countersinking in one operation (Ref. 48).

Quackenbush portable drilling machines also can be used. One style is a 500-rpm pneumatic-powered unit with a positive mechanical feed mechanism capable of providing 0.001-ipr feed (Ref. 49).

Drills. Drill strength and rigidity are highly important factors for the successful drilling of nickel- and cobalt-base alloys (Ref. 51). Generally speaking, drills are made from special high-speed steels, in helical designs with polished flutes, and in short lengths. They should be the heavy duty type with heavy webs (Refs. 18,24,40). The length of the drill should be kept as short as possible, not much longer than the intended hole, to increase columnar rigidity and decrease torsional vibration which causes chatter and chipping.

After certain turning operations, parts may require stress relieving. The following treatments are suggested:

- Anneal after rough machining
- Stress relieve thin-wall parts after semifinish operations
- Stress relieve all finished parts.

DRILLING

Introduction. Drilling can be a difficult machining operation to perform if good practices are not used (Refs. 18,23,46). In the first place, the thrust and torque forces are higher for nickel- and cobalt-base alloys than those needed for drilling steels and aluminum alloys. Secondly, the center web of the drill, which does not cut, extrudes the metal in its vicinity. Consequently, the bottom of the hole may work harden enough to cause early drill failure (Ref. 18). Work hardening can be minimized by using sharp drills with thin webs, together with constant, positive feeds throughout drilling (Ref. 18).

Difficulties resulting from poor drilling action include out-of-round, tapered, or smeared holes that cause problems in subsequent reaming or tapping operations. These difficulties can be minimized by employing five important techniques. These include: designing holes as shallow as possible; using short, sharp drills with large flutes and special points; flushing the tool-chip contact site with suitable cutting fluids; employing low speeds and positive feeds; and supporting the exit side of through-holes where burrs otherwise would form (Refs. 18,22,28,36,42).

Machine Tools. Drilling machines must be sturdy and rigid enough to withstand the thrust and torque forces built up during the cutting. Hence, the spindle overhang should be no greater than necessary for a given operation. Excessive clearances in spindle bearings cannot be tolerated; the radial and thrust bearings should be good enough to minimize runout and end play. Finally, the feed mechanism should be free of backlash in order to reduce the strain on the drill when it breaks through the workpiece (Ref. 28).

Machines for drilling operations are made in many different types and sizes. Size or capacity is generally expressed either in terms of the largest diameter disk, the center of which is to be drilled, or in horsepower. Heavy-duty machines are exceptions.

A heavy duty stub-type screw machine drill is recommended for drilling operations on workpieces other than sheet (Ref. 22). For drilling deep holes, oil-feeding drills, gun drills, or a sequential series of short drills of various lengths may be employed. Oil feeding drills cool, lubricate, minimize welding, and help in chip removal (Ref. 18). The NAS 907, Type B or C drill can be used for drilling sheet material.

Drill Design. Drill geometry is a sensitive and important factor in the successful drilling of nickel- and cobalt-base alloys. Two ostensibly similar drills can have substantially different tool lives, either because of minute differences in geometry, or because of thermal damage during grinding. Hence, uniform grinds are needed for reproducible tool lives (Ref. 22).

The choice of helix angles will depend on the job conditions and on the alloy being drilled. Both low- and high-helix angles can be used. For example, low-helix, heavy duty type drills have outperformed Type 3300 and Type C drills when drilling 1/2-inch through-holes in aged-hardened René 41. The helix angles of the drills compared above are 12, 33, and 28 degrees respectively (Ref. 51). On the other hand the 3300 style performs well in drilling shallower holes (1/8-inch through-holes (Ref. 51). Generally speaking, drills with 28-degree helix angles represented by the regular helix, heavy duty types can be used for most drilling applications (Ref. 42).

The choice of relief angles is of extreme importance to drill life. Small angles tend to cause excessive pickup, while excessively large angles will weaken the cutting edge. Relief angles between 3 and 15 degrees have been used successfully by different investigators (Refs. 22,24). Drills with 118-degree point angles usually have large relief angles, for example 12 degrees. The flatter point angles (from 130 to 140 degrees) can be used with relief angles running moderately low, for example, around 6 degrees.

Point angles have a marked effect on drill life. The choice of 90, 118, or 135 degrees will depend on the feed, drill size, and type of workpiece. Generally the drill life increases as the included point angle increases from 90 to 140 degrees. The flatter points tend to develop lower thrust forces than 90-degree points and also provide maximum support in the critical area of the chisel edge which can become damaged from high axial loads on the drill (Ref. 51). Occasionally the cutting corners of the drill are chamfered (with a smaller angle than the drill point angle) to protect them from premature breakage (Ref. 18). Thus a double angle, 118/90 degrees, can give very good results (Ref. 41).

Special point grinds are used and include crankshaft, notch-type drills and split points with positive rake notchings (Refs. 23,24,28). Crankshaft points minimize work hardening caused by the extrusion action of the conventional chisel point (Ref. 22), and are useful for deep holes (Ref. 24). High-tensile-type notch and split points also give good performance (Ref. 51).

Webs are often thinned to reduce pressure at the drill point during drilling (Ref. 23). When doing so, however, the effective rake angles of the cutting edges should not be altered.

Drill Quality. The geometry of drills should be checked against recommendations before they are used. If necessary, drills should be reground accurately on a drill grinder, and the point angle, relief angle, and web thickness rechecked. Drills should never be sharpened by hand.

The apex of the point angle should be held accurately to the center line of the drill, and the cutting lips should have the same slope. This combination avoids uneven chip formation, drill deflection, and oversized holes (Ref. 52). When dull drills are reconditioned, resharpening the point alone is not always adequate. The entire drill should be reconditioned to insure conformance with recommended drill geometry. Machine-ground points with fine finishes give the best tool life (Ref. 48). A surface treatment such as chromium plating or a black oxide coating of the flutes may minimize welding of chips to the flutes.

Tool Materials. High-speed steels are generally used for drilling superalloys. The types used include M2, M3, M33, and M36 (Refs. 21,24,28,42). Carbide drills can be used for deep holes when the cost is justified. However, their high cost coupled with the high incidence of breakage usually prohibits their use. Only small amounts of lip and corner wear are permissible with carbide drills (Ref. 22).

Conventional molybdenum-tungsten high-speed-steel drills are usually used in production (Ref. 28). Cobalt high-speed steels (T15) generally perform better than the standard grades of high-speed steel (Refs. 22,28). The M33 grade performs very well, as does the ultrahard M41 grade (Refs. 21,42).

Setup Conditions. Setup conditions selected for drilling should provide over-all setup rigidity and sufficient spindle power to maintain drill speeds during cutting (Ref. 18).

Thin-sheet-metal parts must be properly supported at the point of thrust. This can be done with backup blocks of AISI 1010 or 1020 steel (Ref. 28). Where this is not possible because of part configuration, a low-melting-point alloy can be cast about the part (Ref. 22). Proper alignment of the supported work and drill is also necessary to prevent premature drill breakage.

Drill rigidity is also important (Ref. 23). Drills should be as short as possible (Ref. 36). Heavy duty stub drills can be used instead of jobbers-length drills to prevent deflection that causes out-of-round holes (Refs. 22,28). Drill jigs and bushings are used whenever added rigidity is needed (Ref. 36). For deep-hole drilling several lengths of short drills may be employed in sequence. A drill bushing should be incorporated, if possible, in the setup for additional rigidity (Refs. 23,36).

When drilling stacked sheet, the sheets should be clamped securely with clamping plates to eliminate gaps between sheets.

Setup also involves speeds, feeds, and coolants. Successful drilling of nickel- and cobalt-base alloys depends on being able to reduce the temperature at the cutting lips. This can be accomplished by:

- Using low cutting speeds
- Employing proper feed rates
- Supplying adequate cooling at the cutting site.

Cutting Speed. Since the cutting zone is confined, drilling requires low speeds for minimum cutting temperature. The choice of speed to be used will depend largely on the strength level of the material and the nature of the workpiece. Thus, speeds up to 75 fpm should be used on aged René 41 and Udimet 700 (Refs. 42,51). Lower speeds should be used for deep holes to compensate for inadequate lubrication and cooling (Ref. 22). Speeds also should be lowered as feed increases. In large drills slow speeds and heavy feeds give the best production rate (Ref. 22).

Feed. The best approach in drilling nickel- and cobalt-base alloys is to keep the drill cutting. The drill should never ride in the hole without cutting since the rubbing action promotes work hardening, galling of the lips, and rapid dulling of the cutting edge. The best technique is to use equipment having positive, mechanical feeds (Ref. 36).

Assembly drilling of sheet should also be done with portable power drills having positive feed arrangements. This equipment was described on page 54.

Hand drilling is not recommended (Ref. 18). The high axial thrust required to keep the drill cutting, especially in solution-treated-and-aged alloys, can cause rapid operator fatigue. Furthermore, allowing the drill to advance rapidly on breakthrough, as is generally the case with hand feeding, will seriously shorten drill life by chipping the corners of the drill.

The selection of feeds depends largely on the size of the drill being used. Generally, a feed range of 0.0005 to 0.004 ipr is used for drills up to 1/4-inch diameter. Drills of 1/4 to 3/4-inch diameter will use heavier feeds depending on the alloy (Refs. 42,51).

Cutting Fluids. Drilling nickel and cobalt alloys requires the use of cutting fluids with good lubricating and anti-weld properties (Ref. 51).

Lubricating and chemically-active cutting fluids like sulfurized oils or sulfurized-chlorinated oils are recommended (Refs. 22,51). Sulfo-chlorinated oils are better than the straight chlorinated oils, or a water soluble mixture (Ref. 51). Highly sulfurized oils are often diluted 1:1 with light machine oil, particularly when carbide tools are used (Ref. 21).

A steady, full flow of fluid, externally applied, is used. However, a limiting hole depth, of twice the diameter, seems to exist for external applications of cutting fluids. Hence, oil-feeding drills work best for deep holes.

General Supervision. Setup conditions such as speeds, feeds, and cutting fluids are given in Table XXII. Figure 10 shows the drill designs used in these setups.

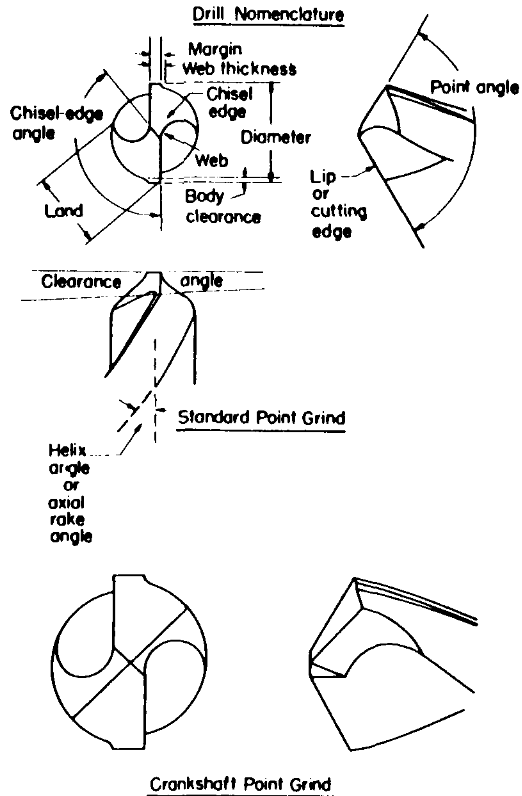
TABLE XXII. DRILLING DATA FOR NICKEL- AND COBALT-BASE ALLOYS (REFS. 10, 18, 21-24, 28, 36, 39, 41, 42, 44, 46-51)

Alloy: Group	Alloy: Representative Alloy	Alloy Condition(a)	High-Speed Steel Drills: Grade(b)	Design(c)	Cutting Speed, fpm	Cutting Fluid(d)
A	Nickel, wrought	CD	T15, M33	D, F	50-75	IIa, I
B1	Monels, wrought	CD	T15, M33	D, F	45-55	IIa, I
B2	Monels, cast	AC	T15, M33	F	40	IIa, I
C1	Incoloys	Ann	T15	D	25-35	IIa, I
C2	Hastelloy B, C	ST	T15, M33	F	20	IIa, IIIa, IV
C3	Hastelloy X	ST	T15	A	17-25	IIIa
D	Inconels Inconel X750	ST	T15, M33	D, E, F	10-20	IIa, I, IIb, IIIa, IV
	Nimonics	STA	T15, M33	D, E, F	7-12	
E	René 41	ST	T15, M33	B, F	8-15	IIIa, IIIb IIa, IV
		STA	T15, M33	B, A, F	10-20	
	Udimet 500	ST	T15, M33	F	8-15	IIIa, IIa, IV
		STA	T15, M33	F	10-20	
	Inconel 700	ST	T15, M33	F	15	IIIa, IIa, IV
		STA	T15, M33	F	10-20	
F	J1570	ST	M2, T4 M35	F	10-25	IIa, IIIa, IV
		STA	T15, M33	F	15	
	HS25 (L605)	ST	M2, M3 T15	A, F	15-30	IIIa
	HS21	ST	M2	F	25	IIa, IIIa
		STA	T15, M33	F	15	
G	N155	STA	M2	E	15-20	IIa, IIIa, IV

Drill Diameter, inch	Feed for Drill Diameter Shown, ipr: Nickel Monels, Incoloys	Hastelloys B, C	Hastelloy X	Inconels 10 Inconel X250: ST	Inconels 10 Inconel X250: STA
1/8	0.001 to 0.002	0.0005	0.001	0.0005	0.001
1/4	0.002 to 0.004	0.001	0.003 to 0.004	0.001	0.002
1/2	0.004 to 0.006	0.003	0.004	0.003	0.004
3/4	0.005 to 0.009	.0.005	0.005	0.005	0.007
1	0.006 to 0.012	0.007	0.006	0.007	0.010
2	0.012	--	--	--	--
3	0.015	--	--	--	--

Drill Diameter, inch	Feed for Drill Diameter Shown, ipr: Solution-Treated Alloys	Solution-Treated and Aged Alloys
1/8	0.0005-0.001	0.001
1/4	0.001-0.004	0.002
1/2	0.003-0.004	0.004
3/4	0.005	0.007
1	0.006-0.007	0.010
2	0.007	0.010

(a) Ann = annealed; CD = cold drawn; AC = as cast; ST = solution treated; STA = solution treated and aged.
(b) AISI designations.
(c) See Figure 10 for drill geometries involved.
(d) See page 26 for types of cutting fluids recommended.



	Tool Design Symbols					
	A	B	C	D	E	F
Drill Elements						
Drill Diameter	1/8"-1-1/4"	All	All	All	All	All
Helix Angle, degrees	--	29	29	30	30	24-32
Clearance Angle, degrees	--	3	7	12	6-12	8-10
Point Angle, degrees	118	118/90	118	118	130-140	118
Type Point	Split	Split	Crankshaft	Thin wet at chisel point	Thin web to 50-70 per cent original thickness	Standard

FIGURE 10. TOOL DESIGNS USED FOR DRILLING NICKEL- AND COBALT-BASE ALLOYS

The first consideration in planning a drilling setup is to select a drilling machine on the basis of the rigidity, condition, power, and feed/speed characteristics required for nickel- and cobalt-base alloys. The next consideration would be the selection of drills, bushings, fixtures, and cutting fluids.

When starting the drilling operation, the drill should be up to speed and under positive feed as it contacts the work. The drill must be sharp, and the proposed hole location marked with a triangular center punch. A circular-type center punch must not be used since the drill will not start because of the work-hardened surface produced.

The margin of the drill should be examined periodically for smearing as well as for breakdowns that might occur at the outer corner of the lips. An arbitrary drill replacement point should be established to prevent work and drill spoilage.

The drill should be pulled out of the hole frequently to free it from chips and to permit intermittent cooling of the drill unless the cutting fluid successfully flushes away the chips (Ref. 36).

When drilling holes deeper than one diameter, retract the drill once for each half diameter of drill advance to clear the flutes. Retract simultaneously with the stop of the feed to minimize dwell. Re-engage drill quickly, but carefully, with the drill up to speed and under positive feed.

When drilling through-holes do not drill all the way through on a continuous feed. Instead, retract drill before breakthrough and flush the drill and hole to remove the chips. Then return drill under positive feed and drill through carefully avoiding any "feed surge" at breakthrough.

Drilled holes will require reaming to meet the tolerances of Class I holes, unless a bushing is used immediately adjacent to the part. Drilled holes in sheet will probably require exit-side deburring.

All assembly drilling should be done using portable, fixed-feed jig-mounted drilling machines.

TAPPING

Introduction. Tapping is one of the most difficult machining operations to perform on nickel- and cobalt-base alloys, particularly the high-temperature varieties (Ref. 22). The problem of chip flow in taps plus a galling/welding action more severe than that in stainless steel can result in poor threads, improper fits, excessive tap seizures, and broken taps. This is complicated by the fact that these alloys like other high-strength high-ductility alloys tend to upset into the roots of the tap profile. This upsetting tends to seize the tap. A hole drilled for a 75 per cent thread will not allow re-entrance of the plug gage after tapping (Ref. 15).

As taps dull and cutting temperatures rise, metal welds on the cutting edges and flanks of the tap. The immediate consequence is that the metal in excess of the normal profile is removed to cause oversized holes, and rough threads. Galling also increases friction between tap and hole, and torque requirements. The additional torsional strain distorts the lead of the tap and increases the tapping stresses until the tap seizes and breaks. Shank breakage from high torque is a common tap failure (Ref. 22).

Tapping difficulties can be minimized by reducing the thread requirements to a range of 50 to 60 per cent full thread and then tapping the fewest threads that the design will allow (Ref. 15). Thread-strength tests show that any increase in thread height above 60 per cent for the tapped member does not necessarily increase the static strength of a threaded fastener. In general, the bolt will break at 55 per cent engagement (Ref. 23). Standard tap-drill-selection tables in use for many years, based on a 75 per cent thread engagement, were prepared on low-strength materials like brass.* Modern high-strength alloys, however, possess adequate holding strength with a lower percentage of thread engagement (Ref. 23). This is accomplished by using larger tap-drill sizes than those recommended.

Designers should also avoid specifying blind holes or through-holes with lengths exceeding 1-1/2 times the tap diameter (Ref. 39). In both cases, the chips are confined and can cause rough threads and broken taps. Some relaxation in class-of-fit tolerances also should be considered when difficult materials must be tapped.

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*Some companies have successfully tapped 75 per cent threads in certain nickel- and cobalt-base alloys.

The tapping operation requires sharp taps of modified conventional design, low tapping speeds, and an effective tapping lubricant to minimize seizure.

Tapping Machines. A lead-screw tapping machine is recommended to insure proper lead, a regulated torque, and a uniform hole size. Lead-screw tapping heads should be equipped with friction clutches. The clutch should prevent tap breakage when galling occurs since a very small amount of smear may result in immediate tap breakage (Ref. 36).

Tapping machines should be rigid, accurate, and sensitive. Machine tapping unless done on a sensitive machine by a competent operator can result in excessive tap breakage and poor quality work.

The electro-pneumatic oscillating-type tapping machine when properly set cannot break a tap. Before any force is applied that might break a tap, the forward motion is interrupted, and reversed. The tap is driven by balanced spiral springs and the tension is set just under the static breaking torque of the size of the tap being used. When the tap meets excessive resistance (which would ordinarily break the tap) the machine automatically reverses one-half revolution and then goes forward again (Refs. 41,53).

Taps and Their Modifications. A number of different types of taps have been used successfully, including the plug, chip-driving, and gun designs.

Modifications of the conventional two-flute spiral-point plug-style H2-pitch-diameter taps can be used. The taps are modified by grinding away the threads behind the cutting edges down to the minor diameter, but leaving full-thread lands 0.015-inch wide backing up the cutting edges.

Chip-driving spiral-point taps with interrupted threads and eccentric pitch-diameter relief also have been successful (Ref. 36).

Taps should be precision ground in a machine setup rather than by hand (Refs. 22,36). Extreme care should be used in grinding in order to provide equal chip loads on all cutting edges during tapping (Ref. 15). Stress relieving taps after grinding is also helpful. Normally the minimum number of flutes is recommended (Ref. 15). Two-fluted taps are usually used for 5/16-24 holes and smaller (Ref. 21), while three-fluted taps are best for 3/8-16 holes and greater, and for other tapping situations (Refs. 23,36,40,43). Taps with two flutes normally do not give the support the three-fluted taps provide.

If rubbing between the relief surface and the threaded hole is encountered during tapping, it may be decreased by:

- Using interrupted threads with alternate teeth missing
- Grinding away the trailing edge of the tap
- Grinding axial grooves in the thread crests along the full length of the lands
- Employing either eccentric or coneccentric thread relief (Refs. 23,36).

The bearing surfaces of the tap lands should be as narrow as possible to minimize the work hardening of the tapped hole that occurs when these tap lands rub in the holes (Ref. 39). All taps should have some back taper, around 0.001 inch per inch of length (Ref. 36).

Generally speaking, spiral-point taps featuring eccentric pitch-diameter relief with either full or interrupted threads, have been the most successful (Ref. 22). However, a spiral-pointed tap cannot be expected to propel chips forward in holes that are more than two diameters long.

Tap Design. Taps should have tool angles that encourage good chip flow, minimize seizure, and provide good shearing action. This usually means:

- A spiral-point angle large enough to allow chips to flow out of the hole ahead of the tap (between 10 and 17 degrees)
- A relief angle large enough to prevent seizure but not so large as to cause jamming when backing out the tap (between 2 and 4 degrees)
- Sufficient cutting rake to provide a good shearing action (between 5 and 8 degrees) (Refs. 23,36,39).
- A chamfer of not more than 3 to 5 threads in order to get under the work-hardened surface (Ref. 39). A shorter chamfer results in high torque and possible

tap breakage. A long chamfer produces long, stringy chips which may jam the tap during back-out operations. In any case, a tap will not cut properly unless its chamfer is ground evenly on each flute (Ref. 36).

- Where bottoming holes require complete threads close to the bottom of the hole, a series of two or three taps with successive shorter chamfers may be required. One investigator suggests five to ten chamfered threads on starting taps, four to five chamfered threads on intermediate taps, and one to two chamfered threads on finishing taps (Ref. 36).

Tap Materials. High-speed-steel taps (AISI M10) are used for tapping nickel- and cobalt-base alloys (Refs. 40,43). Carbide taps usually are not practical (Refs. 15,24). Carbide strength is inadequate, and surface speed is too low for the inherent quality of carbide taps, particularly where breakage is the prevalent failure (Ref. 15).

Setup Conditions. The shortest tap possible for the hole being tapped should be used for maximum tool rigidity (Refs. 15,22). Additional precautions in setups for tapping parallel those recommended for drilling. Lead screw tapping is recommended since less dependence is placed on the operator. The tapping head must be set for as short a stroke as possible. Hand tapping is not recommended since it lacks the required rigidity and is extremely slow and difficult.

Tapping Speed. Tapping speeds should be limited to values between 5 and 25 fpm depending on the alloy and heat-treated condition. This is important because cutting torque increases extremely rapidly beyond a certain critical threshold speed for each alloy (Refs. 40,43).

Size of Cut. The size of cut determines the incidence of tap seizure, and the size of cut is determined by the chamfer given the tap. The normal chamfer of three or four threads should produce smaller chips and minimize jamming the tap during the back-out phase.

Tapping Lubricants. The selection of tapping lubricants is important because of the susceptibility of taps to seizure. Highly active cutting fluids are recommended (Ref. 21). Highly chlorinated oils usually give the best results. The next best lubricant is a heavy sulfurized mineral oil (Refs. 40,43). Mechanical filler materials like molybdenum disulfide may be added to relieve persistent seizures. Ordinary soluble oils are unsatisfactory for tapping because they lack the extreme pressure properties needed to withstand the cutting pressures involved. The action of various cutting fluids during machining is explained on pages 23-26 inclusive.

Some fabricators recommend pretreating taps with colloidal molybdenum disulfide. The tap is dipped in a suspension of MoS_2 and white spirits, and then baked for 40 minutes at 200 C.

General Supervision. Clean, round holes are essential for tapping (Ref. 36). Hence, as a first requirement, holes for tapping should have been produced by sharp drills operating under proper drilling conditions. Dull drills produce surface-hardened holes that will magnify tapping difficulties. Sharp, clean taps must be used at low tapping speeds with recommended tapping compounds and under rigid tool-work setups.

Immediately before tapping a hole, the tap should be covered with a liberal amount of lithopone paste. If sulfurized oil is used it should be forced on the tap throughout the tapping operation.

Taps should be inspected carefully after each use for possible smearing of the tap lands. Smear-type buildups may be hard to see but can cause premature tap breakage and oversized holes. The workpiece also should be inspected for possible torn threads and dimensional discrepancies. It should be remembered that most tapping is done on parts which are 80 to 90 per cent finished, hence, parts scrapped because of faulty tapping operations can be very costly.

Operating data for tapping all nickel- and cobalt-base alloys are contained in Table XXIII. Tap designs are shown in Figure 11.

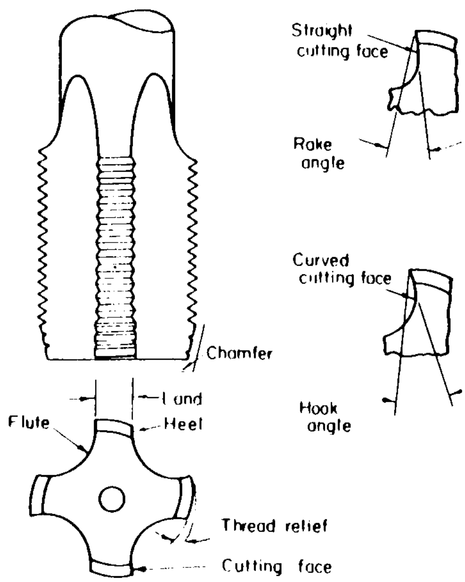
REAMING

Introduction. Nickel- and cobalt-base alloys can be reamed successfully, but it is done only when high finish and accuracy are required. Adhesion of metal to the reamer is a problem and must be prevented to avoid the production of oversized holes and poor finishes. Chatter also can be a problem and may originate from a lack of rigidity, misalignment, the wrong tool geometry, or dull tools (Ref. 23).

TABLE XXIII. TAPPING DATA FOR NICKEL - AND COBALT-BASE ALLOYS (REFS. 18,21-23,39,41,44)

Alloy			Tap Designation			
Group	Representative Alloy	Alloy Condition(a)	High-Speed Steel Grade(b)	Tap Geometry(c)	Cutting Speed, fpm	Cutting Fluid(d)
A	Nickel, wrought	CD	M2	A, B	20	IIa, IIIa, IV, V
B1	Monels, wrought	CD	M2	A, B	20	IIa, IIIa, IV, V
B2	Monels, cast	AC	M2	A, B	15	IIa, IIIa, IV, V
C1	Incoloy	Ann	M2	A, B	10-15	V
C2	Hastelloy B, C	ST	M2	A, B	10	IIIa, IV
C3	Hastelloy X	ST	M2	A, B	10	IIIa, IV
D	Inconels	ST	M2	A, B	5-10	IV
	Inconel X-750					V
	Nimonics	STA	M2		5-10	
	Rene 41	ST	M2	A, B	5	IIIa
		ST	M10		12	
		STA	M2, M10		5	IV
E	Udimet 500	ST	M2	A, B	5	IIIa
		STA	M2, M10		5	IV
	Inconel 700	ST	M2	A, B	5	IIIa
		STA	M2, M10		5	IV
F	J1570	ST	M2	A, B	15	IIIa
	S816	STA	M2		10	IV
	HS25	ST	M10	A, B	5	IIIa

(a) Ann = annealed; CD = cold drawn; AC = as cast; ST = solution treated; STA = solution treated and aged.
(b) AISI designations.
(c) See Figure 11 for tap geometry involved.
(d) See page 34 for types of cutting fluids recommended.



	Tap Design Code		
	A	B	Remarks
Tap Elements			
Rake or Hook angle, degrees	5 to 8	--	--
Relief angle, degrees	2 to 4	--	--
Chamfer, number threads	3 to 5	8 to 10	Plug tap
	2-1/2	4 to 5	Semibottom tap
	1-1/2	1 to 2	Bottom

FIGURE 11. TAP DESIGNS FOR NICKEL- AND COBALT-BASE ALLOYS

Types and Designs of Reamers. Fluted reamers for nickel- and cobalt-base alloys are available as standard items. Spiral-fluted reamers can be identified as those usually possessing right-hand cuts, along with positive axial and radial rake angles (Ref. 23). These reamers afford a smoother cutting action and are less apt to dig in or chatter than straight-fluted reamers. Nevertheless, the straight-fluted styles are usually preferred when extreme accuracy is required.

Reamers should be as short as possible, not only for maximum rigidity, but also to lessen the possibility of reaming bell-mouthed or tapered holes. Furthermore, they should possess the correct tool geometry. The conventional reamer has three basic tool angles: a chamfer angle, a rake angle, and a relief angle. The first two angles do not have any pronounced effect on reaming operations. The relief angle is the most influential and should exceed 5 degrees to minimize smearing. On the other hand, relief angles in excess of 10 degrees cause vibration and chatter marks on the surface of reamed holes.

Reamers with margins about 0.010 inch wide produce acceptable holes. Scoring is a problem with wider margins, and excessive chatter is likely to occur when margins are less than 0.005 inch.

Tool Materials. AISI M2 and M10 high-speed-steel reamers can be used on nickel- and cobalt-base alloys. Carbide-tipped reamers, however, can operate at somewhat higher speeds and have much better tool life.

Setup Conditions. There seems to be a rather narrow set of reaming conditions which will give optimum results. Consequently, the basic precautions for machining work-hardening alloys should be heeded. These include adequate rigidity of setup, sharp tools, and a positive feed to prevent riding without cutting. Chatter can be eliminated by altering tool design, size of cut, and cutting speed. Honed reamers produce smoother surfaces and last longer between grinds (Ref. 23).

Cutting Speed. The recommended cutting speed for commercially pure nickel is around 30 fpm for high-speed steel reamers, and 90 fpm for carbide-tipped reamers. Nickel- and cobalt-base alloys require lower speeds, 10 to 25 fpm for high-speed-steel reamers and 40 to 70 fpm for carbide reamers.

Feed. Small feeds are required to produce acceptable holes, and they may range between 0.002 and 0.020 ipr depending on the reamer diameter and the alloy (Refs. 23,44). Too low a feed will result in glazing and excessive wear. Conversely, an excessive feed rate reduces dimensional accuracy, impairs concentricity, and adversely affects surface finish (Ref. 23).

Depth of Cut. Sufficient stock must be removed during reaming so that the unworked subsurface layer is cut. This means that the depth of cut may vary between 0.010 inch for a 1/4-inch hole, 0.015 inch for a 1/2-inch hole, and 0.025 inch for a 1-1/2-inch hole (Ref. 23).

Cutting Fluids. The most effective fluids for reaming nickel- and cobalt-base alloys are the chemically active types including the sulfochlorinated oils, the highly chlorinated oils, and the highly sulfurized oils. These are recommended for reasons cited on page 25.

Operating Data. Cutting speeds and feeds are suggested in Table XXIV. Reamer design for these data is shown in Figure 12.

BROACHING

Introduction. Broaching is a machining operation that shaves metal from slots or holes using multiple-stepped cutting edges on a tool which is either pulled or pushed through the work. Cylindrical or square holes and slots can be finished by broaching tools designed for the particular cut or opening involved.

Nickel- and cobalt-base alloys can be broached under the general setup conditions of rigidity, positive feed, etc., required for turning, milling, and other machining operations. Because of the interrupted nature of cutting, welding of metal to the cutting followed by edge chipping (as in milling) can be quite troublesome. Alloys in the Group D, E, F, and G categories can be broached more cleanly in the aged condition (Ref. 23).

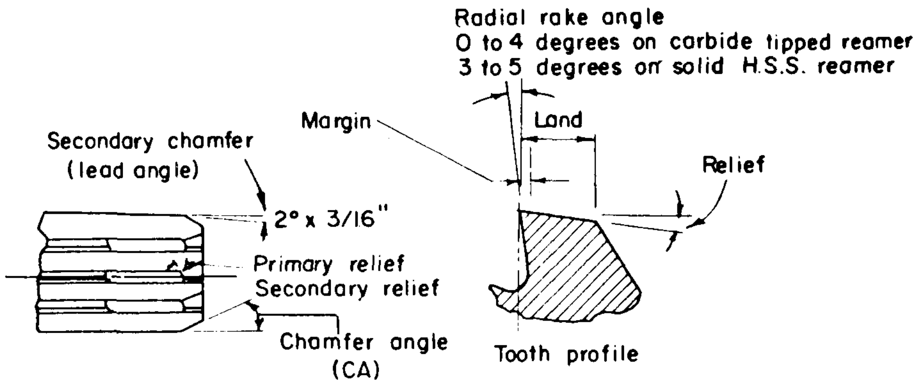
Types of Broaches.

Design. Tool design has noticeable effects on broaching performance. The relief angle, rake angle, and the rise per tooth seem to be the more important elements. Teeth should have a positive rake so that the chips will curl freely into the gullets. The

TABLE XXIV. REAMING DATA FOR NICKEL-AND COBALT-BASE ALLOYS (REFS. 10, 23, 36, 41, 44)

Alloy		Alloy Condition(a)	Tool Material(b)		Cutting Speed, fpm		Cutting Fluid(34)	Reamer Diameter, inch	Feed For Reamer Diameter and Alloy Shown, ipr		
Group	Representative Alloy		High-Speed Steel	Carbide	High-Speed Steel	Carbide Tipped			Group A Group B Alloys	Group C Group D(d)	Group E Group F Group G(e)
A	Nickel, wrought	CD	T5, M2	C-2	30	90		1/8	0.003	0.002	
B1	Monels, wrought	CD	T5, M2	C-2	30	90	I	1/4	0.005	0.003	
B2	Monels, cast	AC	T5, M2	C-2	25	80	I	1/2	0.009	0.005	
C1	Incoloys	Ann	T15	C-2	20-25	75	I	1	0.016	0.008	
C2	Hastelloy B, C	ST	T15	C-2	20	70	IIa IIIa, IIIb	1-1/2	0.020	0.010	
C3	Hastelloy X	ST	T15	C-2	15-20	60	IIa IIIa IIIb	2	0.020	0.010	
D	Inconel Inconel X-750 Nimonics	ST	T15	C-2	10-15	50	IIa IIIa IIIb IV				
		STA	T15	C-2	10-15	40					
E	René 41	ST	T15	C-2	10-25	50	IIa	1/8			0.002
	Udimet 500						IIIa				
	Inconel 700	STA	T15	C-2	10-70	40	IIIb	1/4			0.003
							IV				
F	J 1570	ST	T15	C-2	10	30	IIa	1/2			0.005
	S-816						IIIa				
	HS25 (L605)						IIIb				
	HS21	STA	T15	C-2	15	45	IV	1			0.008
G	N155	ST	T15	--	7-13	--	IIa	1-1/2			0.010
		STA	T15	--	7-13	--	IIa	2			0.010

(a) Ann = annealed; CD = cold drawn; AC = as cast; ST = solution treated; STA = solution treated and aged.
(b) AISI designations for high-speed steels; CISC designations for carbides; see Figure 12 for design.
(c) See page 26 for types of cutting fluids recommended.
(d) For all heat-treated conditions.



Reamer Nomenclature	Type Reamer: Straight Fluted	Type Reamer: Helical Fluted
Helix angle, degrees		5 to 8
Radial Rake angle, degrees	3 to 5 (high-speed steel) 0 to 4 (carbide)	 7 to 10
Relief* angle, degrees	5 to 10	5 to 10
Primary Chamfer angle, degrees	30 to 45	30 to 45
Secondary Chamfer or Lead angle, degrees	2	2
Chamfer Relief Angle, degrees	4	4
Chamfer Secondary Relief Angle, degrees	8	8
Margin, inch	0.005 to 0.015 (high-speed steel) 0.005 to 0.010 (carbide)	

*Depends on reamer diameter.

FIGURE 12. REAMER DESIGNS FOR NICKEL- AND COBALT-BASE ALLOYS

gullet size should be large enough to accommodate the chips formed during the operation.

Broaches are sometimes made slightly oversize (0.0005 inch) to compensate for the slight springback that will occur when the cut is completed.

Nickel- and cobalt-base alloys usually require relief angles between 1/2 to 2 degrees, values normally used in broaching other materials. If the relief angle is too small, metal pickup on the land relief surface can seriously affect the quality of the broached surface.

A rake or hook angle of 20 degrees is normally recommended for broaching conventional materials. For nickel- and cobalt-base alloys, however, smaller angles down to 8 degrees, depending on the alloy, will improve broaching performance to a marked degree. The smaller rake angles provide greater support for the cutting edge and improve heat transfer from the cutting zone. The maximum rake is about 18 degrees for Group A and B alloys, 15 degrees for Group C1 and C2 alloys, and 10 degrees for Group D alloys. Increases beyond these values invite tool failure.

The normal recommendation for the rise per tooth in broaching steel is 0.0005 to 0.003 inch. Nickel- and cobalt-base alloys, however, should be broached at 0.0015 to 0.004 inch per tooth. The lower value of this range should provide smaller cutting forces and better surface finishes.

Tool Materials. Any type of high-speed steel should work reasonably well as a broaching tool. The standard AISI types T1, T4, M2, M4, and M10 should give good performance in the speed ranges recommended (Ref. 23).

Setup Conditions. Rigidity of work and tool is necessary to avoid a consecutive series of "flat surfaces" on the workpiece (Ref. 36). Surface broaching requires much greater rigidity in fixturing than does hole broaching. Hole broaching provides an inherent rigidity derived from the cutter motion against the work-holding device or fixture.

The broach should not ride on the work without cutting.

Cutting Speed. Some nickel- and cobalt-base alloys have shown a marked sensitivity to cutting speed. Thus, it appears reasonable to recommend low, constant speeds for this type of operation to minimize cutting temperature and tool wear.

Cutting speeds should be restricted to the range of 10 to 18 fpm for Groups A, B, and C alloys, and 4 to 8 fpm for the superalloys.

Depth of Cut. The depth of cut is governed by the "rise per tooth" of the broach. A rise per tooth in the range of 0.002 to 0.005 inch has been used successfully when a +5-degree relief angle is employed. If a 2-degree relief angle is used, the rise should be reduced to 0.0015 ipt for superalloys and 0.002 ipt for the Group A, B, and C alloys.

Cutting Fluid. A generous supply of cutting fluid must flow to the cutting edges of the teeth. It should be free flowing and of sufficient body to provide good lubricity (Ref. 23). Sulfurized oils seem to give the best results since they minimize friction, improve surface finish, and reduce wear rates (Ref. 23). A prior application of an oil with a high-strength film to the surface to be broached will greatly minimize the chip-welding tendency and prolong tool life between grinds.

General Supervision. Chips should be removed from broaching tools before each succeeding pass. Any excessive wear and smearing along the cutting edge should be corrected at that time. Tools should be kept sharp to reduce the tendency of smearing of the land which eventually leads to tool failure. Tools must be reground at the first sign of dulling (Ref. 23). Teeth should be polished or honed to remove all peaks and irregularities left by the grinding wheel. The gullets should be polished for better chip flow.

Operating data for broaching these alloys are shown in Table XXV; Figure 13 illustrates the broaching designs.

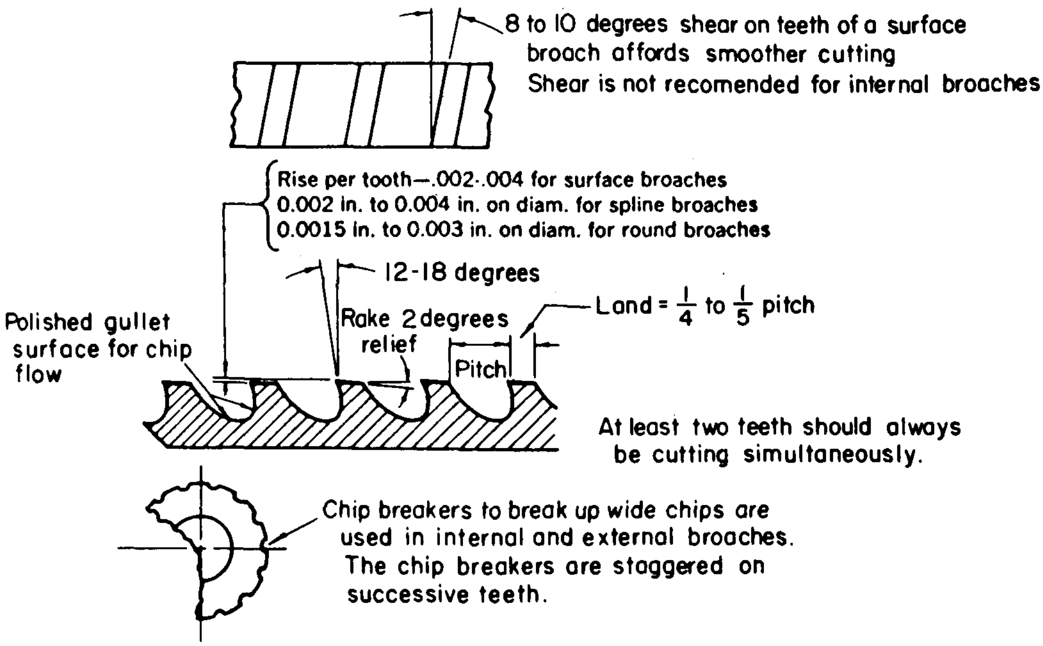
PRECISION GRINDING

Introduction. Methods of grinding nickel- and cobalt-base alloys do not differ greatly from the practices followed for steel (Ref. 23). However, grinding these alloys improperly can induce unusually high cutting temperatures and chemical reactions between the workpiece and the abrasive. This causes dulling of wheels (or belts) by "capping" of the grains with welded-on metal or by glazing and burnishing of the surface being ground. The troubles can be avoided by following three basic precautions:

TABLE XXV. BROACHING DATA FOR NICKEL- AND COBALT-BASE ALLOYS (REFS. 23,44)

Alloy			High-Speed-Steel Tool		Operating Data		
Group	Representative Alloy	Alloy Condition(a)	Grade(b)	Design(c)	Chip Load, ipt	Cutting Speed, fpm	Cutting Fluid(d)
A	Nickel, wrought	CD	T15	A	0.002	10-18	I, IIa IIIa, IV
B1	Monels, wrought	CD	T15	A	0.002	10-18	I, IIa IIIa, IV
B2	Monels, cast	AC	T15	A	0.002	10	I, IIa IIIa, IV
C1	Incoloys	Ann	T15	B	0.002	5-12	I, IIa IIIa, IV
C2	Hastelloy B, C	ST	T15	B	0.0015	10	IIa, IIIa, IV
D	Inconels	ST	T15		0.0015	5-12	IIa, IIIa
	Inconel X750	STA	T15	C	0.0015	6	
	Nimonics						
E	Rene 41	ST	T15	C	0.0015	6	IIa, IIIa
	Udimet 500	STA	T15	C	0.0015	4	
	Inconel 700						
F	J1570	ST	T15	C	0.002	8	IIa, IIIa
	S816						
	HS25	STA	T15	C	0.002	8	
	HS21						
G	N155	ST	T15	C	0.002	8	IIa, IIIa
		STA	T15	C	0.002	8	

(a) CD = cold drawn; Ann = annealed; ST = solution treated; STA = solution treated and aged; AC = as cast.
(b) AISI designations used.
(c) See Figure 13 for broach designs.
(d) See page 26 for recommended cutting fluids.



	Broach Design		
	A	B	C
Alloy Group	A and B	C1 and C2	D
Rake Angle, degrees	12 to 18	10 to 15	8 to 10
Relief Angle, degrees	1/2 to 2	1/2 to 2	1/2 to 2
Rise Per Tooth, inch	0.002 to 0.004	0.0015	0.0015

FIGURE 13. BROACH DESIGNS FOR USE ON NICKEL- AND COBALT-BASE ALLOYS

- Choosing an abrasive wheel (or belt) that allows controlled, progressive intergranular chipping as flat spots develop on the grits

- Using appropriate speeds to minimize grinding temperatures and welding reactions

- Utilizing a chemically active grinding fluid that will develop a low shear-strength film between chip and grit.

Low grinding temperatures also minimize the residual stresses in a finish-ground part.

Nickel- and cobalt-base alloys can be ground at about the same rate as hardened high-speed steels and die steels. Moderately light cuts are recommended, and periodic dressings are required to keep the wheel in proper condition. Excessive wheel loading leads to poor grinding action and causes poor surface finish, high residual tensile stresses, and low grinding ratios. Grinding ratios involve the volume (cubic inches) of metal removed to the volume of grinding wheel removed by wear during grinding. Low ratios mean poor wheel life. It is analogous to tool life in machining where cubic inches of metal removed are related to flank wear.

If a choice of finish-machining methods exists in a potential grinding situation, serious considerations are usually given to turning, boring, or milling operations rather than grinding. These operations require less time than grinding and give excellent surface finishes. Nevertheless, when only a small amount of material is to be removed, the finishing operation can be done on a grinding machine using a rough and then a finish grind (Ref. 23).

Machine-Tool Requirements. There are many high quality grinders available today. Most of the existing machines can be set for the required light downfeeds, although they have no means of adjusting the spindle speed. Furthermore, not many production grinders are equipped with automatic wheel-wear compensation. These devices improve dimensional control, especially when softer wheels are used (Ref. 21).

Several existing grinders are being modernized to provide wheel speeds needed for high-strength alloys. Devices for automatic gaging and sizing, wheel dressing, and wheel compensation are being added to the ultraprecision grinders. Increased rigidity in the spindle system, together with automatic wheel balancing, are highly recommended features for grinding the high-strength high-temperature-resistant materials (Ref. 21).

Grinding Wheels. Properly operated grinding wheels should wear by attrition and fracture of the bond.

Normal attrition involves, as a continuous process, a gradual smoothening of the individual abrasive grains during cutting. It is followed by intergranular fractures that are supposed to provide successively new sharp-edged cutting surfaces until the entire grain leaves the wheel.

If the grains break away too slowly, the workpiece material is deposited on and in between the abrasive grains. As wheel loading continues and the wheel becomes smoother, the grinding rate decreases. Glazing is similar, except that the tips of the grain wear smooth and become shiny through friction. Smooth wheels, resulting from either cause, burnish the workpiece and may result in burning, high residual stresses, and cracked surfaces.

If the grains break away too rapidly, either during grinding or by frequent wheel dressing, wheel wear is excessive.

Generally speaking, grinding wheels should be sufficiently soft to wear at a moderate rate. Hard wheels are likely to become embedded with particles of metal that dull the wheel rapidly. This situation requires frequent wheel dressing. Furthermore, some of the abrasive grains of hard wheels may become embedded in the ground surface of the workpiece. These grains may cause scratching of a contacting part during service (Ref. 23).

Grinding wheels are available in various combinations of grit sizes, wheel hardnesses, and bond materials. These attributes influence metal-removal rates and wear for specific grinding conditions. Table XXVI shows the wide choices available and indicates the characteristics of a typical wheel used for grinding nickel- and cobalt-base alloys.

Abrasives. The choice of a silicon carbide or aluminum oxide wheel depends on the grinding application.

Silicon carbide wheels are usually used for cylindrical, centerless, and internal grinding (Ref. 23). On the other hand, aluminum

TABLE XXVI. CHART OF MARKINGS ON GRINDING WHEELS

Abrasive Symbols[a]		Grit Size				Grain	Wheel Grade			Structure			Bond	Bond Type and Manufacturer's Symbols
Silicon Carbide	Aluminum Oxide	Coarse	Medium	Fine	Very Fine	Combination	Soft	Medium	Hard	Dense	Medium	Open	Form	
5C	A	10					A			0			V=vitrified	Modification bond[b]
6C	2A	12	36	90	240	1 Coarse	B			1	5	9	R=rubber	
CA	97A	14	46	100	280	2	C			2	6	10	B=resinoid	See manufacturer's brochures
C2A	4A	16	54	120	320	3	D	I		3	7	11	E=shellac	
C4A	9A	20	60	150	400	4	E	J		4	8	12	M=metal	
7C		24	70	180	500	5	F	K				13	S=silicate	
		30	80	220	600	6	G	L	Q			14		
						7 Fine	H	M	R			15		
								N	S					
								O	T					
								P	U					
									V					
									W					
									X					
									Y					
									Z					
A typical marking sequence[c]	4A	46				1 - J				8 - VL				

Description of Various Grades of Silicon Carbide and Aluminum Oxide Abrasives[a]

C - Silicon Carbide	A - Aluminum Oxide
5C - green silicon carbide	A - tough aluminum oxide
6C - black silicon carbide	2A - semifriable
CA mixed aluminum	97A - friable mixture
C2A oxide and	4A - special friable
C4A silicon carbide	9A - very friable (white)
7C - mixed silicon carbide	

(a) Cincinnati Milling Machine Company nomenclature.
(b) Some manufacturers also add a number designating whether the wheel grade is either exact, one-third softer, or one-third harder than the better grade indicated (J in the example shown).
(c) The sequence shown represents a grinding wheel used on nickel alloys.

oxide wheels are preferred for surface grinding because they are used at somewhat lower speeds. The optimum speed for silicon carbide wheels is much higher than for aluminum oxide wheels. In fact, if a wheel must be operated beyond 6000 fpm because of limited equipment availability, silicon carbide wheels should give better results than aluminum oxide wheels.

Aluminum oxide wheels with abrasives like 38A and 32A* (or their equivalents) are satisfactory for the Groups A, B, and C alloys and Groups D, E, and F alloys, respectively.

Table XXVII shows some abrasive-grain classifications which may be comparable, listed by manufacturer. However, grinding wheels from different suppliers are not necessarily identical.

TABLE XXVII. TYPES OF ALUMINUM OXIDE AND SILICON CARBIDE ABRASIVES USED FOR GRINDING NICKEL- AND COBALT-BASE ALLOYS

Abrasive Manufacturer	Type of Abrasive: Special Friable Aluminum Oxide	Type of Abrasive: White Aluminum Oxide	Type of Abrasive: Black or Regular Silicon Carbide
	Abrasive Symbols		
Norton	32A	38A	37C
Cincinnati	4A	9A	6C
Carborundum	--	AA	C
Bay State	3A - 8A	9A	2C
Chicago	52A	53A	49C
Desanno	7A	9A	C
Macklin	26A	48A	C
Simonds	7A	8A	C
Sterling	HA	WA	C

Grit Size. The size of the abrasive grains influences the efficiency of grinding by affecting the rate of intergranular fracturing and the supply of fresh cutting edges. Smaller grains tend to leave the wheel prematurely, resulting in faster wear. Larger grains dull excessively before leaving the wheel.

The optimum grit size for both silicon carbide and aluminum oxide wheels is between 46 and 60.

Wheel Hardness. The material used to bond the abrasive grits determines the wheel hardness. It is usually desirable

*Norton Company symbol.

to use the hardest wheel that will not result in burning or smearing of hard alloys, or chatter on softer alloys.

For this reason, the medium grades I to L seem to be the most suitable for nickel- and cobalt-base alloys, although softer grades like E to H have been used. The softer grades usually permit lower residual stresses in ground surfaces than harder wheels.

Type of Bond. Vitrified bonds seem to give the best performance possibly because they are more porous. As such, they permit better swarf (chip) clearances and result in lower grinding temperatures.

Setup Conditions. The following recommendations are suggested in order to provide the good grinding environment needed for nickel- and cobalt-base alloys.

- High quality grinders with variable table and spindle speeds
- Rigid setup of work and wheel to avoid vibrations that cause surface damage
- Arbors for external grinding
- Oxidized machine centers to prevent galling of a running surface of a spinning part being ground.

Troubles originating from resonant vibrations can usually be corrected by improved jigs or by backing up thin, slender sections to prevent deflection.

Adjustments in wheel speed, work speed and feed, truing conditions, and the grinding fluid will usually compensate for the selection of a wheel with less than optimum characteristics.

Wheel Speeds. For a given grinding wheel and coolant an optimum grinding speed can produce much higher grinding ratios (G-ratios) than a speed a few hundred feet per minute faster or slower. For the aluminum oxide wheel 32A46J8VBE, the optimum speeds appear to be between 3000 and 6000 fpm for grinding-oil coolants.

For silicon carbide wheels the optimum speed seems to be in the range from 6000 to 6500 fpm when using a grinding oil. Consequently, when it is necessary to use grinders having the normal grinding speed of about 6000 fpm, silicon carbide wheels give the best wheel life.

Wheel speeds of 4000 fpm can be used with aluminum oxide wheels and sulfochlorinated oils to produce a good combination of surface finish and dimensional tolerance with relatively low residual stresses. Low residual stresses are produced at low wheel speeds (2000 fpm) using aluminum oxide grinding wheels and a highly sulfurized oil (Ref. 41).

A word should be added about table speed. The G-ratio on René 41, STA. for the 32A46 J8VBE wheel running at 6000 fpm peaks at 240 ipm table speed. This speed, however, is too slow for practical grinding. Hence, the recommended table speeds are in the somewhat higher range of 300 to 500 ipm (Ref. 41).

Feeds. Two types of feeds are involved in grinding: the downfeed and the cross-feed. The former is similar to the depth of cut in machining while the latter corresponds to the feed.

The lightest downfeeds (0.0005 ipp) seem to give the highest G-ratios over a wide range of cross-feeds (between 0.025 and 0.25 ipp). However, as the downfeed is successively increased from 0.0005 ipp the grinding ratio falls and does so more rapidly as the unit cross-feed is increased. Hence, a cross-feed of around 0.050 ipp is normally used together with downfeeds between 0.0005 and 0.001 ipp. Heavier downfeeds can cause burning and excessive wheel wear (Refs. 21,41).

Grinding Fluids. It is important to use a grinding fluid that will cool efficiently and inhibit the chemical reaction between the alloys and the abrasive wheel. Cobalt- and nickel-base alloys should never be ground dry. Dry grinding results in excessive residual stresses and smeared surfaces.

Water alone is not suitable, and ordinary soluble oils do not produce good grinding ratios. Chemical coolants diluted 40:1 produce rather low grinding ratios (Ref. 21). The basic composition of these coolants is described on page 25.

The highly sulfurized oils diluted 1:1 with light machine oil give some of the highest G-ratios. Some of the highly chlorinated grinding oils also have proved quite satisfactory.

The degree of concentration or dilution of a grinding fluid plays an important part in the grinding action. Maximum G-ratios are usually obtained with undiluted oils. When grinding oils are diluted with plain mineral oil, some of their advantages are lost, but not as much as in the case of titanium (Ref. 21).

The rust inhibitors can be used at about 3 per cent concentration, but very low grinding ratios usually result (Ref. 21).

All fluids should be filtered to remove grit and to prevent "fish tail" marks* on finished surfaces. Fluids should be changed more often than is customary in grinding steel.

General Supervision. Grinding operations should be supervised and controlled very carefully. When the grinding procedure used is questionable, quick checks to indicate possible surface cracking can be made by dye and fluorescent penetrants.

Wheels used to grind nickel- and cobalt-base alloys must be dressed more frequently than those used to grind steels because of wheel loading.

If an extremely accurate ground finish is required and particularly if the material is of hard temper, it is advisable to remove the workpiece from the grinder after the final roughing cut and set it aside to cool to room temperature. This procedure allows redistribution of internal stresses in complete freedom and the resulting distortion, if it occurs, can be corrected in the final grinding operation (Ref. 23).

Data on speeds and feeds found suitable for silicon carbide and aluminum oxide wheels are shown in Table XXVIII.

BELT GRINDING

Introduction. Nickel- and cobalt-base alloys can be belt ground to close dimensional tolerances.

The carrier-type machine is usually used in the abrasive belt grinding of sheet. The work is held on a table that oscillates back and forth under the grinding belt. A billy-roll directly under the contact roll maintains the pressure between the work and the belt.

*Actually pollywog-shaped marks.

TABLE XXVIII. SURFACE GRINDING CONDITIONS FOR NICKEL- AND COBALT-BASE ALLOYS (REFS. 21, 23, 41)

Alloy		Alloy Condition[a]	Grinding Wheel		Downfeed, ipp[d]		Cross-Feed, ipp	Table Speed, ipm	Wheel Speed, fpm	Grinding Fluid
Group	Representative Alloy		Aluminum Oxide Type[b]	Typical Wheel Marking[c]	Rough	Finish				
A	Nickel, wrought	CD	White	38A60-I8VBE	0.001	0.0005	0.05	400-480	5000-6000	IIc
B	Monels, wrought and cast	CD or AC	White	38A60-I8VBE	0.001	0.0005	0.05	400-480	5000-6000	IIc
C2	Hastelloy B, C	ST	Special friable	No data	0.001	0.0005	0.05	600	4000	IIc
D	Inconel Inconel X750	STA	Special friable	32A60-G12VBEP	0.001	0.0005	0.05	420-600	3000-5400	IIc, IIIb
E	Rene 41 Udimet 500 Inconel 700	STA	Special friable	32A60-J8VBE 32A60-L8VBE	0.001	0.0005	0.05	480-600	3000-6000	IIc, IIIb
F	J1570 S816 HS25 (ST only) HS21	STA	Special friable	32A46-L8VBE	0.001	0.0005	0.05	480-600	3000-6000	IIc, IIIb
G	N155	*	*	*	*	*	*	*	*	*

(a) CD = cold drawn; AC = as cast; ST = solution treated; STA = solution treated and aged.
(b) See Table XXVII for manufacturer's designations.
(c) Norton symbols.
(d) ipp = inches per pass.

*No data, but probably the same as Group G.

metal contact wheels show little significant increase in stock removal and grinding rate to warrant the considerable noise, vibration, poorer surfaces, and higher power consumption.

Rubber contact wheels are available in various degrees of hardness, measured in terms of Durometer units. These values may range from 10 (sponge rubber) to about 100 (rock hard). The softest rubber (other than sponge) has a value of 20. The harder the contact wheel, the faster an abrasive belt will cut and the coarser the surface finish becomes. Softer wheels produce better surface finishes. However, even soft wheels become effectively harder as spindle speeds increase and they present more support to the belt. Softer rubber wheels can be used for blending and for spotting operations to remove isolated defects. The best rubber contact wheel is one which is firm enough to give restricted contact and good penetration by the grit but resilient enough to eliminate shelling failure of the belt at the high loads (Refs. 56,57).

Abrasive Belts. Aluminum oxide abrasive belts are usually recommended under normal feeds and for the belts speeds considered optimum for nickel- and cobalt-base alloys. These belts must possess a dense texture (closed coat).

Roughing and spotting operations are normally carried out on belts coated with medium- or fine-grain abrasives. The fine grit size 80 is slightly superior to medium grit sizes 40 and 60. Extra-fine grain abrasives (grits 120 to 220) are used for finish belt-grinding operations.

Synthetic-resin bonds provide maximum durability for abrasive belts used on nickel- and cobalt-base alloys. They are available in a waterproof or nonwaterproof backing.

Setup Conditions.

Belt Speeds. Cutting speed affects the rate of metal removal, belt life, and surface finish. Lower belt speeds reduce cutting temperatures as well as the tendency toward burning or marring the surface by incandescent chips.

Although the optimum speed varies with the contact wheel, grit size, and work thickness, a speed of 3000 to 6000 fpm generally gives good results.

These belt grinders have produced flat surfaces on sheet with only 0.004-inch maximum deviation over areas up to 36 x 36 inches.

Another important application involves the finishing of aerofoil sections of compressor and turbine blades. Two methods are used for their manufacture. The grinding-to-form technique employs an abrasive belt which is guided by a contact wheel. The latter is controlled by a stylus and tracer mechanism. The second technique causes the abrasive belt to pass over a contour block.

Machine rigidity is important in all cases for achieving close dimensional tolerances (Refs. 54,55).

Abrasive-Belt Contact-Wheel Systems. Paper-backed belts used either dry or with a grinding oil, are suitable for flat sheet work. Cloth-backed belts are used when a more rugged backing is needed. Cloth belts are generally available in two types: drills (X-weight) which are the heavier and stiffer of the two, and jeans (J-weight). The flexible J-weight backing is used for contour polishing; the X-weight provides the best belt life and fastest cutting (Refs. 56,57). Fully waterproof, cloth-backed belts are necessary when water-base grinding fluids are used. All belts are usually manufactured to close thickness tolerances to permit grinding to precise dimensions.

Contact Wheels. The contact wheel, which supports the belt at the pressure point, regulates the cutting rate and controls the grain breakdown (Refs. 56,57).

Plain-faced contact wheels are normally used when unit pressures are high enough to promote the necessary breakdown of abrasive material for best grinding action. They usually produce a better surface finish than do most serrated wheels. They minimize extreme shelling*. They also permit off-hand grinding and polishing of curved and contoured parts.

The contact wheel should be small in diameter and as hard as practicable. This combination provides almost a line contact and, hence, a high unit pressure between the abrasive grits and the work.

Suitable contact-wheel materials for abrasive belts include rubber, plastic, or metal. Rubber is usually recommended because

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*Shelling is the tendency for the abrasive grains on the abrasive belt to loosen and flake off.

Feeds. Feeds in belt grinding are controlled indirectly by adjusting the pressure. The correct feed permits an economical rate of metal removal and avoids loading the belt with chips. Feeds should be controlled to give the best dimensional tolerances. If feed pressures must be increased, it may be advisable to use a softer contact wheel.

A definite correlation exists between grinding pressure and belt speed. Higher speeds require less pressure and vice versa. Feed pressures between 80 and 120 psi have been used, depending on the belt speed.

Grinding Fluids. Lubrication is a most significant factor in abrasive belt grinding. Dry grinding, except for certain intermittent operations (blending, spotting, etc.), is not recommended (Ref. 54).

A grinding fluid should be used when taking continuous cuts over fairly large areas. It reduces grinding temperatures and quenches sparking. Sulfochlorinated grinding oils that possess high flash points (above 325 F) should be used and applied close to the grinding point for rapid spark quenching.

Soluble-oil emulsions in water are normally poor grinding fluids but can be used where the alternative is to grind dry.

With waterproof belts, water-base fluids containing certain inorganic compounds give good results. Aqueous-solution lubricants seem to give the best performance in grinding setups where high loads are used, for example, stock removal operations. The following water-base fluids have been used:

- Sal soda (1 lb sal soda to 25 gallons water) (Ref. 23)
- Sodium phosphate (up to 12 per cent solution)
- Potassium phosphate (up to 30 per cent solution).

All sodium and potassium phosphate solutions are caustic enough to remove paint from machine tools. The more concentrated solutions, however, are not much worse in this respect than the weaker solutions (5 per cent) and are considerably more effective as grinding lubricants.

Grinding fluids can be applied by spraying or by immersing the belt.

Operating Data. Sometimes a roughing operation is first made using a 50 grit belt to remove gross surface imperfections. An intermediate grind (80 grit) is then used to reduce the grind marks, followed by a finishing operation using a 120 grit belt.

The correct treatment of belt troubles requires an understanding of the difference between glazing and loading. Glazing occurs on abrasive belts when the grinding pressure is insufficient to break down the abrasive particles properly. A loaded belt contains workpiece material on and in between the abrasive grains, a condition which impairs cutting ability. Proper lubrication is one way to minimize loading (Ref. 57).

The same inspection procedures recommended in the precision grinding section also apply to belt grinding.

Table XXIX summarizes the pertinent data required for the belt grinding of nickel- and cobalt-base alloys.

ABRASIVE SAWING

Introduction. Nickel- and cobalt-base alloys can be cut with abrasive wheels. However, the peripheral cutting edge and adjacent surfaces of the wheel can load with metal during the cutoff operation in much the same manner as described on page 78. The occurrence of wheel loading may cause high residual stresses on the cut surfaces. Stress-relief treatments may be necessary to prevent delayed cracking of cut surfaces. When proper techniques are used, however, the cut surfaces are bright, smooth, and straight. Surface finish between 10 and 14 microinch rms can be obtained.

Machine-Tool Requirements. Rigid setups and abrasive cutoff machines that have wheel heads capable of oscillating and plunging motions are recommended. It is also advisable that the cutoff machine be equipped with hydraulic feed mechanisms that can be set to produce any desired cutting rate.

Cutoff Wheels. The choice of the right combination of abrasive grit, wheel hardness, and type of bond will do much to alleviate difficulties. These characteristics are identified for cutoff wheels in much the same way as shown in Table XXVI for grinding wheels.

TABLE XXIX. BELT GRINDING CONDITIONS FOR NICKEL AND COBALT ALLOYS (REFS. 23, 57, 58)

Alloy		Alloy		Abrasive Belt				Contact Wheel(d)			
				Abrasive							
Group	Representative Alloy	Condition(a)	Type Operation(b)	Type	Size(c)	Coat or Texture(d)	Belt Backing(d)	Type	Hardness (Durometer)	Belt Speed, fpm	Grinding Fluid
A and B	Nickel and Monels	--	--	--	--	--	--	--	--	--	--
C	Hastelloys	ST	Roughing	Al_2O_3	24-50 80	Closed	X, J	Smooth face rubber	70-90	4,000-5,000	Sulfochlorinated grease
D	Inconel X-750	STA	Polishing	Al_2O_3	40-100 120-150	Closed	X, J	Serrated rubber	70	4,000-5,000	Light grease
	Nimonic 80 90 100	STA	Fine polishing	Al_2O_3	100-150 80-220	Closed	X, J	Smooth rubber	50	4,000-5,000	Light grease
E	Waspaloy	STA									
F	HS27	AC									

(a) AC = as cast; ST = solution treated; STA = solution treated and aged.
(b) In finishing operations with fine grits, a light pressure is required to prevent shelling. A dull belt, but cutting well, often produces a finer finish than a new, sharp belt of the same grit.
(c) Fine grits tend to fail by shelling at pressures which coarser grits will easily withstand.
(d) See text on this subject, pp 85-86.

Aluminum oxide cutoff wheels are generally used on nickel- and cobalt-base alloys. Resinoid-bonded wheels, for example, A301-R6-B4A or A60-Q8B, are recommended for dry cutting, while rubber-bonded wheels, for example, A602-M-RA, should be used for wet cutting (Ref. 23).

Conditions of Setup. The choice of speeds and feeds depends on the diameter of the work and the mode of cutting (oscillating, non-oscillating, work rotation). Some combinations which have given satisfactory results are given below.

Speed. Speeds from 5000 to 5500 fpm have been used successfully in abrasive cutoff operations (Ref. 23).

Feeds. Successive, overlapping, shallow cuts should be taken in order to keep the work-wheel contact area as small as possible at all times. Maximum feeds permitted by the machine's capability are used depending on setup conditions and wheel speed (Ref. 23).

Cutting Fluids. A rust-inhibitor type of coolant should be supplied at the rate of about 20 gallons per minute to the work-wheel contact area in order to reduce cutting temperatures enough to avoid heat cracking of the cut surfaces.

The coolant should penetrate to the work-wheel contact area. It should be applied equally to both sides of the wheel to avoid cracked cuts and wheel breakage.

Soluble-oil coolants can be used, but they have a tendency to foam. Soluble-oil coolants are available that minimize the objectionable rubber-wheel odor.

The size of the workpiece influences the choice of cutting techniques. A small stock around 1 inch in diameter can be cut dry without an oscillating head or rotation of work. Bars from 1 inch to 3 inches in diameter should be cut wet and may require either an oscillating or a nonoscillating wheel. Both should be tried in order to determine which is better for the given situation (Ref. 23).

Bars larger than 3 inches in diameter usually require rotation of the work as well as an oscillating wheel. The work should be rotated slowly, or indexed, so that the wheel can cut toward the center without cutting too far beyond center.

It may be desirable to stress relieve the workpiece after cutting.

BAND SAWING

Introduction. Band sawing can be used for making both straight and contour cuts in nickel- and cobalt-base alloys, although it is not recommended for Group D alloys of thick section (Ref. 23). Generally, band sawing of nickel- and cobalt-base alloys is recommended only when shearing or abrasive-wheel cutting cannot be used efficiently. Sawing is usually considered a rough trimming operation that requires finish trimming, either by hand or by machine, to meet the requirements of aircraft-quality parts (Ref. 28).

Pure nickel is very difficult to saw because of its high ductility. Nickel- and cobalt-base alloys are stronger and even more difficult to saw (Ref. 59). Difficulties in sawing these materials can be minimized by selecting a saw band with the proper pitch, and by using a feeding pressure suited to the work thickness involved. The combination of band velocity and feed also influences the economic tool life.

Machine-Tool Requirements. Rigid high-quality band-saw equipment powered with motors providing at least 2 horsepower should be used. The machines should provide automatic positive feeding and band-tensioning features. In addition, they should have a positive-flow, recirculating-type coolant system.

Saw Bands. Precision and claw-tooth saw bands are used for cutting nickel- and cobalt-base alloys. The widest and thickest band that can produce the smallest radius desired on the part should be selected. The following band widths will cut the minimum radii indicated:

Saw Width, inch	Minimum Radii Cut, inch
1/16	Square
3/32	1/16
1/8	1/8
3/16	5/16
1/4	5/8
3/8	1-7/16
1/2	2-1/2
5/8	3-3/4
3/4	5-7/16
1.0	7-1/4

Wider saw bands provide greater stability when the saw is pretensioned.

Figure 14 illustrates some of the common terms used in describing sawing operations.

Saw-Band Design. The two important design features of a saw band are the "pitch" or the number of teeth per inch, and the "set" of the teeth. The selection of the pitch for a saw band cutting high-temperature metals depends mainly on the cut thickness opposed by the saw teeth. This thickness varies in the case of round bars. If the pitch is too coarse, the feeding force on each tooth will be excessive. On the other hand, if the pitch is too fine, the chips will crowd or fill the gullets. In general, the coarsest pitch consistent with the desired finish should be selected; however, at least two teeth should always contact the cut, and the chip load at any one time should not exceed 0.005, ipt.

The saw set creates clearance to prevent the trailing surfaces of the band from binding. It determines the slot and hence the amount of metal removed. A fine-pitch saw band with a light set usually gives the best finish, particularly when used with higher band velocities and low feed rates. This combination also produces a slot that approaches the over-all saw-set dimension.

The following tabulation gives some data for raker and wave-set, precision-type band saws used.

Width,	Gage,	Raker Set Pitch (Nominal)							Wave Set Pitch (Nominal)				
inch	inch	6	8	10	12	14	18	24	8	10	12	14	32
1/16	0.025	--	--	--	--	--	--	0.038	--	--	--	--	0.038
3/32	0.025	--	--	--	--	--	0.042	--	--	--	--	--	0.042
1/8	0.025	--	--	--	--	0.043	0.042	0.042	--	--	--	--	--
3/16	0.025	--	--	0.044	--	0.043	0.042	0.042	--	--	--	--	0.042
1/4	0.025	--	--	0.044	0.043	0.043	0.042	0.042	--	--	--	--	0.042
3/8	0.025	--	0.045	0.044	--	0.043	0.042	0.042	--	--	--	--	0 --
1/2	0.025	0.045	--	0.044	--	0.043	0.042	0.042	--	0.044	--	0.043	--
5/8	0.032	--	0.055	0.055	--	0.054	0.052	0.050	--	0.057	--	0.057	--
3/4	0.032	0.055	0.055	0.055	0.054	0.054	0.052	--	0.057	0.057	0.057	0.057	--
1	0.035	0.058	0.058	0.058	--	0.057	--	--	--	0.063	--	--	--

A right-left raker set combined with the coarsest pitch consistent with the work thickness and the desired finish is usually adequate for most applications other than light-gage sheet and thin-wall tubing (Ref. 23). Saws with wave-set teeth are best for sawing thin sections (Ref. 23).

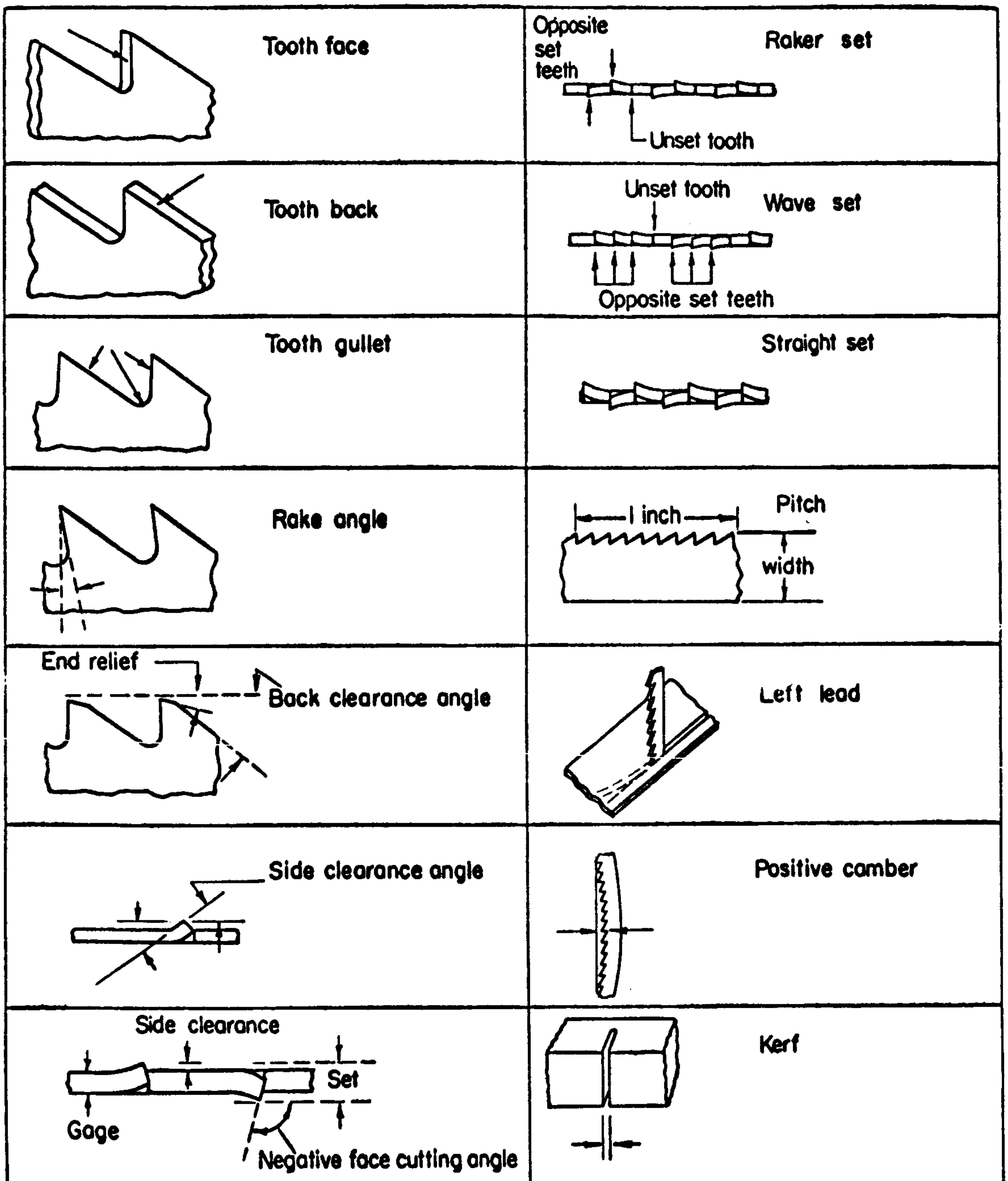


FIGURE 14. ILLUSTRATIONS OF SOME COMMON TERMS USED IN SAWING

Tool Materials. Saw bands with high-speed steel-teeth and flexible backs are recommended for sawing nickel- and cobalt-base alloys (Ref. 23). An appropriate heat treatment produces a microstructure that remains strong at elevated temperatures and a reasonably flexible band.

Setup Conditions. Hand or gravity-type feeds do not produce satisfactory results when sawing these alloys. Vibration-free machines with positive mechanical feeds are necessary to prevent premature band failure.

Maximum rigidity is favored by using the widest and thickest band permitted by the band wheel and the radii to be cut. The band should be pretensioned to approximately 12,000 psi to minimize unnecessary bending of the saw band in the cut. Guide inserts should be adjusted to a snug fit to insure accurate cuts and minimum "lead" (Figure 14). For the same reasons, the band support arms should be close to the work.

Cutting Speeds. Band velocity is a critical variable in sawing high-temperature alloys. Excessive cutting speeds cause high cutting temperatures and unwanted vibrations.

Band velocities used for sawing nickel- and cobalt-base alloys usually range from 30 to 125 fpm depending on the alloy, work thickness, surface finish, cutting rate, saw pitch, and tool life desired.

Feeds. The saw should constantly "bite" into the work; otherwise the blade will rub and work harden the material being cut (Ref. 23).

Unit feeds in the range of 0.00014 to 0.0005 inch per tooth can be used successfully. The smaller feeds give the best tool life, but the heavier feeds increase productivity and may be more economical. Excessive feeds clog the teeth with chips before they emerge from the kerf and reduce cutting rates.

Feeding forces must be reduced as the saw pitch decreases to prevent overloading individual teeth. On the other hand, feeding pressures so light that the teeth do not penetrate the work cause work hardening, excessive abrasion, and rapid dulling.

Cutting Rate. The cutting rate in band sawing is determined mainly by the thickness of the workpiece. Faster cutting rates (up to 2.7 square inches/minute) are achieved in sawing solid bars 1 inch or greater in thickness (or diameter) since more teeth can be loaded uniformly at the same time. For thinner sections, the limited number of engaged teeth requires a reduction in cutting rate to reduce the feed per tooth. In this case, cutting rates should not exceed the 0.9 square inch per minute minimum rate for nickel alloys and 0.45 square inch per minute for superalloys. Higher rates may cause inaccurate cutting and damage the saw set. In general, when band sawing tubing and structural shapes the minimum cutting rates must be reduced below those used for bars and plates.

Cutting Fluids. Cutting fluids used in band sawing nickel- and cobalt-base alloys include soluble oils, sulfochlorinated, sulfurized, or chlorinated oils (Refs. 23,44,59). Fluids flowing forcefully from shroud-like nozzles will penetrate the kerf and prevent chips from adhering to the tooth faces and gullets. An atomized spray of soluble oil under 40 psi of air pressure also has been used with good results. A pressure-resistant oil may be brushed on the saw teeth to prevent chip welding (Ref. 23).

General Supervision. Heavy oxide films may cause problems in band sawing. This trouble can be solved by breaking or removing this surface at the line of cut with a used saw blade or by other suitable means.

During the sawing operations, the saw band must not skew in the cut. If the cutting time starts to increase rapidly, the saw band should be replaced.

A problem of sawing may be encountered on thin gage material (0.010 inch). Scrap template stock, or a narrow-kerf accessory block used under the material to be sawed, can alleviate this condition (Ref. 28).

Conditions suitable for band sawing sheet, plate, bars, and tubing are suggested in Tables XXX to XXXIII inclusive.

TABLE XXX. RECOMMENDED SPEEDS, FEEDS, AND CUTTING RATES FOR BAND SAWING NICKEL- AND COBALT-BASE ALLOYS[(a)]

Group	Representative Alloy	Band Speed, fpm	Cutting Rate, sq in./min	Unit Feed, in./tooth	Cutting Fluids
A	Commercially-pure	50-105	0.90 to 2.7		
B	Monels	50-125	0.90 to 2.7	0.00014	Soluble oils
C	Hastelloy X	50-70	0.67 to 1.3	to	Sulfurized and
D	Inconels, Nimonics	50-70	0.45 to 1.3	0.0005	chlorinated oils
E	Rene 41; J1570	30-70			

(a) Based on 5-inch rounds and a 6-pitch saw.

TABLE XXXI. PITCHES OF BAND SAWS RECOMMENDED FOR SAWING DIFFERENT WORK THICKNESSES

Work Thickness, inch	Appropriate Pitch, teeth per inch
7/64 to 5/32	18-32
5/32 to 3/16	14-18
1/4 to 3/8	10-14
1/2 to 1.0	6-14
1.0 and greater	6-10

TABLE XXXII. RECOMMENDED MODIFICATIONS OF CUTTING RATES FOR PIPE, TUBING, AND STRUCTURAL SHAPES

Minimum Wall Thickness to be Sawed, inch	Fraction of Minimum Cutting Rates Shown in Table XXXIII
Up to 3/16	0.40
1/4 to 3/8	0.50
1/2 to 5/8	0.60
3/4 to 1.0	0.70
1.0 inch and over	1.00

TABLE XXXIII. BAND SAWING NICKEL- AND COBALT-BASE ALLOYS (REFS. 23, 28, 44, 59)

Group	Representative Alloy	Alloy Condition (b)	Band Speed For the Pitch Indicated In Parentheses, fpm — Work Thickness, inches: 0 to 1/4	1/4 to 1/2	1/2 to 1	1 to 3	Cutting Rate, and Unit Feed, For Thickness Shown — Less Than 1 inch: Cutting Rate, sq. in. /min	Unit Feed, ipt	1 to 3 inches: Cutting Rate, sq. in. /min	Unit Feed, ipt	Cutting Fluids(b)
A	Nickel, wrought	CD	90-105 (14-24)	75-90 (10-14)	50 (8-14)	50 (6-10)	0.9	0.00014 to 0.00022	2.7	0.00025 to 0.0005	I, IIa, IIIa, IV
B1	Monels, wrought	CD	125 (18-24)	75-100 (10-14)	50-75 (10)	50 (6-8)	0.9	Ditto	2.7	Ditto	I, IIa, IIIa, IV
C1	Incoloys, wrought	Ann	90 (18-24)	75 (10-14)	50 (10)	50 (6-8)	0.9	"	2.7	"	I, IIa, IIIa, IV
								"		"	I, IIa, IIIa, IV
C2	Hastelloy B, C	ST	70 (18)	60 (10)	50 (6)	50 (4)	0.9	"	2.3	"	I, IIa, IIIa, IV
C3	Hastelloy X	ST	60-70 (18-24)	50-60 (10-14)	50 (10-14)	50 (6-10)	0.67	"	1.3	"	I, IIa, IIIa, IV
D	Inconels	ST	70 (18)	60 (14)	50 (10)	50 (6)	0.45	"	1.3	"	I, IIa, IIIa, IV
E	Nimonics René 41 Udimet 700	ST	60 (18-24)	50 (10-14)	40 (10-14)	30 (6-10)	0.45	"	1.3	"	I, IIa, IIIa, IV
F	J1570 HS25	ST	60-70 (18-24)	50-60 (10-14)	50 (10-14)	50 (6-10)	0.45	"	1.3	"	I, IIa, IIIa, IV

(a) Ann = annealed; ST = solution treated; CD = cold drawn.
(b) See page 26 for types of cutting fluids involved.

ELECTROCHEMICAL MACHINING (ECM) OF NICKEL- AND COBALT-BASE ALLOYS

INTRODUCTION

The need for fabricating parts from high-strength and heat-resistant metals and alloys has created difficult metal-removal problems. To meet these problems, new or improved metalworking methods have been developed.

Among some of the novel nonmechanical methods developed and used for machining accurate and complex components from the tough alloys frequently used in aircraft, rockets, and missiles, are: electrochemical machining or shaping (ECM), chemical milling, electric-discharge machining (EDM), ultrasonic machining, electron-beam machining, and others. This and the following section of the report will deal with the first two of the above methods, with special emphasis being placed on machining or shaping nickel- and cobalt-base alloys.

THE ECM PROCESS

General. Metal removal in ECM is by dissolution brought about by passage of an electrical current between the workpiece (anode) and a shaped tool(s) (cathode) through a suitable electrolyte. ECM can be likened to an electroplating process operating in reverse. General discussions of the electrochemical machining processes are given in References 60, 61, and 62.

The rate of metal removal in ECM is directly proportional to the current and is in accordance with Faraday's laws. The high velocities of electrolyte-solution flow used in ECM together with the close spacing (e.g., 0.002 to 0.040 inch) between the workpiece and the other electrode allow the passage of high currents at relatively low voltages (e.g., 3 to 30 volts) and result in high rates of metal removal. For example, current densities of 40 to 1500 amp/sq in. or more are common for ECM, whereas current densities of 0.1 to 2.5 amp/sq in. are typical for many electroplating operations. Electrolyte pumping pressures for ECM range from about 10 to 450 psi.

The schematic representation of a drilling operation shown in Figure 15 illustrates the workings of the ECM process. At the start, the drilling tool is brought to the desired gap distance (e.g., 0.002 to 0.020) from the nickel- and cobalt-base-alloy workpiece surface and then the voltage is applied causing current to pass through the electrolyte. As the drilling operation proceeds, the workpiece dissolves and the drilling tool, through which the electrolyte is pumped, is steadily advanced to maintain a constant machining gap. The tool shown is insulated on the outside to minimize side cutting and to produce a hole with straight sides.

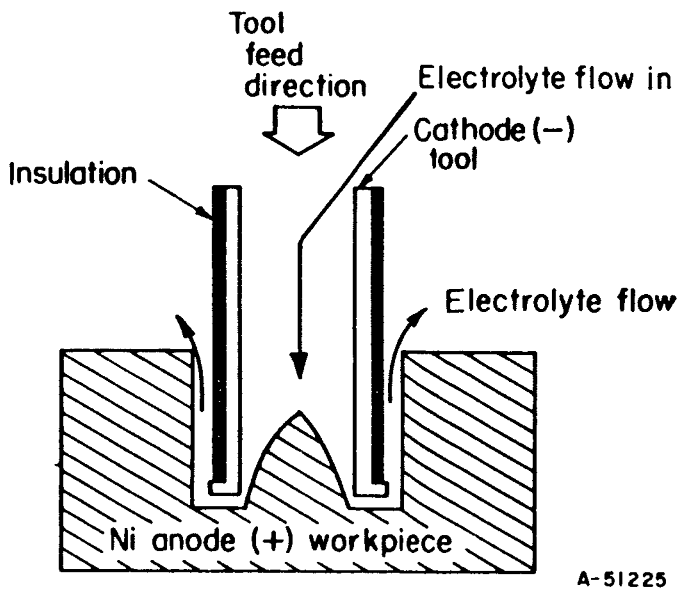


FIGURE 15. ECM DRILLING OPERATION

The general procedure described above can be used for trepanning, broaching, cavity sinking, and other contouring or shaping operations. For cavity-sinking and contouring work, the electrolyte-flow path is often of the flow-past type (i.e., electrolyte flow is roughly parallel to the electrodes) rather than the flow-through type shown in Figure 15. For example, three-dimensional cavities can be produced by ECM using a single-axis movement of a tool electrode that closely resembles the reverse image of the desired cavity form. ECM is especially suited for multiple-hole and irregular-shaped-hole drilling. Representative parts produced by various ECM operations in nickel- and cobalt-base alloys are shown later in this report.

Equipment. A typical general-purpose ECM installation that can be used for cavity sinking, broaching, drilling, trepanning, contouring, etc., is shown in Figure 16 (Ref. 63). The ECM-zone enclosure together with the control console is at the center, while the power pack is at the right. The electrolyte pumping and handling system is at the left.

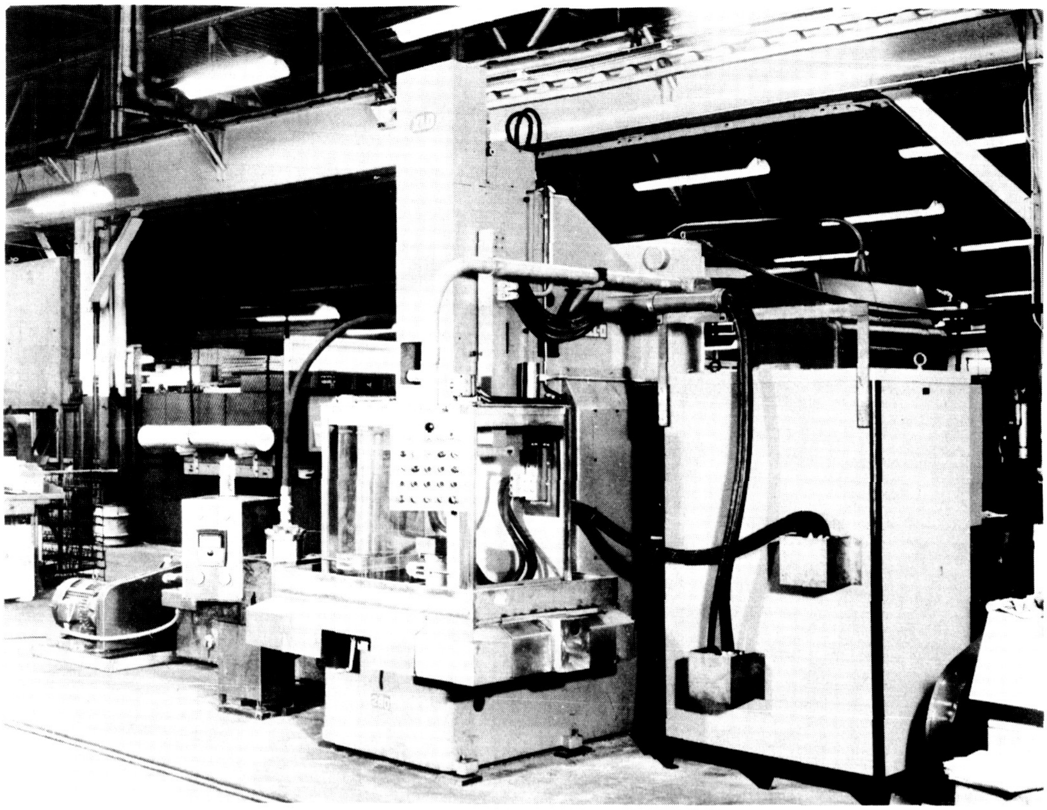


FIGURE 16. GENERAL PURPOSE ECM INSTALLATION

ECM units with current capacities ranging from about 50 amperes to 10,000 amperes are available commercially. Units having 10,000-ampere capacities are already in operation in industry; larger units of 20,000 amperes and more are being planned.

ECM Tooling and Fixturing. The ECM electrode tool(s) generally conform closely to the reverse image of the shape to be produced. Detailed information on the design of cathode tools is proprietary and has not been generally disclosed. ECM electrodes are usually made of copper, brass, stainless steel, or other conductive and corrosion-resistant materials. Custom or specially designed fixturing is usually needed to provide good controlled electrolyte flow to the electrodes for efficient and accurate ECM operation.

Tooling costs for certain types of ECM operations may be fairly expensive. For that reason, ECM is generally better suited to production-type work than to single or small-lot jobs, unless, of course, the unique capabilities of ECM justify the cost of using the process for machining small lots of parts of hard-to-machine metals or shapes.

Electrolytes. Electrolyte composition, operating conditions, and the chemistry and microstructure of the nickel- and cobalt-base alloys being machined are especially important in determining how effectively ECM will machine and the quality of the surfaces produced. Specific information on electrolyte compositions for machining the nickel- and cobalt-base alloys is usually proprietary and has not been generally disclosed. Neutral- and acid-type electrolytes have been used for the nickel- and cobalt-base alloys.

Some of the electrolyte formulations are based on the use of sodium chloride plus other compounds added to enhance the ability of the electrolyte to give good ECM cutting performance and surface finishes. Alkaline- or neutral-salt electrolytes involve precipitate- or sludge-handling problems, whereas with acid electrolytes the problem of plating out on the cathode tool may occur. Some specific data on electrolyte compositions are presented later. Proprietary formulations for ECM of specific nickel- and cobalt-base alloys and other metals and alloys are marketed.

Metal-Removal Rates and Tolerances. Typical metal-removal rates based on feeds or rate of tool travel for cavity-sinking or blade-contouring operations are from about 0.005 inch to 0.200 inch or more per minute. Penetration rates for drilling operations are usually higher and range from about 0.030 to 0.500 inch or more per minute. Planing or broaching operations can be carried out at rates of 1 inch to 5 inches or more per minute with removal of about 0.010 to 0.050 inch of metal (depth of cut) from the surface.

Penetration rates for nickel, cobalt, and other metals at various current densities are shown in Figure 17. These are theoretical rates based on anodic dissolution efficiencies of 100 per cent. Rates for nickel- and cobalt-base alloys and other high-temperature alloys are shown in the shaded area of Figure 17. For most ECM operations, the dissolution efficiencies are high and range from about 85 to 100 per cent for the majority of metals.

Tolerances in ECM depend on the type of operation being performed. Hole diameters can be machined to ±0.001 inch. Tolerances for other shapes can range from about ±0.002 inch to about ±0.030 inch depending on configuration and the particular type of ECM operation involved.

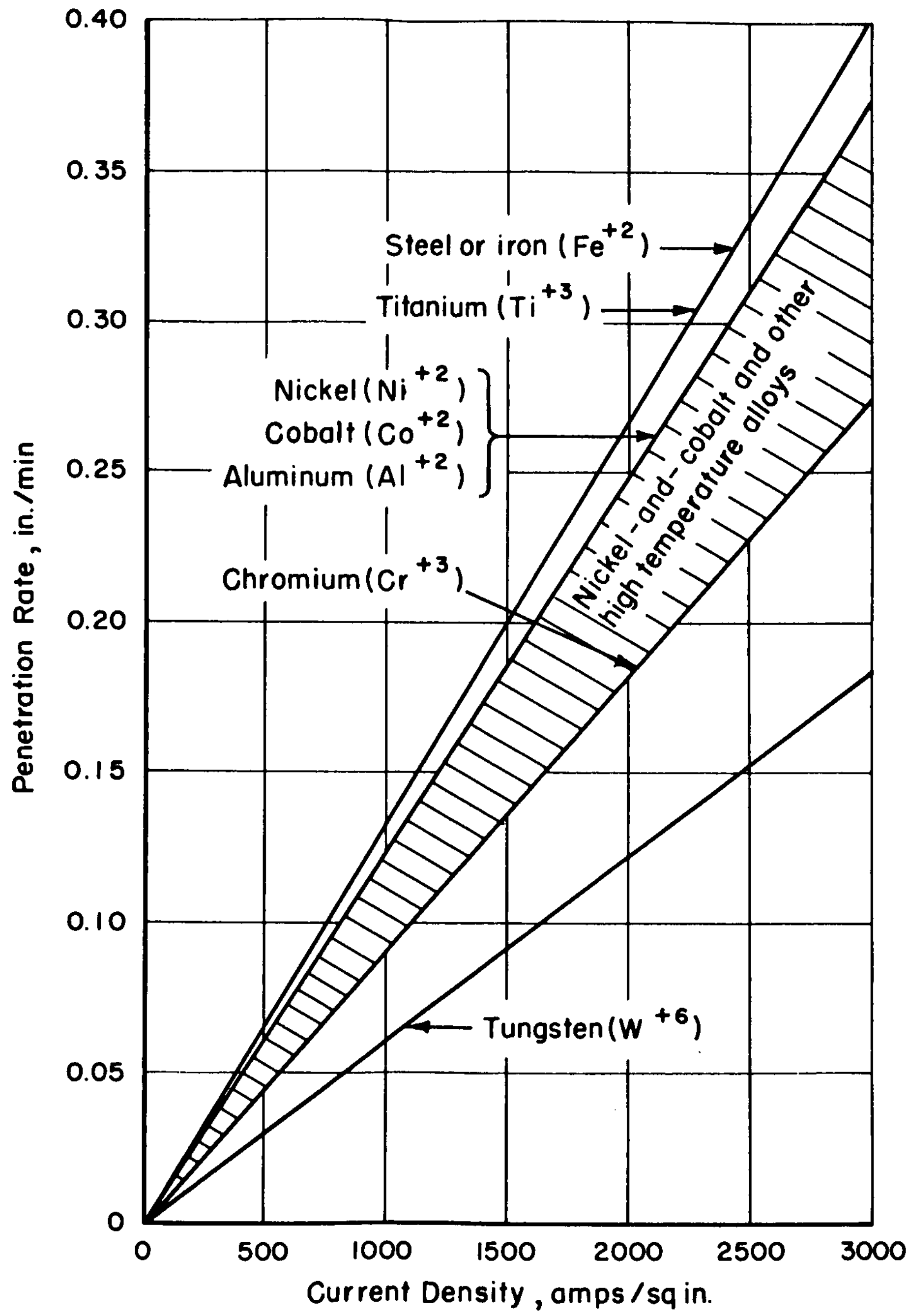


FIGURE 17. THEORETICAL PENETRATION RATES FOR NICKEL, COBALT, AND OTHER METALS IN THE VALENCE STATE INDICATED

Favorable Features of ECM. Some unique characteristics or advantages of ECM for machining or shaping the nickel- and cobalt-base alloys are:

(1) Stress-free machining

(2) Burr-free machining

(3) No tool wear

(4) No burning or thermal damage to workpieces.

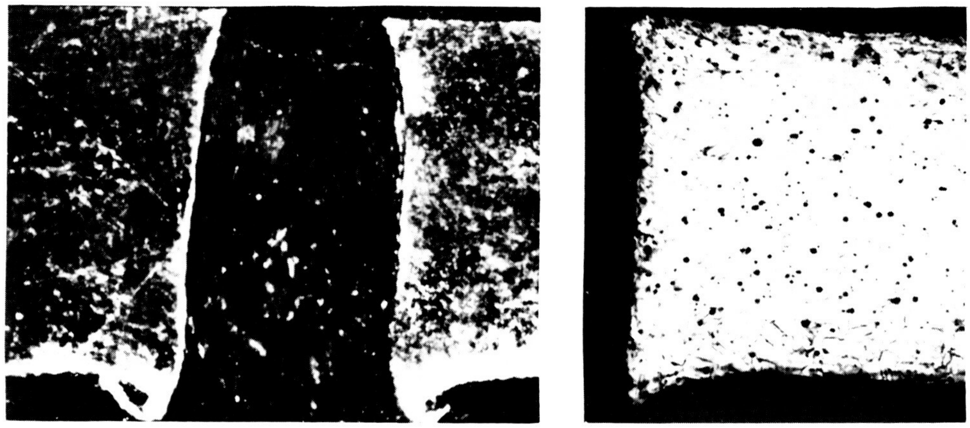
Since the cathode tool does not touch the workpiece, no mechanical stresses are imparted, and no distortion occurs in thin-sectioned or fragile parts. The fact that the tool does not wear, erode, or change during ECM means that once a suitable tool is developed, it can be used or reused indefinitely to produce replicate parts, without any need to compensate for tool wear.

The stress-free and burr-free machining characteristics of ECM are illustrated in Figure 18 by a comparison of the appearance and microstructure of 0.035-inch-diameter holes drilled by ECM and by mechanical methods (Ref. 62). The material is Haynes Alloy No. 25 plate, 1/16 inch thick. Figures 18a and 18c show cross sections of both holes, illustrating the burr and disturbed area left by mechanical drilling as contrasted with the burr-free and smooth-surface hole produced by ECM.

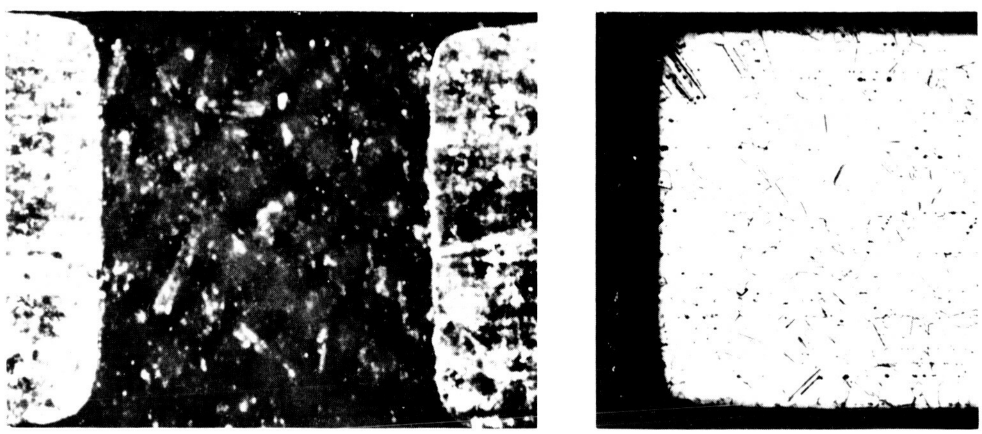
Figure 18b shows the microstructure damage and disturbance caused by mechanical drilling as contrasted with the unaffected microstructure shown for ECM drilling in Figure 18d.

ECM Operating Conditions for Nickel- and Cobalt-Base Alloys. As mentioned earlier, much of the specific data and information on ECM electrolyte compositions and operating conditions are proprietary and have not been publicly disclosed. However, some of the data and information that are available on electrolytes and operating conditions for the nickel- and cobalt-base alloys are presented below.

Representative operating data from work by Bayer et al. (Ref. 64), together with surface-roughness data for exemplary nickel- and cobalt-base alloy parts produced by various ECM techniques, are presented in Table XXXIV. Production of the exemplary parts was



Mechanically Drilled Holes



c. d.

ECM-Drilled Holes

FIGURE 18. COMPARISON OF HOLES DRILLED IN HAYNES ALLOY 25 BY MECHANICAL METHODS AND BY ECM

Courtesy of the Cincinnati Milling Machine Co.

TABLE XXXIV. REPRESENTATIVE OPERATING CONDITIONS AND SURFACE ROUGHNESSES PRODUCED ON EXEMPLARY NICKEL- AND COBALT-BASE PARTS BY DIFFERENT ECM TECHNIQUES (REF. 64)

Run	Material	ECM Operation	Electrolyte: Composition: Component	Electrolyte: Composition: Concentration, lb/gal	Electrolyte: Tank Temperature, F	Electrolyte: Inlet Pressure Range[a], psig	Electrolyte: Flow Rate[a], gal/min	Feed Rate, in./min	Depth of Cut or Ram Travel, inch	Applied Voltage or Voltage Range[a], volts	Current Range[a]	Surface Roughness Range, microinches (AA)[b]	Comments or Remarks
A	Hastelloy X (0.030-inch-thick sheet)	Blanking (cut-through operation)	NaCl	2.05	75	265/210	2.5/3.1	N. A.[c]	N. A.	8.0/8.0	383/33	N. A.	Cutting time, 65 sec; dwell time, 160 sec
B	M252 (rectangular bar)	Trepanning	NaCl	2.05	103	205/265	N. A.	0.200	4.0	20.0	150/160	26-120	Intergranular attack (IGA) occurred in some areas
C	René 41	Blanking (embossing grooves)	NaCl	2.1	73	230/215	1.6/1.6	N. A.	0.07	10/10	280/90	12-20	Cutting time, 10 min; surface roughness data are for embossed grooves
D	René 41	Drilling (deep rectangular hole)	NaCl	2.1	103	320/355	N. A.	0.200	4.5	28.0	250/590	15-30	Cutting gap bottom of stroke 0.012 inch; surface roughnesses are for hole walls
E	René 41	Contouring	NaCl	2.1	94	240/240	3.9	0.040	0.195	11.0	650	7-18	Current value given for end of run

(a) Data given in the table are representative of one or more runs made of a particular operation on the various nickel- and cobalt-base alloys. At the start, during, and at the end of the ECM runs, some operating variable values change considerably; the values shown are generally those observed at the start and end of the run.
(b) Surface-roughness height was rated in microinches arithmetic average (AA) deviation from the mean line.
(c) The notation, N. A., indicates that these data were either not available or not applicable to the particular operation involved.

carried out to demonstrate the over-all capabilities (feed rates, tolerances, surface finishes, etc.) of the ECM process.

The surface finishes obtained varied with the type of ECM operation and also with the alloy being machined. The best surface-smoothness values (7 to 20 microinches) were obtained for embossing and contouring operations on René 41 (Table XXXIV, Runs C and E). Rougher surfaces were observed for the trepanning of blade-like projections from rectangular bars of M252 and Ti-8Al-1Mo-1V alloys (Table XXXIV, Run B, and Figure 19). The relatively high roughness values in certain areas of these trepanned parts were attributed to machining at low current densities.

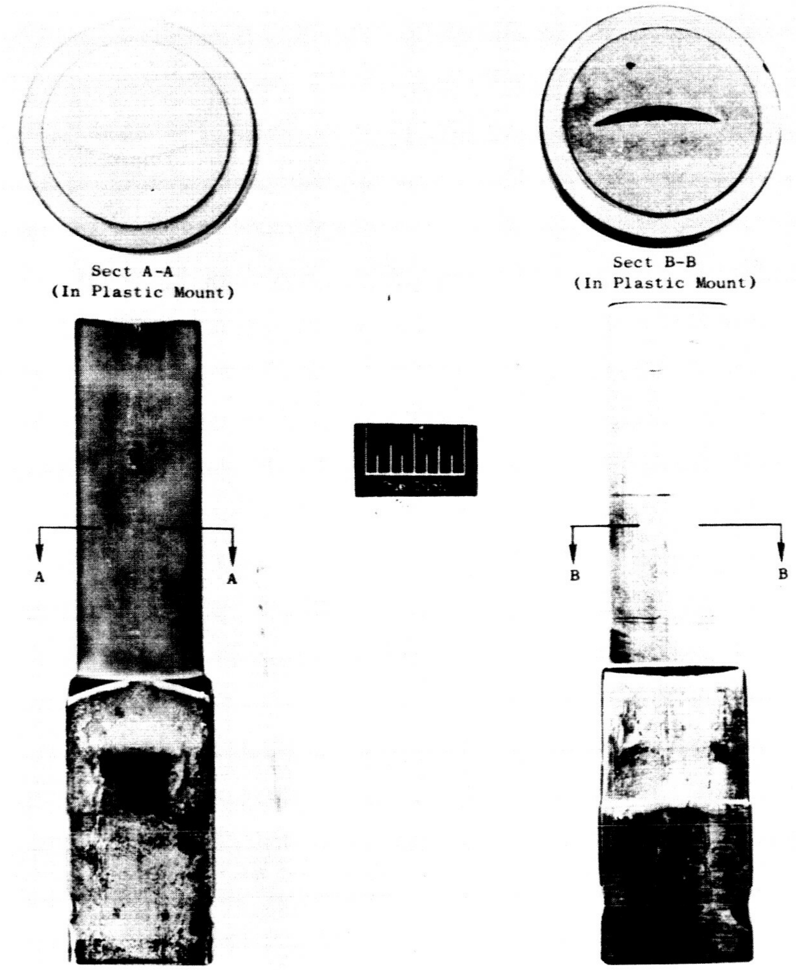
When the ECM workpiece-electrolyte combination or operating conditions are not "right", nonuniform dissolution of metals and alloys can occur. This shows up as inability to cut the particular alloy at all, or as intergranular attack (IGA), pitting, or selective etching. Bayer, et al., from a study of nonuniform dissolution during ECM of some nickel- and cobalt-base multiconstituent alloys, concluded that:

(1) Selective etching occurred at low current densities (below 40 amp/sq in.) for René 41 machined with a sodium chloride (2 lb/gal) electrolyte.

(2) Selective attack was localized around precipitates in the alloy.

(3) Selective attack occurs as intergranular attack on precipitation-hardening nickel-base alloys when they are machined in the age-hardened condition, i.e., when the precipitates are in the grain boundaries (Ref. 64).

Figure 20 shows intergranular attack (0.002 inch deep) for a trepanned M252 surface subjected to ECM at various current densities.



Material: Ti-8Al-1Mo-1V

Location	Surface Roughness, microinches (AA)
Concave, top section	220-280
Concave, root section	220-240
Concave, length	220-260

Material: M252

Location	Surface Roughness, microinches (AA)
Concave, top section	100-120
Concave, root section	26-32

FIGURE 19. EXEMPLARY PARTS TREPANNED IN M252 AND TITANIUM ALLOYS

See Table XXXIV, Run B, for trepanning operating conditions for the M252 part.
Courtesy of General Electric Co. (Ref. 5)

FIGURE 20. CROSS SECTION OF TREPANNED M252 (AGE HARDENED) PART SHOWING INTERGRANULAR ATTACK

Courtesy of General Electric Co. (Ref. 64)

It should be indicated that the surface-roughness data given in Table XXXIV and Figure 19 are for exemplary parts machined with a certain set of operating conditions. They do not necessarily represent the best surface finishes that might be obtained under different operating conditions.

In practice, the problems of intergranular attack or selective etching have been greatly minimized or eliminated by developing electrolytes and operating conditions, so as to promote uniform dissolution of the alloy. Also, changes in the heat-treat operations, aimed at producing alloy parts with more uniform dissolution characteristics, can help minimize these problems. In general, most of the nickel- and cobalt-base alloys have been successfully processed by ECM with good surface properties.

Figure 21 shows a portion of an M252 gas turbine bucket on which certain operations were carried out by ECM (Ref. 65). The airfoil-shaped tip cavity was machined using a salt-type electrolyte at a penetration rate of 1/8 inch per minute.

Waspaloy turbine blades measuring about 11 x 4 inches before (left) and after (right) electroshaping are shown in Figure 22 (Ref. 65). The blade was electrochemically machined from both sides simultaneously at a metal-removal rate of about 0.006 to 0.008 inch per

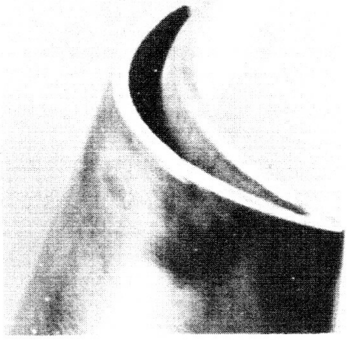


FIGURE 21. M-252 BUCKET WITH A TIP CAVITY PRODUCED BY ELECTROCHEMICAL MACHINING

Courtesy of the Steel Improvement and Forge Co. (Ref. 65)

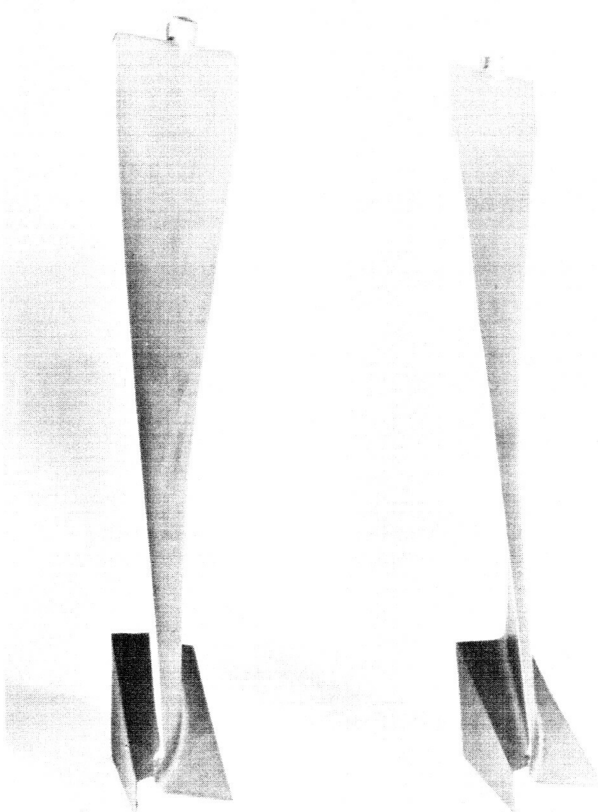


FIGURE 22. WASPALOY TURBINE BLADES BEFORE AND AFTER ELECTROSHAPING

Courtesy of the Steel Improvement and Forge Co. (Ref. 65) minute using an acid-type electrolyte. Edges of the airfoil have been shaped to a thickness of 0.005 inch.

An Inco-718 ring-support part used in missile applications is shown in Figure 23 (Ref. 65). The slotted configuration on the internal diameter was put in by ECM in a single plunge-type operation. A salt-type electrolyte was used; the plunge rate was about 0.60 inch per minute.

Figure 24 shows a typical root design used on gas-turbine buckets (Ref. 65). ECM was used to produce two rectangular pockets (3/4 x 1-1/2 inches), one on each side of the M252 bucket, about 0.3 inch deep simultaneously at a rate of about 0.1 inch per minute, using a cavity-sinking-type operation. The surface roughness of the pockets was 10 to 20 microinches rms.

ELECTROLYTIC GRINDING OF NICKEL- AND COBALT-BASE ALLOYS

The term electrolytic grinding (EG) as used in this report refers to metal removal by a combination of electrochemical action and mechanical abrasion. Electrolytic grinding might be considered as a specialized form of electrochemical machining. In EG a conductive wheel (cathode) impregnated with abrasive particles is rotated against the workpiece (anode). The abrasive particles in the metal-bonded wheels serve to maintain the proper working gap between the cathodic base and the workpiece, and also to remove the film- or solid-type electrolysis products from the workpiece, thus permitting electrochemical action to continue. Generally about 85 to 95 per cent or more of the metal removal is by electrochemical action, with abrasion accounting for the remainder. Because of this, the wheel pressures in electrolytic grinding are generally much lighter and the wheels generally more than 5 to 10 times longer than conventional wheels. Electrolytes for electrolytic grinding are usually aqueous solutions of salts such as sodium nitrite or sodium nitrate, plus addition agents. Electrolyte formulations aim at providing good conductivity, good surface finish, good grinding performance, and also at being nontoxic and noncorrosive to personnel, machines, and surroundings. Special proprietary formulations are marketed for electrolytic grinding of nickel- and cobalt-base alloys and most other metals and alloys.

Data and results from a study on electrolytic grinding (mechanically assisted) of Inconel X and L605 alloys are given in Table XXXV (Ref. 66). Data on heat-treat conditions of the materials

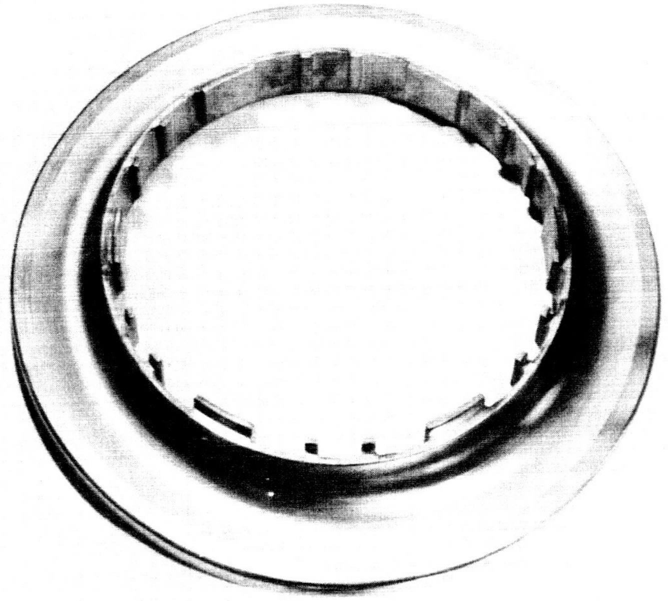


FIGURE 23. ECM-PROCESSED INCO-718 RING SUPPORT

Courtesy of the Steel Improvement and
Forge Co. (Ref. 65)

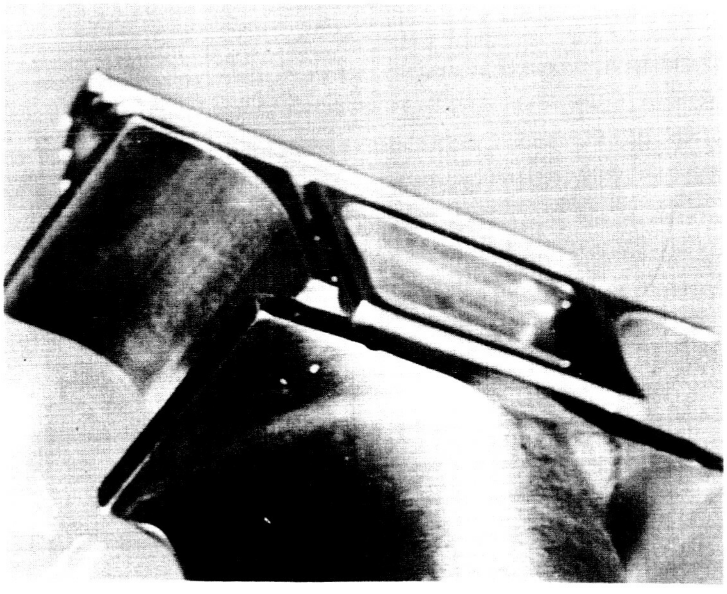


FIGURE 24. POCKET IN M252 BUCKET SUNK BY ELECTROCHEMICAL MACHINING

Courtesy of the Steel Improvement and Forge Co. (Ref. 65) are given in Footnote (a) of Table XXXV. Metallographic examination showed that electrolytically ground surfaces were satisfactory (i.e., uniform in appearance, no intergranular attack, free of pits, etc.).

TABLE XXXV. DATA AND RESULTS OF ELECTROLYTIC GRINDING OF INCONEL X AND L605[a, b, c] (REF. 66)

Material[a]	Depth of Cut[b], inch	Feed Rate, inch/min	Applied Voltage, volts	Current, amperes	Return Pass[c]	Surface Produced
Inconel X						
Top	0.005	2.0	9	80	Yes	Satisfactory
Bottom	0.005	2.0	9	80	No	Satisfactory
L605	0.005	5.6	10	50	Yes	Satisfactory

(a) The Inconel X (MIL-N-7786) material was procured in the mill-annealed condition and aged prior to grinding; the L605 (AMS-5537) material was procured and ground in the heat-treated condition.

(b) Grooves were made in the test plates using an electrolytic grinder equipped with an A3HC-60-1/2 metal-bonded aluminum oxide wheel. Full-strength solutions of Anocut No. 90 (Anocut Engineering Company, Chicago, Illinois) electrolyte salts were used.

(c) A return pass means feed in one direction and rapid traverse (14 inches/min) return to the current and electrolyte flow applied.

The favorable results reported for electrolytic grinding in Table XXXV indicate that the process would be especially suitable for grinding nickel- and cobalt-base alloy parts where there might be some danger of surface cracks or heat checks being produced by conventional mechanical grinding. Also, the production of burr-free surfaces together with the ability to machine fragile or delicate workpieces such as honeycombs, are favorable features of electrolytic grinding.

COMMENTS ON MECHANICAL PROPERTIES OF ECM-PROCESSED NICKEL- AND COBALT-BASE PARTS

Published data on the mechanical properties of ECM-processed nickel- and cobalt-base alloy parts are scarce. However, DMIC Report 213 indicated that ECM generally had a neutral effect, i.e., no significant gain or loss, on mechanical properties such as yield strength, ultimate tensile strength, sustained-load strength, ductility, and hardness for most metals and alloys, including the nickel- and cobalt-base alloys (Ref. 67).

This same DMIC report further indicated that metals, including nickel- and cobalt-base alloys, for which mechanical surface treatments or cold working increase fatigue strength, will appear to be weakened about 10 to 20 per cent by ECM or electropolishing (Ref. 67). The mechanical-finishing methods often impart compressive stresses to the metal surface and raise fatigue strength. In contrast, ECM or electropolishing, by removing stressed layers or forming none, leaves a stress-free surface that allows measuring the true fatigue strength of the metal. The conclusion is that ECM and electropolishing are safe methods to use for processing metals. Where maximum fatigue strength is important, use of a post-ECM or post-electropolishing treatment, such as vapor honing or shot peening, is indicated. These subsequent mechanical treatments can restore or impart compressive stresses to the surface so that ECM or electropolished parts, thus treated, will exhibit comparable or better fatigue properties than mechanically finished parts.

SUMMATION COMMENTS

Electrochemical machining and electrolytic grinding have been found to be very well suited to machining the tough nickel- and cobalt-base alloys. This is especially true for operations such as production of complex shapes or cavities, blade contouring, broaching, trepanning of round- or irregular-shaped holes, and deburring. In general, very good surface roughnesses, ranging from about 5 to 40 microinches, are obtained by electrochemical machining the nickel- and cobalt-base alloys. It is expected that ECM, which is already being widely used in industry, will be more extensively used for machining nickel- and cobalt-base-alloy parts used on advanced aircraft or missiles, especially since the electrochemical-machining process is readily adaptable for production work and automation, and does not require highly skilled personnel for routine production operations.

CHEMICAL MILLING OF NICKEL- AND COBALT-BASE ALLOYS

INTRODUCTION

The term chemical milling generally refers to the shaping, contouring, machining, fabricating, or blanking of metal parts by controlled chemical dissolution with suitable chemical reagents or etchants. The process is somewhat similar to the etching procedures used for decades by photoengravers, except that for chemical milling the etch rates and depths of metal removal are generally much greater.

Much of the early chemical-milling work was done on aluminum and magnesium parts for the aircraft industry. Chemical milling saved labor, time, and materials. It also provided increased design capability and flexibility in fabricating parts for advanced aircraft, missiles, and space vehicles. During the last 4 or 5 years, there has been an increased interest in the use of chemical milling for the production of parts of high-strength, heat-resistant metals and alloys, including the nickel- and cobalt-base alloys. Some of the technical information on procedures, etchant solutions, and techniques is of a proprietary nature and has not been disclosed.*

Chemical milling is particularly useful for removing metal from the surfaces of formed or complex-shaped parts or their sections, and from large areas to shallow depths. The resulting weight reductions are especially important in aircraft and space vehicles. Metal can be removed from an entire part or else selective metal removal can be achieved by etching the desired areas while the other areas are protected from chemical attack by a mask. Tapering, step etching, and sizing of sheets or plates can be done readily by chemical milling.

*CHEM-MILL is the registered trademark of North American Aviation, Inc., which has granted Turco Products, Inc., Wilmington, California, the exclusive right to sublicense other firms to use the CHEM-MILL process.

"Chem-Tol" refers to the proprietary chemical dissolution process developed by the United States Chemical Milling Corporation, Manhattan Beach, California, for production of sheet material and parts to close tolerances.

"Chem-Size" refers to a proprietary chemical-dissolution process developed by Anadite, Inc., South Gate, California, for improving the tolerances of as-rolled sheet and plate, and of parts after forming.

Simultaneous chemical milling of a part from both sides can be carried out with a two-fold reduction in milling time, while also minimizing the danger of warpage due to release of residual stresses (if present) in the part. The amount of metal removal or depth of etching is determined by the time of immersion in the etching solution and its composition. Generally, no elaborate tools or complex holding fixtures are required. Many parts may be processed at the same time; the production limitations being governed by the tank dimensions or volume.

PROCESSING PROCEDURES

The complete chemical-milling procedure consists of four operations or steps, namely:

(1) Cleaning or surface preparation

(2) Masking

(3) Chemical etching or dissolution

(4) Rinsing and stripping or removal of the mask.

Masking and etching are probably the most critical operations for good chemical-milling work.

Cleaning. The surfaces of nickel-base and cobalt-rich alloys are usually cleaned by conventional methods, such as vapor degreasing, wiping with a solvent-dipped cloth, and alkaline cleaning to remove all grease and dirt. When scale, oxidation products, or other foreign materials are firmly attached, acid pickling or vapor blasting may be needed to produce a clean surface. Thorough rinsing followed by drying completes the cleaning step. Failure to properly clean the nickel- and cobalt-base-alloy surfaces will cause masking difficulties and uneven attack by the etching solution.

Masking. Masking for nickel- and cobalt-base alloys involves the application of a protective, acid-resistant coating to the areas where no metal removal is desired. The mask is usually applied by dipping, spraying, or flow-coating techniques. Brush-on roller-type applications are also used. The particular coating method employed depends on size and configuration of the part.

Plastic coatings (Ref. 68), such as polyvinyl chloride, polyethylene, and chlorinated rubber resins, are frequently used as maskants because of their ability to withstand the strong acid-and-oxidizing solutions generally used for etching the nickel- and cobalt-base alloys. Multiple coats of three or more are usually employed to provide sufficient mask thickness and good coverage. Total mask thicknesses may run about 10 mils or more. The intermediate coats are usually air dried. After the final coat, the mask is usually cured by baking at about 200 to 300 F for approximately 1 to 3 hours to improve mask adhesion, tensile strength, and chemical resistance.

Other desirable characteristics of a good mask material are: (1) suitable for accurate pattern transfer on contours and complex configurations; it must maintain straight lines in the etched design, regardless of its complexity, (2) good scribing qualities, (3) easy removal after scribing to present clean surfaces for etching, and also (4) good stripping after etching to yield clean surfaces for possible subsequent processing.

The patterns on the masked workpiece are usually applied by means of templates, followed by scribing, and then manual peeling of the mask from the areas to be etched. Mask patterns can also be applied to workpieces using photosensitive resists or silk-screen techniques. These latter techniques are generally employed on jobs where fine detail and shallow cuts are required. Photographic techniques are frequently employed for the blanking or piercing of relatively thin parts, e.g., thicknesses usually less than about 1/16 inch. Photoresists are often used in the production of printed circuits, name plates, dials, etc., by chemical-etching procedures.

Etching. A good chemical-milling solution should be capable of removing metal at a predetermined and uniform rate, without adversely affecting dimensional tolerances and the mechanical properties of the workpiece. Pitting, intergranular attack, uneven attack of the workpiece surface, or production of rough surface finishes are all bad features of an etchant system.

The more commonly used etchants for milling of nickel- and cobalt-base alloys are aqueous solutions of raw-mineral acids, such as modified aqua-regia mixtures ($HCL-HNO_3$). The exact solution compositions are proprietary. In addition to these main components, the solutions may contain special additives to enhance their etching characteristics. The presence of dissolved metal, e.g., nickel, cobalt, iron, etc., in the etchant solution helps its performance, so that "partially aged" baths (made by mixing new reagents with a portion of a spent bath) are generally employed.

Solutions containing ferric chloride as the principal reactant, and mixtures of ferric chloride and acids have been used for milling nickel- and cobalt-base alloys. The former solutions are frequently used in the spray etching of fine detailed parts or in blanking-type operations.

Etchant solutions are usually forced to circulate over the workpiece surface in order to promote uniform dissolution or attack. Parts are also periodically moved, turned, or rotated to achieve uniform metal removal over the entire surface. In some applications the etchant is sprayed over the part. Careful control of the composition and temperature of the etchant is needed in order to maintain uniform and predictable rates of metal removal.

Typical production tolerances for chemical milling are ±0.002 inch (Refs. 69,2). To this must be added the actual raw-stock tolerance prior to chemical milling. The following figures can be used as a guide to depth-of-cut limitations for chemical milling (Ref. 2):

	Maximum Depth of Surface, in.
Sheet and plate	0.500
Extrusion	0.150
Forging	0.250

Because chemical etching proceeds sideways at about the same rate as down, the minimum widths that can be machined are about three times the etch depths.

Etching rates for nickel- and cobalt-base alloys range from about 0.2 to 5.0 mils/min. Typical industrial-production rates are about 0.3 to 1.5 mils/min. A generalized comparison of the performance characteristics of etching systems for milling of nickel- and cobalt-base alloys, titanium, steel, and aluminum alloys is given in Table XXXVI (Ref. 69). As indicated, the solutions used for milling the nickel- and cobalt-base and steel alloys are generally more complex than those used for the aluminum and titanium alloys.

Additional data and information on etching of specific nickel- and cobalt-base alloys are presented in the section of this report dealing with effects of chemical milling on mechanical properties of metals and alloys.

TABLE XXXVI. COMPARISON OF DATA AND CHARACTERISTICS OF SYSTEMS FOR CHEMICAL MILLING TITANIUM, STEEL, ALUMINUM, AND NICKEL- AND COBALT-BASE ALLOYS

Item	Titanium Alloys (Ref. 70)	Steels (Ref. 70)	Aluminum Alloys (Ref. 70)	Nickel- and Cobalt-Base Alloys[(a)]
Principal Reactants	Hydrofluoric acid	Hydrochloric acid-nitric acid	Sodium hydroxide	Nitric acid-hydrochloric acid-ferric chloride
Etch Rate, mils/min	0.6 to 1.2	0.6 to 1.2	0.8 to 1.2	0.4 to 1.5
Optimum Etch Depth, inch	0.125	0.125	0.125	0.125
Etchant Temperature, F	115 ± 5	145 ± 5	195 ± 5	140 ± 10
Average Surface Finish, rms microinches	40-100	60-120	80-120	40-150

(a) Data were compiled by the authors from published articles and reports.

Rinsing and Stripping. After etching is completed, the parts are thoroughly rinsed in water. The mask is then either stripped by hand or the part is immersed in a suitable solvent to facilitate its removal. Proprietary solvents are marketed for handling the various types of mask-out materials used.

EFFECTS ON MECHANICAL PROPERTIES

The general feeling is that chemical milling does not adversely affect the mechanical properties of metals and alloys providing good, uniform metal dissolution is achieved; i.e., no intergranular attack, pitting, or selective etching. Published data on effects on mechanical properties are rather scarce and more such data are needed.

Sanz and Shepherd of North American Aviation, Inc., have reported results of production chemical milling of Inconel X (annealed) and other high-alloy steels (Ref. 70). Photomicrographs of the production-milled alloys showed no intergranular attack resulting from chemical milling. Tensile tests, 1000 F stress-rupture tests, and 1000 F fatigue tests carried out at North American Aviation, Inc., have not detected any effects of chemical milling on the properties of Inconel X (Ref. 71). Chemical milling was used to form pockets on contoured-shaped Inconel X parts. The metal-removal rate was about 0.001 inch/min; the surface roughness was about 100 rms microinches; and the thickness tolerances were ±0.002 inch over the original thickness tolerances.

In a feasibility study carried out at the Boeing Company swaged René 41 tubes, for use on Dyna-Soar structures, could be tapered successfully to within the required engineering tolerances by chemical milling (Ref. 72). Good surface finishes with roughnesses to rms microinches or better were achieved at etch rates of about 0.00025 to 0.00045 inch/min/side at withdrawal rates of about 0.30 inch/min. The tubes were milled in the vertical position in an acid-type bath containing ferric chloride plus other metallic ions at a temperature of about 140 F.

Prior to etching, the tube surfaces were activated by a 10 to 20 minute immersion in concentrated hydrochloric acid. Metallurgical examinations after chemical milling showed no intergranular attack of the tube metal, the weld metal, or the weld zone. There was, however, a slight difference in the appearance of the seam because of the smoother surface finish of the weld zone. The etching rate was the same or slightly less along the weld seam than in the unwelded zone. However, no production problems were anticipated because of the slight difference in milling characteristics of the weld seam in the René 41 tubes.

Although the weld zones were not a problem with the René 41 tubes cited above, it should be indicated that weld zones are potentially problem areas for chemical milling because of differential milling rates that may occur in these areas. For that reason, attention should be paid to devising etchant solutions and operating conditions to promote uniform dissolution of both the weld and parent metal.

Boeing also carried out a study on the effect of chemical milling on the mechanical properties of René 41 as part of its overall evaluation for the X-20 vehicle after anticipated high-temperature flight environments (Ref. 73). Various thermal exposures from none to 9 cycles at 1600 F, or 9 cycles at 1800 F were used in the test program for comparing the chemically milled material with the nonchemically milled material.

The results of various tests showed that the ultimate tensile strength of chemically milled René 41 was slightly lower than that of nonchemically milled material at test temperatures to 1400 F. Above this temperature to 1800 F, the strengths of both the chemically milled and nonchemically milled material were for the most part comparable; no significant difference between the tensile and compressive yield strengths of the two materials was observed.

Chemical milling did, however, lower the tensile elongation values of René 41. At a test temperature of 80 F, the elongation, expressed as a percentage of the elongation of nonchemically milled material, was about 85 per cent, while at 1400 F it was about 60 per cent, and about 80 per cent at 1800 F. Part of the loss of ductility was attributed to intergranular attack by the milling solution in combination with the surface scaling that occurred during the thermal exposures.

Although generalized comments are frequently made regarding the absence of intergranular attack (IGA) or selective etching during chemical milling, nonuniform dissolution can and does occur with some materials. These occurrences may be the result of not having the "right" combination of etchant composition and milling operating conditions to match the particular chemistry and microstructure of the alloy. Information that might be useful for estimating the extent of loss of fatigue strength that may occur in nickel- and cobalt-base alloys because of nonuniform dissolution is given in Table XXXVII (Ref. 74).

TABLE XXXVII. EFFECT OF INTERGRANULAR ATTACK ON FATIGUE PROPERTIES OF CHEMICALLY MILLED ALLOYS (REF. 74)

Alloy	Condition[a]	Intergranular Attack Depth, inch	Endurance Limit, 10^3 psi
René 41	Parent metal	--	~ 47.5
	Chemical milled[b]	0.0004	~ 40.0
Hastelloy X	Parent metal	--	~ 38.8
	Chemical milled[b]	0.0006	~ 32.5
A-286	Parent metal	--	~ 30.0
	Chemical milled[b]	None	~ 30.0

(a) About 20 mils were removed from each side of the sheet by chemical milling.

René 41 and Hastelloy X lost about 15 per cent of their fatigue life due to slight intergranular attack (depths of 0.0004 to 0.0006 inch) that occurred during chemical milling. With the A286 alloy, where no intergranular attack occurred, no loss of fatigue strength was observed. Somewhat similar behavior in fatigue properties might be expected with other nickel- and cobalt-base alloys if intergranular attack or nonuniform dissolution occurs during chemical milling.

The heat-treat condition of the alloy together with its chemistry greatly influences the surface finishes that can be obtained and also the chemical-milling solutions and operating conditions that must be used. For example, development work at General Electric indicated that fully hardened René 41 was more difficult to chemically mill than the annealed material because of its tendency to passivate after being in the etchant for 2 or 3 minutes (Ref. 74). Surface roughness on the annealed René 41 was about 40 to 50 rms microinches, whereas the heat-treated material had roughness values of 80 to 120 rms microinches. Annealed René 41 was milled satisfactorily at a rate of about 0.005 inch/min. Typical surface roughness values reported for Hastelloy X and Inconel X were 100 to 150 rms microinches.

Some of the examples cited above indicate the importance of developing etchant systems and operating procedures that will provide good, uniform dissolution of workpieces. In some instances, where nonuniform dissolution has occurred and part performance might be adversely affected, mechanical finishing methods might be employed to reverse the thin, nonuniformly etched or detrimental surface layer. These supplemental operations add to production costs and would best be avoided by development of better chemical-milling techniques to obtain parts with good surface properties.

SUMMATION REMARKS

Chemical milling is being used successfully and economically to produce nickel- and cobalt-base-alloy parts for aircraft and space vehicles and in other applications. The use of chemical milling for fabricating nickel- and cobalt-base alloys and other high-strength, high-temperature alloys is expected to increase considerably in the immediate future as better etchants, better maskants, and over-all chemical-milling procedures and techniques are evolved.

CONCLUSIONS AND RECOMMENDATIONS

The basic problems experienced in machining nickel- and cobalt-base alloys originate from a combination of mechanical, physical, and chemical properties. These alloys generally exhibit high strengths and excellent ductility but work harden appreciably during deformation. They also tend to react with cutting tools at elevated temperatures.

The original properties of the workpiece, and those developed during machining, control the cutting forces on the tool. The high strengths of nickel- and cobalt-base alloys increase the horsepower requirements for machining. Ordinarily about 95 per cent of the energy expended during cutting is converted into heat. Since these alloys exhibit poor thermal diffusivities, cutting temperatures are much higher than those usually experienced when machining other metals at equal tool stresses. High cutting temperatures lead first to welding and then progressive "buildup" of particles from the chip on the tool. This is followed by progressive edge chipping and poor surface finishes as the welded-on metal breaks away from the tool. Higher cutting temperatures also adversely influence tool life by lowering the strength of the cutting tool. Abrasion by the hard chips accelerates this wear still more.

High temperatures experienced in grinding lead to reactions between the abrasive grains and the workpiece. This causes dulling of grinding wheels by "capping" the grains with welded-on metal. The grains then may break down prematurely or the wheel may glaze depending on the hardness of the wheel. If glazing occurs, burning, high residual stresses, and cracked surfaces may result.

Cutting temperatures are minimized by using slow machining speeds and efficient cooling methods for applying chemically active fluids. Work-hardening effects are reduced by using rigid setups on heavy-duty machine tools; strong, sharp tools, and positive relatively heavy feeds. Tool "buildup" and edge-chipping experienced in milling can be reduced by using climb-milling techniques. Out-of-round, tapered holes resulting from poor drilling action can be corrected by using short drills with large flutes and special points.

In spite of recent improvements in machining techniques, these are two areas that need to be investigated. They include new cutting-tool materials and improved machine tools, both to be designed especially for the high-strength and heat-resisting alloys.

A comprehensive research program on new cutting materials sponsored by the U. S. Air Force is now in progress. The goal is to produce tool materials suitable for machining space-age metals at higher speeds and longer tool life. The investigation includes high-speed steel, cobalt cast alloys, and cemented carbides. Suitable additions are made to each base material and the processing variables involved are investigated and refined. The goal for each class of tool material is to produce a very high volume of carbides in a suitable matrix. Results to date are encouraging.

The quality, rigidity, and versatility of machine tools are also important factors for the successful machining of nickel- and cobalt-base alloys, as well as for the other aerospace metals. Lathes and grinders need improving, and new profile milling machines need to be developed.

A major problem for lathes is spindle speed. The overall range of spindle speeds available on existing lathes is not broad enough to cover some of the lower speeds needed for the aerospace metals. Lathes suitable for turning nickel- and cobalt-base alloys should have a suitable means of controlling spindle speeds in steps of 20 per cent or less. This situation, however, is now being recognized, since the trend in new lathes is toward variable-speed drives. Rigidity, dimensional accuracy, rapid indexing of tools, and flexibility are additional features which are being emphasized. Variable speed and feed features are also being added to lathes with tracer or numerical controls so they can be optimized during contouring operations.

The situation for grinders resembles that for lathes. Not many grinders have sufficient means for adjusting spindle speeds to those needed by the high-strength materials. There is also a need for grinders providing automatic wheel-wear compensation to improve dimensional control using softer grinding wheels. Finally a need exists for greater rigidity in the spindle system together with automatic wheel-balancing devices.

Advanced aerospace vehicles are also requiring more and more profile machining of parts from high-strength, heat-resisting materials. Furthermore, there is a need for more parts to be profile machined to closer tolerances. These high-strength materials cannot be machined to the desired tolerances on obsolete, light-duty profiling machines that do not have the necessary power, spindle speeds, or rigidity. Consequently, the use of the so-called aerospace metals makes necessary the development and use of big, rugged, high-powered equipment capable of machining those materials to very close tolerances at slow cutting speeds. These metals can be cut and fashioned efficiently into complex curves, channels, and intricate contours of aerospace vehicle parts by making full use of numerically controlled profiling machines.

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MACHINING AND GRINDING OF NICKEL- AND COBALT-BASE ALLOYS

By C. T. Olofson, J. A. Gurklis, and F. W. Boulger

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This document has also been reviewed and approved for technical accuracy.

For Edwin L. Brown

W. A. WILSON
Chief, Methods Development Branch

R. J. Schwinghamer / for

J. P. ORR
Chief, Manufacturing Research and Technology Division

for WERNER R. KUERS
Director, Manufacturing Engineering Laboratory