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FABRICATION DEVELOPMENT FOR ODS-SUPERALLOY, AIR-COOLED TURBINE BLADES

FINAL REPORT

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16. Abstract

MA-6000 is a gamma prime and oxide dispersion strengthened superalloy made by mechanical alloying. At the initiation of this program, MA-6000 was available as an experimental alloy only and did not go into production until late in the program. The objective of this program was to develop a thermal-mechanical-processing approach which would yield the necessary elongated grain structure and desirable mechanical properties after conventional press forging.

Forging evaluations were performed to select optimum thermal-mechanical-processing conditions. These forging evaluations indicated that MA-6000 was extremely sensitive to die chilling. In order to conventionally hot forge the alloy, an adherent cladding, either the original extrusion can or a thick plating, was required to prevent cracking of the workpiece. Die design must reflect the requirement of cladding. MA-6000 was found to be sensitive to the forging temperature. The correct temperature required to obtain the proper grain structure after recrystallization was found to be between 1010-1065°C (1850-1950°F). The deformation level did not affect subsequent recrystallization; however, sharp transition areas in tooling designs should be avoided in forming a blade shape because of the potential for grain structure discontinuities. Starting material to be used for forging should be processed so that it is capable of being zone annealed to a coarse elongated grain structure as bar stock. This conclusion means that standard processed bar materials can be used.

The program also demonstrated that MA-6000 can be successfully formed into near-net turbine blade shapes using conventional forging practices. The importance of proper die design was again demonstrated with respect to the effect sharp transition areas have on proper grain structure. It was shown that gradual transition areas, for example, a larger radius between the platform and airfoil of the turbine blade, improves the ability to recrystallize the material to a more continuous grain structure. Elevated tensile properties for the forged blades were found to be comparable to those found in the standard hot-rolled bar. However, the stress rupture properties were somewhat degraded although the forged and recrystallized grain structure appeared to be normal.

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FOREWORD

The work described in this final report was performed in the Materials and Manufacturing Technology Center of TRW Inc. under NASA Contract NAS 3-22507, TRW Project No. 512-004284-88. The work was performed under the direction of Mr. D. J. Moracz, the Program Manager. Technical assistance was provided by Mr. R. J. Nussel and Mr. E. Thomas. Mr. C. M. Austin of INCO Research and Development Center, Inc. was responsible for the production of all starting material and for the evaluation of forged material for proper grain structure development. The contract was administered under the management of the NASA Project Manager, Mr. F. H. Harf, Materials and Structures Division, NASA-Lewis Research Center.

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1.0 SUMMARY

MA-6000 is a gamma prime and oxide dispersion strengthened superalloy made by mechanical alloying. At the initiation of this program, MA-6000 was available as an experimental alloy only and did not go into production until late in the program. The objective of this program was to develop a thermal-mechanical-processing approach which would yield the necessary elongated grain structure and desirable mechanical properties after conventional press forging. The program was divided into two tasks. Task I investigated the forming response of MA-6000 and the determination of the forming parameters. Task II demonstrated the capability of fabricating near-net turbine blade shapes based on Task I results and evaluated the mechanical properties of the formed turbine airfoil hardware.

In Task I, forging evaluations were performed to select optimum thermal-mechanical-processing conditions. These forging evaluations indicated that MA-6000 was extremely sensitive to die chilling. In order to conventionally hot forge the alloy, an adherent cladding, either the original extrusion can or a thick plating, was required to prevent cracking of the workpiece. Die design must reflect the requirement of cladding. MA-6000 was found to be sensitive to the forging temperature. The correct temperature required to obtain the proper grain structure after recrystallization was found to be between 1010-1065^{o}C (1850-1950^{o}F). The deformation level did not affect subsequent recrystallization; however, sharp transition areas in tooling designs should be avoided in forming a blade shape because of the potential for grain structure discontinuities. Starting material to be used for forging should be processed so that it is capable of being zone annealed to a coarse elongated grain structure as bar stock. This conclusion means that standard processed bar materials can be used.

Task II demonstrated that MA-6000 can be successfully formed into near-net turbine blade shapes using conventional forging practices based on the results of the Task I forging trials. The importance of proper die design was again demonstrated with respect to the effect sharp transition areas have on proper grain structure. It was shown that gradual transition areas, for example, a larger radius between the platform and airfoil of the turbine blade, improves the ability to recrystallize the material to a more continuous grain structure. Elevated tensile properties for the forged blades were found to be comparable to those found in the standard hot-rolled bar. However, the stress rupture properties were somewhat degraded although the forged and recrystallized grain structure appeared to be normal.

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2.0 INTRODUCTION

There is a continual need for improvements in high-temperature properties for turbine blade materials. One of the approaches being pursued to provide material capable of higher temperature performance in aircraft gas turbines is through oxide dispersion strengthening (ODS) of superalloys. For these alloys, the high-temperature strength depends upon a characteristic elongated grain structure while the intermediate temperature strength is due to the dispersion of gamma prime precipitates. The elongated grain structure is the result of recrystallization, the propensity for which is developed during the primary working of the material.

INCONEL* alloy MA-6000 is a gamma prime and oxide dispersion strengthened superalloy made by mechanical alloying. Its combination of typical superalloy strength levels at intermediate temperatures with very high strength at high temperatures is attractive for turbine blade applications. The present product form is fully processed rectangular barstock from which turbine blades can be machined. Prior to the initiation of this program, very little was known about the response of MA-6000 to secondary working processes to form turbine blade shapes. Because MA-6000 is quite expensive relative to conventional superalloys, there was an incentive to develop a forging approach to reduce material input, especially for large turbine blades.

In the fabrication of ODS turbine blades, it is imperative to retain the ability to grow the desirable elongated grain structure during secondary processing to the airfoil shape. TRW had developed a directional forging approach which was successfully used to fabricate ODS turbine vanes (1). The present investigation sought to develop a thermal-mechanical-processing (TMP) approach which would yield the necessary elongated grain structures after recrystallization and not crack the material during forging. The TMP approach not only considered the forging variables, but also the correct TMP procedures for the starting forging stock.

Some consideration was given to using fully processed MA-6000 as the starting forging stock. Material in this condition would be more difficult to forge due to the higher yield strengths (higher flow stress) and the possibility of "feathering" the grains. Forging of fully processed material was investigated only to verify concerns.

This report summarizes the results obtained on the NASA-Lewis Research Center Contract NAS 3-22507. It includes a summary of the approaches taken to develop a correct TMP schedule for both the starting forging stock and the forged turbine blade, demonstration of the developed TMP schedule to actual turbine blade hardware, a summary of typical property data for forged MA-6000 turbine blades, and recommendations for future forging of MA-6000 turbine blade shapes.

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* Trademark of the INCO family of companies.

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3.0 PROGRAM OUTLINE

The objective of this program was to develop the technology required to fabricate net or near-net shape air-cooled turbine blades from MA-6000 superalloy. MA-6000 is an oxide dispersion strengthened (ODS) superalloy, trademarked and fabricated under a patented process by the International Nickel Company, Incorporated (INCO). The approaches selected were to be assessed with respect to their applicability for commercial fabrication of ODS turbine blades. In addition, the effect of metalworking on mechanical property requirements was also evaluated. Program goals included the following:

- Demonstration of a production process to fabricate net or near-net shape ODS superalloy turbine blades.
- Fabrication of blade shapes with properties approaching those found in extruded, hot-rolled ODS bar after recrystallization and heat treatment. Stress rupture goals for 100-hour life were 550 MPa (80 ksi) at 760°C (1400°F) and 138 MPa (20.0 ksi) at 1100°C (2012°F).

The approach taken to accomplish the program objectives required the evaluation of the forging response of MA-6000 to conventional, hot forging methods. Initially, a matrix study to evaluate the response to forging was planned. The matrix study evaluated the forging variables of temperature, strain, and direction of metal flow with respect to the initial grain direction. The matrix also included the evaluation of bar processing conditions. This effort had to be redirected after initiation because of the poor forging response of bare MA-6000. A revised approach was substituted which left intact after hot rolling the mild steel can that for the previous trials had been removed. The canned workpiece was conventionally forged; the mild steel can acted as an insulator which prevented die chilling during forging. Based on the results of this effort, the forging approach successfully demonstrated the fabrication of actual turbine blades.

The program was divided into two tasks. Task I investigated the forming response of MA-6000 and the determination of the forming parameters. The task also included the evaluation of the recrystallization response of the formed material. Task II demonstrated, based on Task I results, the capability of fabricating near-net turbine blade shapes and evaluated their mechanical properties.

3.1 Task I - Forging Response

During Task I, forging evaluations were performed to enable the selection of a thermal-mechanical-processing approach that would yield the acceptable grain structure and mechanical properties. Selection of optimum forging parameters for this task was based on the response of MA-6000 to directional recrystallization.

3.1.1 Material Procurement and Forge Tooling Build

INCO Research and Development Center (IRDC) was a major subcontractor in this program. Their major responsibilities included powder preparation, canning, consolidation (by extrusion), and secondary working (by rolling) of the required MA-6000 bar. Powder qualification required that all heats meet the 138 MPa (20.0

ksi) at 1100°C (2012°F) 100-hour stress rupture life requirement.

One of the initial efforts on this program was the design and manufacture of Task I forging tooling. Based on earlier work (1) with ODS alloys, a tooling set was designed that allowed only metal flow in one direction during the forging operation. The die design was a channel cavity 25 mm (1 inch) wide by the length of the die. Forging preforms also were to be 25 mm (1 inch) wide to insure flow in only the longitudinal direction during forging. Originally, these preforms were designed to have the canning material removed.

3.1.2 Forging Response Study

As previously noted, a matrix study to evaluate the response of bare MA-6000 to forging was planned to include the evaluation of the following variables: forging temperature, forging reduction, forging direction, and initial MA-6000 bar condition. Due to the poor response of bare MA-6000 to forging, the program was redirected to include five series of forging trials.

3.1.2.1 First Forging Trial

The first forging trial evaluated the response of bare MA-6000 in four processing conditions to forging temperature, forging reduction, and forging direction. A total of eighteen forgings were produced. This first forging trial was structured to meet the initial program statement of work requirements; however, the poor forging response of MA-6000 led to four additional forge trials.

3.1.2.2 Second Forging Trial

Based on the results of the first forging campaign, a second campaign designed to reduce die chill was performed. Forge preforms were "coated" with various materials to reduce the die chill which had led to severe cracking problems. A total of eleven forgings were produced. Forging variables of temperature, reduction, and bar direction were kept constant for this effort.

3.1.2.3 Third Forging Trial

The third forging trial evaluated two forging temperatures at one reduction for both unrecrystallized and recrystallized bar. In addition, material from several different primary processing routes were included in the evaluation. The focus of this campaign included the evaluation of coatings to reduce die chill.

3.1.2.4 Fourth Forging Trial

The objective of the fourth forging trial was to evaluate the forging response of canned MA-6000 (mild steel can remaining after extrusion left intact). Material in both the recrystallized and unrecrystallized condition was forged at several temperatures and reduction conditions.

3.1.2.5 Fifth Forging Trial

In preparation for the second task of this program, a fifth forge campaign was planned to identify additional processing guidelines. Variables considered were multiple forge strike (with reheat), step-forge (interface with different degrees of work), thick versus thin mild steel can conditions, single reductions as high as 70% and forging temperatures as low as 1038°C (1900°F). All preforms for forging had the mild steel can left intact.

3.2 Task II - Turbine Blade Forging Development

During Task II, blade forging development trials were performed to produce near-net shape turbine blades from the MA-6000 material. The forging approach taken was based on the results of Task I and the thermal-mechanical-processing procedures developed.

3.2.1 Turbine Blade Design Selection

The turbine blade design was selected prior to initiation of this program. A larger blade design, General Electric's first stage CF6-80 turbine blade, was selected because there is more potential in improving material utilization and reducing material costs with larger blade designs.

3.2.2 Forged Blade and Tooling Designs

The initial effort in this task was to design and build tooling that could be used to forge turbine blades from rectangular-shaped blade preform bar stock. Although the initial intent was to forge net-shape airfoils, the program had to be redirected to forge near-net shape airfoils based on Task I results.

Tooling designs allowed metal flow in one direction for the airfoil section, the original extrusion direction. The forging sequence required a two-step approach, a preform, and a finish forge die to form the near-net shape blade.

3.2.3 Blade Forging Trials

Blade forging trials were conducted to develop the forging tooling in order to produce the required near-net forged shape. During the tooling development effort, the dies were reworked twice to produce the desired blade shape and optimum grain structure after directional recrystallization. A total of twenty-six blades were forged during this effort. These blades were evaluated for the desired macrostructure after directional recyrstallization.

3.2.4 Forging of Blades for Evaluation

After the tooling development trials, seventy-four (74) blades were forged for evaluation. These blades were forged in one lot on a 700-ton mechanical press utilizing the developed blade forging tooling and the thermal-mechanical-processing parameters optimized in Task I.

3.2.5 Evaluation of Forged MA-6000 Turbine Blades

The forged MA-6000 turbine blades were recrystallized by IRDC. Recrystallization was by a zone-annealing process capable of producing elongated grains of a length to diameter aspect ratio greater than 10 to 1. The zone annealing was performed in a single run of a traveling tube furnace zone-annealing unit at 90 mm/h (3.5 in/h) with a peak temperature of approximately 1260°C (2300°F) and a thermal gradient of 21°C/mm (150°F/in) at 1190°C (2175°F). Heat treatment consisted of a 1/2 hour soak at 1230°C (2246°F) with air cooling, followed by 2 hours at 955°C (1751°F) with air cooling, followed by 24 hours at 845°C (1553°F) with air cooling.

Evaluations of the material included metallography of both longitudinal and transverse sections of the forged blades after directional recrystallization. In addition, a significant mechanical property testing effort was planned that included the following:

<u>Root</u>

<u>Tensile Tests</u>	<u>Stress Rupture</u>
650°C (1202°F)	650°C (1202°F)

<u>Platform</u>

<u>Tensile Tests</u>	<u>Stress Rupture</u>
760°C (1400°F)	760°C (1400°F)

<u>Airfoil</u>

<u>Tensile Tests</u>	<u>Stress Rupture</u>
760°C (1400°F) 1100°C (2012°F)	760°C (1400°F) 1100°C (2012°F)

4.0 TASK I - FORGING EVALUATION

This task was conducted to select the thermal-mechanical-processing approach that would yield acceptable grain structure and mechanical properties. Selection of optimum forging parameters was based on the response of MA-6000 to directional recrystallization.

4.1 Material Procurement

INCO Research and Development Center (IRDC) was responsible for the powder preparation, consolidation (by extrusion), secondary working (rolling) of the MA-6000 bar, and zone annealing after TRW forging. The experimental procedures used to produce acceptable bar stock are described in the following section.

4.1.1 Experimental Procedures

4.1.1.1 Powder Production

Twenty heats of MA-6000 powder were mechanically alloyed in a 100S attritor (Table I)[2]. Three heats were judged unacceptable, one being an initial wash heat and the other two having high oxygen and high -325 mesh (44 microns) screen fractions. The remaining heats were qualified by the following procedure:

Mild steel cans having dimensions of 89 mm (3.5 in) diameter and 230 mm (9 in) length were filled with 4.2 kg (9.3 lbs) of powder and sealed. After heating for two hours at 1010°C (1850°F), the cans were extruded through a 25 x 32 mm (1.00 x 1.25 in) die. The extruded bars were heated for 30 minutes at 1040°C (1900°F) and given a 50% rolling reduction in height in two passes. The bars were then decanned by pickling and zone annealed at a rate of 89 mm/h (3.5 in/h) with a peak temperature of about 1260°C (2300°F). After heat treatment (1230°C (2250°F)/0.5 h/AC + 955°C (1750°F)/2 h/AC + 845°C (1550°F)/24 h/AC), specimens were machined having 6.4 mm (0.25 in) gage diameter and 32 mm (1.25 in) gage lengths. Stress rupture testing was performed at 1093°C (2000°F) and 138 MPa (20 ksi) and conformed to applicable ASTM standards.

So that the forming study could begin immediately upon project approval, powder available from IRDC stock was used. Table II gives the qualification test results of these and the other heats used to produce forging stock. The excess powder in Table I was returned to stock. Note that step loading was often required to cause specimen failures in reasonable times. For example, the second specimen of heat T-84374 endured 168 h at 138 MPa (20 ksi) without failure, and then failed after an additional 1.7 h at 152 MPa (22 ksi). One specimen in Table I failed in the shoulder and was considered invalid; a duplicate specimen was then tested and greatly exceeded the life requirement of 100 h. All other specimens exceeded the 100 h stress rupture life requirement. Microstructural analysis at IRDC revealed no significant porosity.

Following qualification testing of individual heats, five blends of three heats each were prepared by cone blending for three hours. The blend numbers are given in Table II. The weight of these blends, 90 kg (200 lbs), corresponds to that needed for each large extrusion can.

TABLE I

POWDER ANALYSIS

	Chemistry, Wt. %			Screen Analysis, Mesh Fraction						
Heat No.	O	N	Fe	+20	20/60	60/100	100/200	200/325	-325	Powder Microstructure
T86118	-	-	-	NIL	17	17	21	15	30	N.A. (wash heat)
T86108	0.84	0.33	0.78	NIL	25	21	21	12	22	uniform
T86109	0.80	0.33	0.72	NIL	15	19	27	15	24	uniform
T86110	0.74	0.34	0.80	NIL	20	23	28	12	18	many under-processed particles
T86111	0.81	0.34	0.82	NIL	20	24	28	13	15	many under-processed particles
T86112	0.60	0.35	0.90	NIL	13	25	33	13	15	occasional under-processed particles
T86113	0.66	0.37	0.86	1	27	23	25	10	13	occasional under-processed particles
T86114	0.72	0.37	0.96	NIL	12	17	30	17	23	occasional under-processed particles
T86115	0.62	0.35	0.95	1	9	19	28	19	24	occasional under-processed particles
T86116	1.30	0.38	0.78	1	3	7	17	9	64	N.A.
T86117	1.02	0.32	0.69	NIL	19	18	22	12	28	uniform
T86125	0.81	0.32	0.72	1	19	20	24	12	24	uniform
T86126	0.80	0.32	0.70	NIL	19	21	28	13	20	uniform
T86127	0.75	0.32	0.66	NIL	17	21	26	14	22	uniform
T86128	0.75	0.33	0.68	NIL	18	26	30	11	15	uniform
T86129	0.70		0.74	NIL	15	22	27	17	18	uniform
T86130	0.75		0.74	NIL	12	17	30	19	23	uniform
T86131	0.71		0.75	NIL	17	20	30	14	19	uniform
T86132	0.69		0.71	1	23	22	25	13	16	uniform
T86345	0.73		0.72	1	26	34	16	12	11	uniform

TABLE II

1093°C (2000°F) STRESS RUPTURE TESTS OF POWDER QUALIFICATION BARSTOCK

Blend	Powder Heat	Stress, MPa (ksi) (1)	Life, H (1)
T-86119	T-84374	138(20)	32*
		138(20)/152(22)	168/1.7
	T-84375	138(20)/152(22)/159(23)	168/24/2.1
	T-84376	138(20)/152(22)	168/6.8
T-86120	T-84379	138(20)	123
	T-84498	138(20)/152(22)/159(23)	185/24/0.6
	T-84499	138(20)/152(22)	168/15.4
T-86347	T-86108	138(20)/152(22)	211/8.9
	T-86109	138(20)/152(22)	168/19
	T-86110	138(20)/152(22)	215/20
T-86348	T-86111	138(20)/152(22)/159(23)	168/24/13
	T-86112	138(20)/152(22)	168/20
	T-86113	138(20)/152(22)/159(23)	168/24/2.5
T-86349	T-86114	138(20)/152(22)/159(23)	168/24/1.3
	T-86115	138(20)/152(22)/159(23)	168/24/4.5
	T-86125	138(20)/152(22)	215/1.3

NOTES: * Broke outside gage marks
(1) Multiple entries indicate step-loaded tests

4.1.1.2 Consolidation

A total of five cans were prepared having dimensions as follows:

200 mm (8.0 in) outside diameter,
6.4 mm (0.25 in) wall thickness,
610 mm (24 in) length,
51 mm (2.0 in) thick nose plug,
130 mm (0.5 in) thick tail plug

Each can was filled with one of the powder blends listed in Table II. Powder was poured into the tail end through a 20 mesh screen. The +20 mesh fraction was discarded. Occasional hammer blows were struck against the cans during filling to settle the powder. The cans are identified by their constituent powder blend numbers. Evacuation stems were fitted to the tail plugs. After 5 psi nitrogen pressurization leak checks, the cans were degassed as follows: Each can was placed in a cold electric furnace. After vacuum pumping for 1.5 h, the furnace was set at 260°C (500°F). Two hours later, the furnace was reset to 400°C (750°F). After two more hours, the furnace was reset to 540°C (1000°F). The furnace was shut off two hours later. Vacuum pumping was continued for an additional sixteen hours before the can was removed from the furnace and the evacuation stem sealed. While the can was heated, the pressure as measured at the pumping station was about 26 Pa (200μm Hg). Pressure was 2.0 Pa (15μm Hg) just before the stem was sealed.

Due to tight scheduling of the first extrusions at Brush-Wellman, there was no time to degas can T-86120. This is actually of little concern, for it has been demonstrated that there is no significant benefit to degassing MA-6000. The weight of gas in the can is small relative to the gas content of the mechanically alloyed powder, and all gas quickly combines with the reactive elements present in the alloy. Furthermore, no effect on recrystallization response has ever been noted. MA-6000 is in fact not degassed in the recently established commercial production route.

Two smaller cans were prepared having dimensions of 89 mm (3.5 in) outside diameter and 230 mm (9 in) length. These cans were filled with T-86120 (-20 mesh) and are identified T-86120-2 and T-86120-3. These cans were not degassed.

The large extrusion cans were extruded by Brush-Wellman, Inc., Elmore, Ohio. Extrusion conditions are summarized in Table III. The cans were placed in graphite sleeves and were heated in a gas furnace at 1040°C (1900°F). The extrusion die had a conical entrance and a round-cornered rectangular aperature measuring 57 x 44 mm (2.25 x 1.75 in). An oil-base graphite lubricant was swabbed on the container walls and die. Additionally, glass wool mat was wrapped around each can.

The first two extrusions listed in Table III went well, with the help of other extrusions outside this project in setting proper throttle openings to attain the desired 50 mm/s (2 in/s) ram speed. The last three cans, which were processed at a later date, behaved differently, however, resulting in decreasing ram speed with increasing preheat time and with the third can stalling the press.

TABLE III

EXTRUSION CONDITIONS, BRUSH-WELLMAN PRESS

	Extrusion Can				
Furnace Time	T-86120	T-86119	T-86347	T-86348	T-86349
in	8:50AM	8:30AM	8:45AM	8:41AM	8:38AM
out	12:52PM	1:25PM	12:39PM	12:51PM	12:59PM
elapsed	4:02	4:55	3:54	4:10	4:21
Transfer Times (s)	90	56	135	90	70
Extrusion Force					
MN	23.9	22.3	23.8	24.5	25.2-25.9
Tons	2680	2500	2670	2750	2830-2900
Ram Speed					
mm/s	52	46	42	32	(stall)
in/s	2.1	1.8	1.7	1.3	
Throttle, 96	100	60	100	90	100
Date	12-3-80	12-3-80	2-11-82	2-11-82	2-11-82

NOTES: Gas furnace temperature = 1035-1050°C (1895-1920°F)
Die size = 57.2 x 44.5 mm (2.25 x 1.75 in)
Lubrication = Fiske 604D, glass wrap and nose pad

It is believed that a change in press operation favored more complete compaction prior to extrusion, requiring greater extrusion force for these cans.

The extruded bars were cut into 1.22 m (48 in) sections starting from the tail ends and were labeled "A" (nose sections), "B", "C", and "D" (tail sections). This material was for Processing Routes 2, 3, and 4 and also the final production route for blade forging stock. The Processing Routes are defined in Table IV and are explained below. Portions of the A and D sections contain normal extrusion end defects.

The two small cans were heated two hours at 1010°C (1850°F) and extruded on the IRDC 6.7 MN (750 ton) press fitted with a 25 x 32 mm (1.00 x 1.25 in) rectangular die. This material corresponds to Processing Route 1.

4.1.1.3 Hot Rolling

The intention of Processing Route 4 was to determine the feasibility of preventing "over-working" during forging by first rolling at a temperature higher than normally used for the production of recrystallized MA-6000 bar stock. Forging of this material would then be performed at lower temperature. The success of this approach would potentially facilitate the production by hot rolling of forging stock of arbitrary thickness without disturbing an established forging process.

To determine the upper temperature limit of hot rolling such that later recrystallization is not prevented, a double rolling schedule was used on portions of the small extrusions produced for Processing Route 1. The double rolling schedule was designed to stimulate a high-temperature, hot-rolling deformation followed by a forging operation at a lower temperature. Four pieces were rolled 50% at 1065, 1095, 1120, or 1150°C (1950, 2000, 2050, and 2100°F), allowed to cool, and then rolled an additional 50%, all at 1040°C (1900°F). All four pieces recrystallized after zone annealing. However, the piece rolled at the highest temperature appeared to have a non-optimum grain structure. Therefore, the next highest temperature, 1120°C (2050°F), was selected as the hot-rolling temperature of Processing Route 4. This temperature is 55°C (100°F) higher than the normal temperature for rolling scaled-up MA-6000 extrusions in production. The rolling schedule is shown in Table V.

Material for Processing Routes 3 and 4 was hot rolled after a short section of T-86120 was rolled on a trial basis to verify the suitability of a three-pass rolling schedule. No difficulties were encountered. The rolling schedule is also given in Table V. T-86120-C was cut into four 305 mm (12 in) lengths labeled 1, 2, 3, and 4. T-86120-C-2 was rolled after heating to 1120°C (2050°F); the other three lengths were heated to 1065°C (1950°F).

After decanning, the bars measured 26 mm (1.02 in) thick and 65 mm (2.6 in) overall width. Finished rectangular cross-sections from these bars would measure 25.4 x 53 mm (1.00 x 2.1 in).

A preliminary estimate of the required blank size for the Blade Forging Task indicated that reductions to both the height and width of the previously extruded bars would be required. Cutting to size was no longer a

TABLE IV

PROCESSING CONDITIONS FOR MA-6000 TASK I FORGING STUDY

Processing Route	Billet Temperature For Extrusion	Extrusion Ratio	Billet Temperature For Rolling	% Reduction by Rolling
1	1010°C (1850°F)	7.2:1	*	--
2	1040°C (1900°F)	13.6:1	--	--
3	1040°C (1900°F)	13.6:1	1065°C (1950°F)	33%
4	1040°C (1900°F)	13.6:1	1120°C (2050°F)	33%

* Experimental double rolling schedule.

TABLE V

ROLLING SCHEDULES FOR FORGING BLANKS

Processing Route	Rolling Passes, mm(in)[3] Start	1st	2nd	3rd	4th	5th
3 + 4[1]	45 (1.75)	38 (1.50)	34 (1.35)	29 (1.15)	-	-
Production[2]	57 (2.25)	46 (1.80)	39 (1.55)	43 (1.70)	33 (1.30)	42 (1.65)

NOTES

(1) Processing Routes 3 and 4 used 40-minute preheats at 1065 and 1120°C (1950 and 2050°F) respectively.

(2) Production Route used 45-minute preheat plus 15-minute reheat after second pass at 1065°C (1950°F). Bars are rotated 90° about long axis after each pass so as to make alternate reductions to width and height.

(3) Mill speed was 300 mm/s (11 in/s); mill diameter was 510 mm (20 in).

viable approach since it had been determined that the can had to be left on. The feasibility of performing this hot rolling at IRDC using flat rolls was determined by rolling excess MA-6000 extrusions of the same size. All rolling employed five passes with 90° rotations about the extrusion axis between each pass. Sections 305 mm (12 in) long were preheated 45 minutes at 1040°C (1950°F) and reheated 15 minutes after the second pass. Mill operators had to feed the bars into the rolls very carefully to achieve rectangular cross sections.

The aim of the initial trials was to produce a cross section of 41 x 38 mm (1.6 x 1.5 in). The rolling schedule limited reductions to less than about 30% per pass, taking lateral "spreading" into account. While the first bar rolled was close to the desired dimensions, the bar was not rectangular. The rolling schedule was revised before rolling a second bar. The modification was intended to decrease the height of the bar for each pass and thus reduce the chance of producing a non-rectangular cross section, which results from the difficulty in feeding a bar "high" by hand through the rolls. The bar rolled by this schedule was also non-rectangular, but only due to a loss of control by the operator during feeding on the last pass. A portion of this bar was zone annealed to confirm that a coarse grain structure could be achieved.

The final rolling schedule, listed in Table V, utilized the results of these trials and incorporated the final blank dimensions, 43.2 x 38.1 mm (1.70 x 1.50 in) required for the blade forging task. For the first production rolling, five lengths were rolled; the first two were from excess material (YBB-0021). The mill setting for the last pass was adjusted upwards after these two were measured and found to be undersized. The other three bars were from extrusions produced for this project, T-86119, T-86347, and T-86348. The T-86119 section became badly non-rectangular during the last pass, again due to loss of control by an operator during feeding. The other four bars had rectangular cross sections.

Additional material was rolled by IRDC in order to supply the required 100 forging blanks for the blade forging task. A total of 19 bars suitable for four blanks each and 10 bars suitable for three blanks each were provided.

The cutting of unrecrystallized MA-6000 without cracking is often difficult. Consultation with a manufacturer of abrasive cutoff wheel resulted in the use of Avery grade 1410 wheels with coolant. The initial material supplied was dye penetrant inspected by IRDC for cutting cracks and was found free of cracks. Later bars had to be cut in the canned condition; end cracks were occasionally present in this material, for which cutting was more difficult. These end cracks were always removed by grinding prior to use for forging blanks.

4.2 Forge Tooling Build

The forge tooling required for the first task was designed to accept preforms approximately 25 mm (1 inch) wide. The tooling was machined from AISI H-12 tool steel and hardened to R_c 50-53. The tools were designed to provide a plane strain forging condition such that flow was limited to the long axis of the preform (or airfoil of the blade). The trough-shaped cavity was 27.8 mm (1.095 in) wide and 254.0 mm (10.0 in) long with a three-degree taper on the side walls to allow for easy removal of the forged workpiece.

4.3 First Forging Trial

4.3.1 Forging of MA-6000 Preforms

MA-6000 bar stock was supplied by IRDC for the processing conditions summarized in Table IV and described in Section 4.1. Preform dimensions are given in Table VI. Difficulty was experienced in abrasive cutting of the MA-6000 bar. This difficulty led to cracking and actual chipping of the material. For a quick solution to the problem, the preforms were cut by wire EDM; however, as experience was gained with cutting MA-6000, later preforms were cut with an abrasive wheel.

MA-6000 preforms were forged on a 1300-ton mechanical press shown in Figure 1 in a trough-type die that restricted side flow. The directional forge tooling is shown in Figure 2. The first trial was directed towards "sampling" the forging schedule in Table VII. After analyzing these results, conditions for other forge trials were selected. The results of all the forge trials including directional recrystallization (DR) response and visual examinations are presented in the following sections.

4.3.2 Forging Trials

Preforms were initially forged at the three forging temperatures indicated in Table VII, with 10% and 35% reductions being employed. Pieces were charged into an electrically heated box furnace and heated at temperature for twenty minutes. For forging, the die was heated to 160-204°C (320-400°F) and graphite spray lubricated. The preforms were glass coated with a TRW coating. The order of forging, the material forged, the orientation, and the forging conditions are given in Table VII. Comments concerning the forging appearance are also given. From this table, it is clear that die chill is a major problem as the die side cracked in most cases. Also, a small amount of lateral spread introduced cracking since the preforms did not fit the die channel exactly. This lack of good fit is attributed to the different sizes of forging stock provided. The longitudinal cracks are associated with lateral spread and the transverse cracks with length-wise flow. Die chill enhances the cracking tendency. In cases where flash occurred, edge cracking was associated with flash and the rapid die chill caused in the flash. The forgings are shown in Figure 3. Also shown in the Table VII schedule was some laboratory MA-6000 bar stock supplied by IRDC that was zone annealed. This material was forged 10% at 1205°C (2200°F) and 1260°C (2300°F). These high forge temperatures were selected based on recent IRDC experiments. Some longitudinal cracks were also observed after forging.

4.3.3 Directional Recrystallization Response

The results of the response of the first campaign of forgings to directional recrystallization (DR) are presented in Section 4.4.2 for completeness with second forging trial results. The DR response was actually being determined while the second forge trial was being performed.

4.4 Second Forging Trial

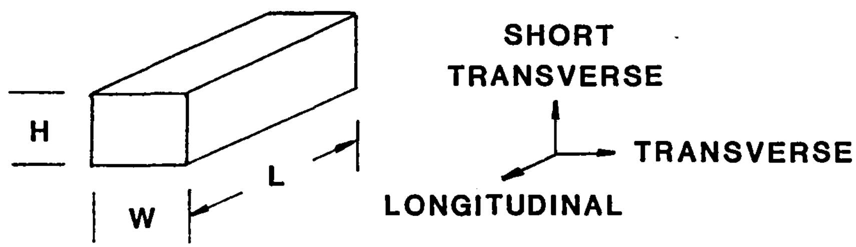
4.4.1 Forging Trials

The second forging trial was conducted using the identical forging

TABLE VI

PREFORM SIZES USED FOR TASK I STUDY

Bar Stock Starting Size	ORIENTATION Longitudinal Preform	Long Transverse Preform	Short Transverse Preform
1.9mm H x 2.5mm W x 5.0mm L	1.9mm H x 2.5mm W x 5.0mm L	1.9mm H x 2.5mm W x 2.5mm L	----------
3.8mm H x 5.0mm W x 5.0mm L	1.9mm H x 2.5mm W x 5.0mm L	1.9mm H x 2.5mm W x 5.0mm L	2.5mm H x 2.5mm W x 1.9mm L
1.9mm H x 5.0mm W x 5.0mm L	1.9mm H x 2.5mm W x 5.0mm L	1.9mm H x 2.5mm W x 5.0mm L	2.5mm H x 2.5mm W x 1.9mm L



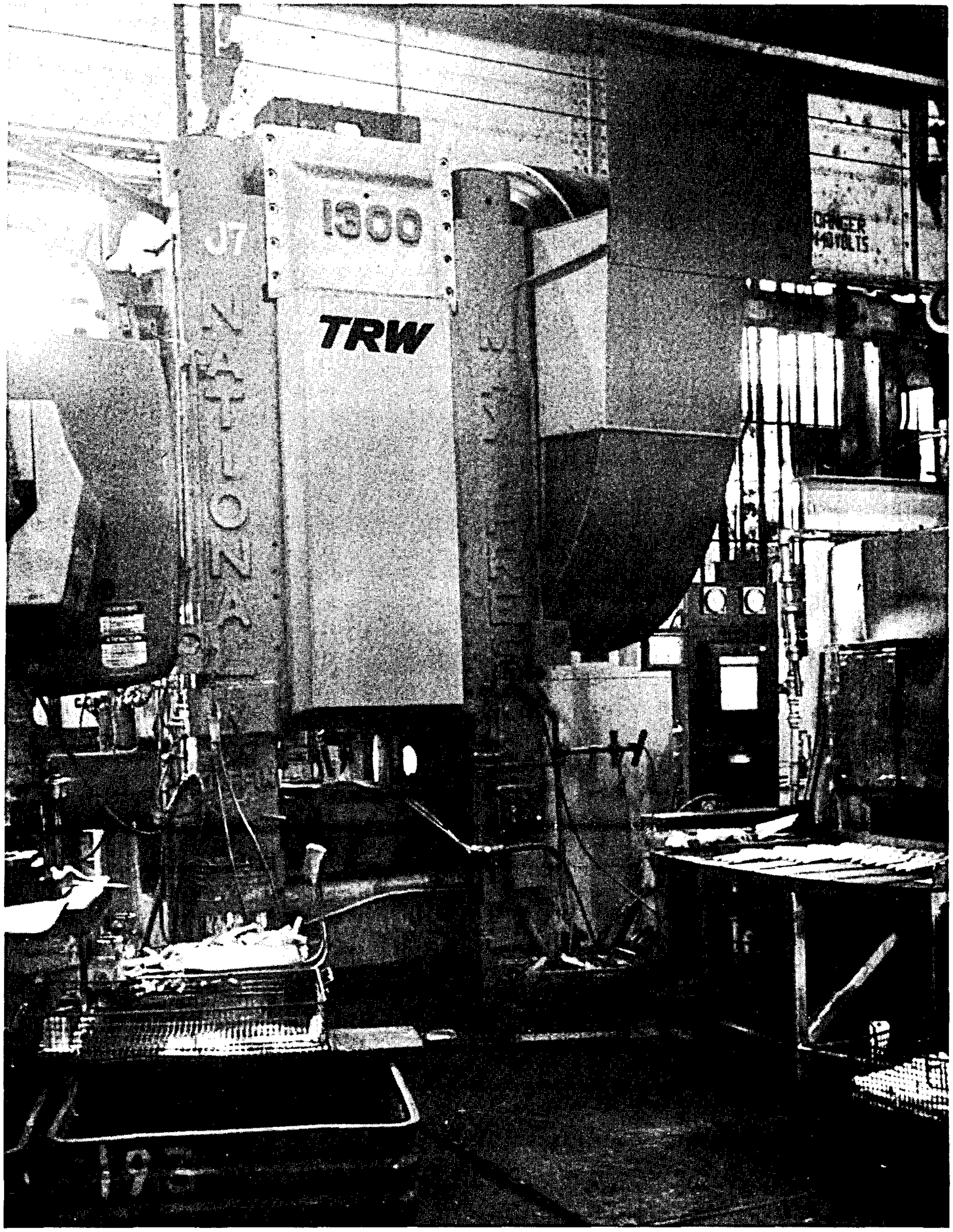


Figure 1. TRW Mechanical Press of the Type Used for Directionally Forging MA-6000.

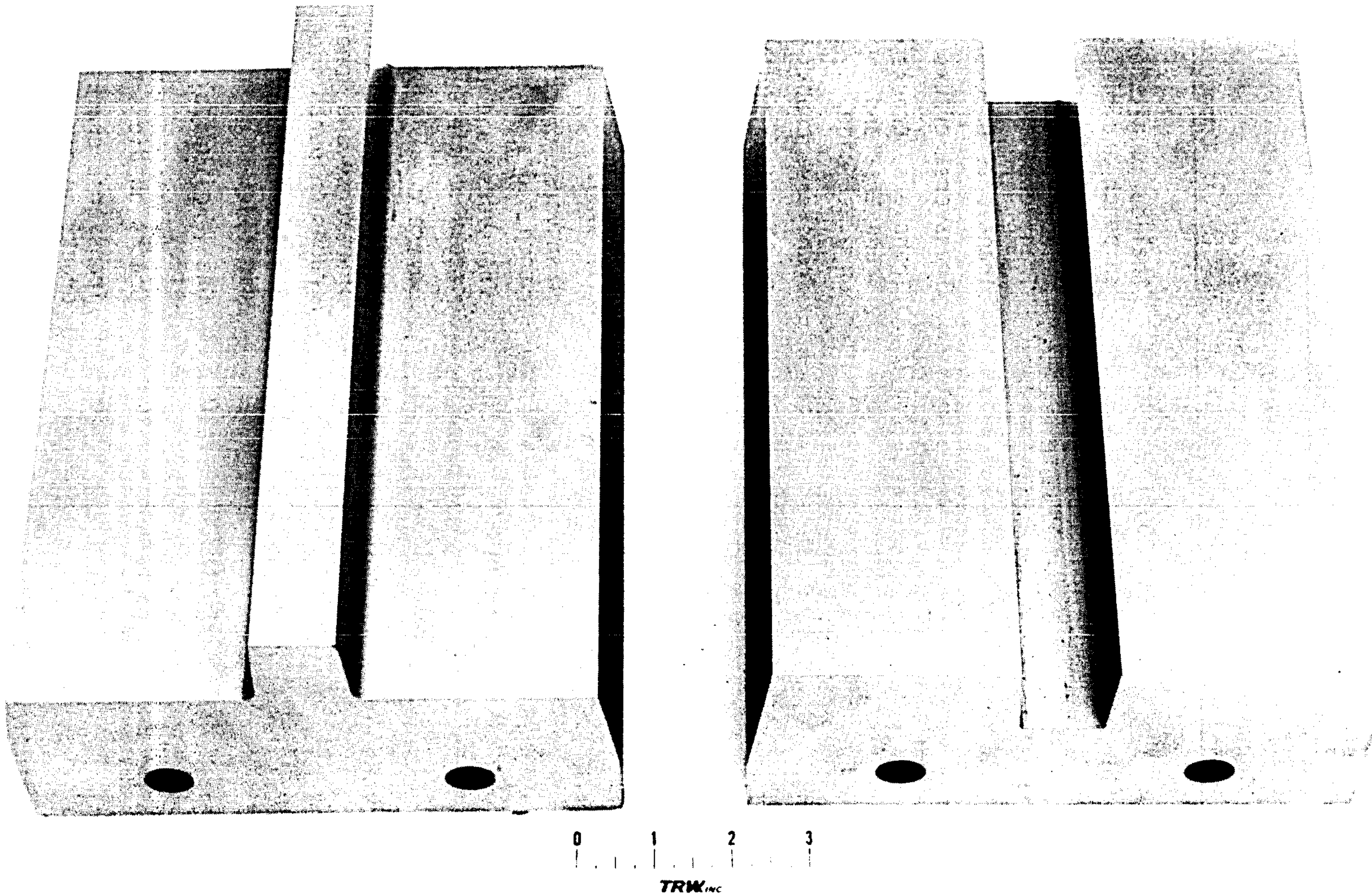


Figure 2. Tool Steel Die and Punch Used for Directionally Forging MA-6000 Preforms.

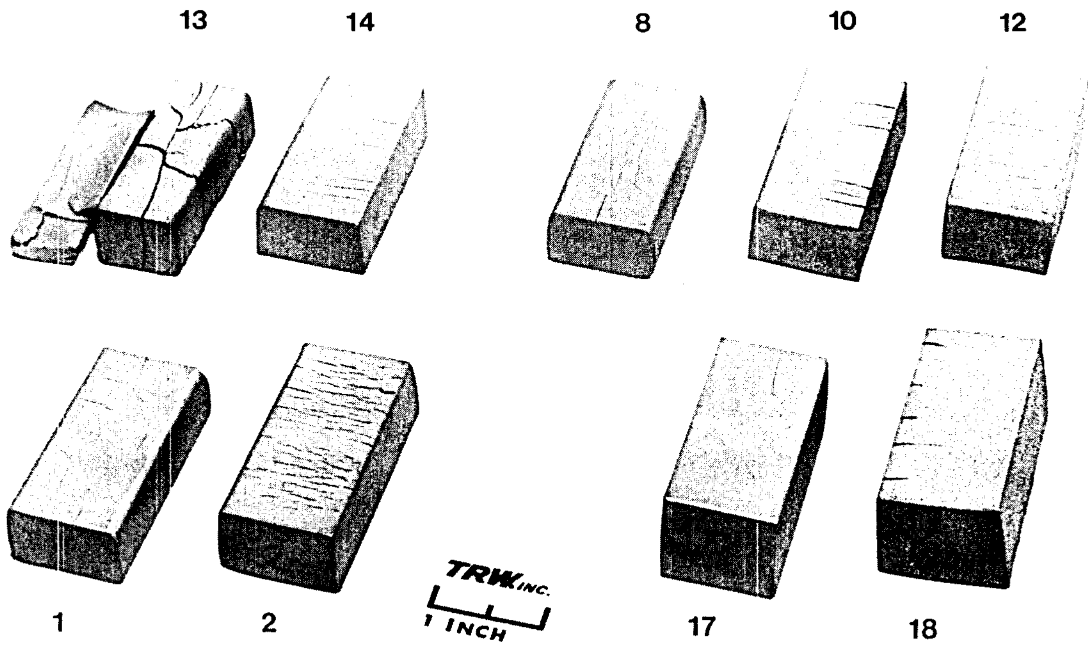
1645-D

TABLE VII

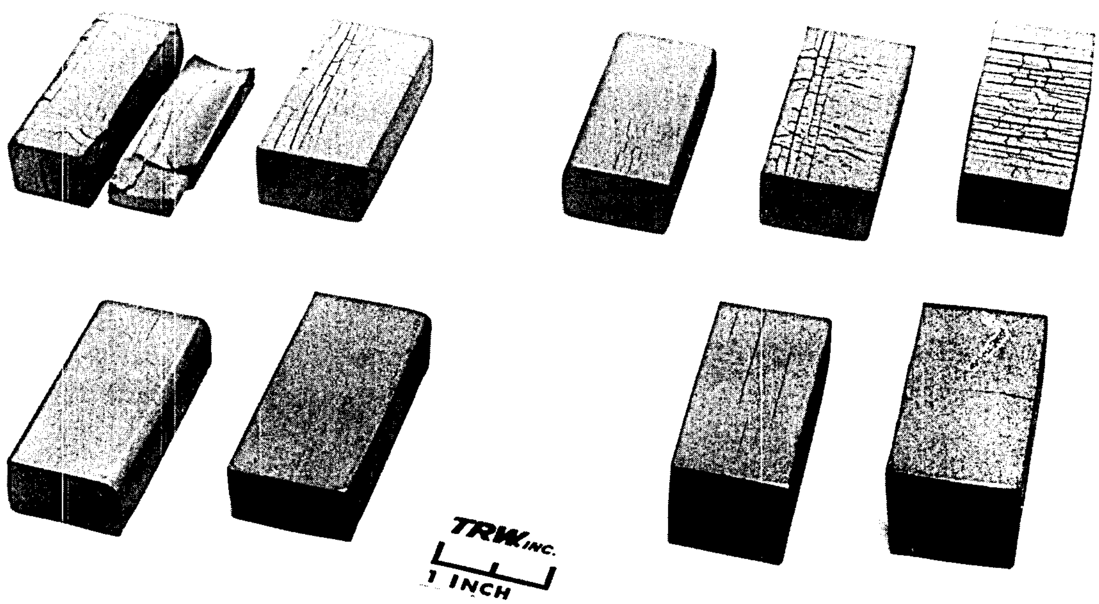
FIRST SERIES OF FORGING TRIALS

Forging Number	Processing Route - Orientation(1)	Forging Temp. °C (°F)	Forge Reduction %	Comments
1	1 - L	1120 (2050)	10	Shallow longitudinal cracks on punch and die side.
2	2 - L	1120 (2050)	10	Transverse cracks on die side.
3	2 - L	1120 (2050)	10	Transverse cracks on die side.
4	3 - L	1120 (2050)	35	Transverse cracks on die side.
5	3 - L	1120 (2050)	35	Transverse cracks on die side.
6	3 - T	1120 (2050)	35	Transverse cracks on die side. Transverse and edge cracks on punch side.
7	4 - L	1120 (2050)	35	Transverse cracks on die side.
8	1 - L	1065 (1950)	10	Shallow longitudinal cracks on punch and die side.
9	1 - L	1065 (1950)	10	Shallow longitudinal cracks on punch and die side.
10	2 - L	1065 (1950)	10	Deep transverse cracks on die side.
11	2 - L	1065 (1950)	10	Transverse cracks on die and punch sides.
12	2 - T	1065 (1950)	10	Transverse and longitudinal cracks on die and punch sides.
13	1 - L	1010 (1850)	10	Severe cracking.
14	2 - L	1010 (1850)	10	Transverse cracks on die side Transverse and longitudinal cracks on punch side.
15	5 - L(2)	1205 (2200)	10	Shallow longitudinal cracks on die side.
16	5 - L	1260 (2300)	10	One longitudinal crack on die side.
17	3 - L	1065 (1950)	10	Cracks on die and punch sides.
18	4 - L	1065 (1950)	10	Transverse cracks and edge cracks on die and punch sides.

Notes: (1) L = Longitudinal; T = Transverse
(2) Processing Route #5 is material from Process Route #1 that has been directionally recrystallized.

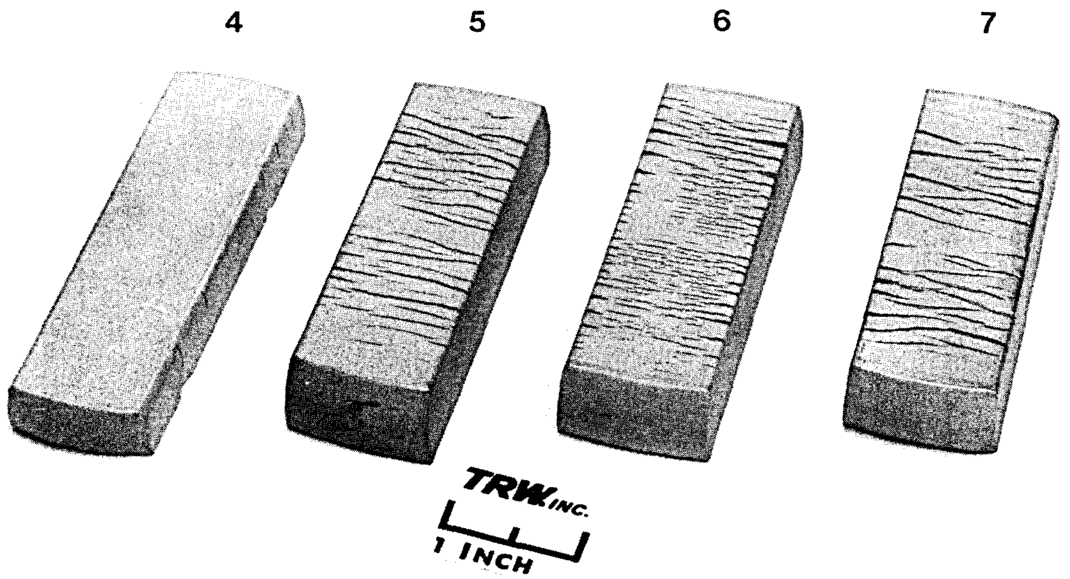


Die Side Up

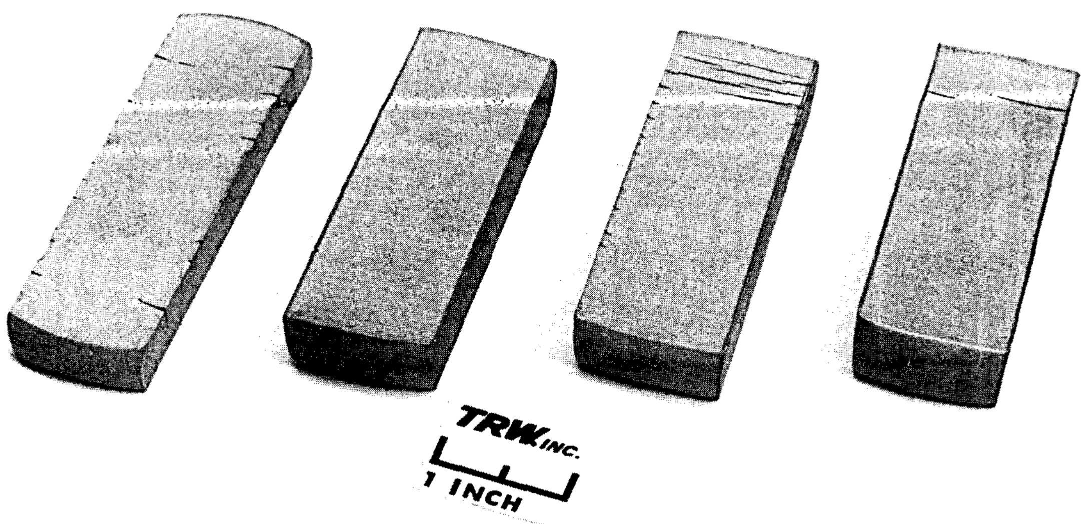


Punch Side Up

Figure 3(a). First Series of Forging Trials - MA-6000 Forgings. See Table VII for Forging Conditions.

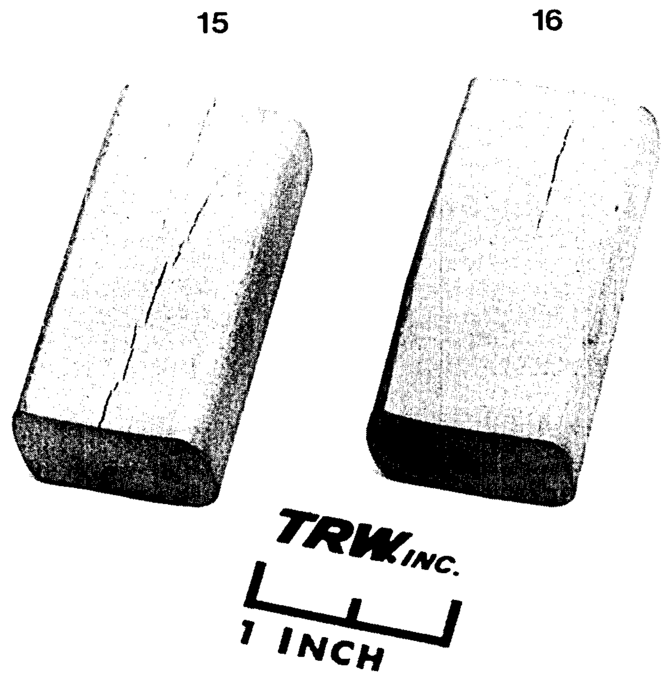


Die Side Up

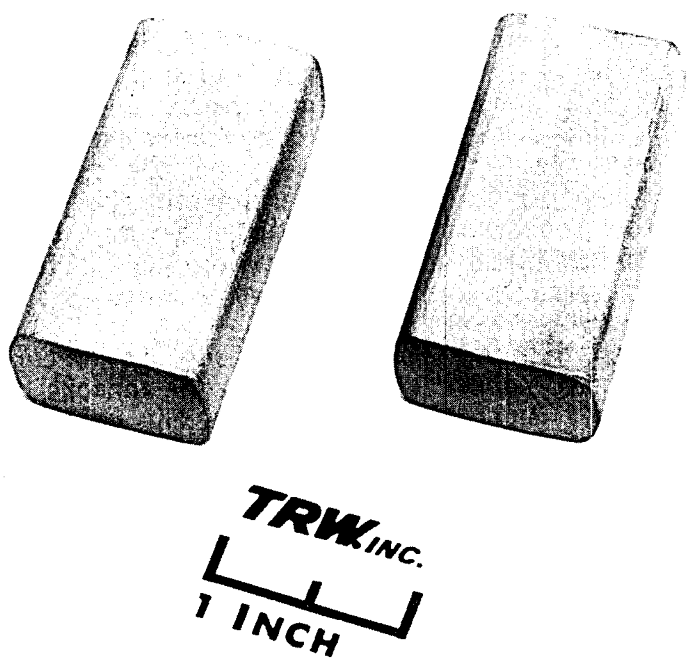


Punch Side Up

Figure 3(b). First Series of Forging Trials - MA-6000 Forgings. See Table VII for Forging Conditions.



Die Side Up



Punch Side Up

Figure 3(c). First Series of Forging Trials - MA-6000 Forgings. See Table VII for Forging Conditions.

conditions, press equipment, and forge tooling utilized for the first forge trial.

Based on the visual results of the first forging trial, several approaches were attempted to reduce die chill and the cracking problems associated with it. These approaches were:

- Heavy glass coating
- Fiberglass
- Fiberfrax wrap
- Steel container around preform
- Steel shims to provide a standoff from die
- Different glass coating (CRT).

Heavy glass coatings were achieved by dipping the preform in the glass slurry. A coating of 4-6 mils was obtained. In the first forging campaign, the preforms were sprayed, and the coating thickness was 1-2 mils. The second approach listed, fiberglass, was accomplished by laying a piece of fiberglass in the bottom die just prior to forging to insulate the heated preform from the cooler (160-204°C) die. The preform was glass coated (4-6 mils). Preforms were also wrapped in fiberfrax and mild steel and then glass coated (4-6 mils). Another approach was to tack weld steel shims to the preform sides to provide a standoff from the die until the punch forced the piece into the die during the forging stroke. This preform was also glass coated prior to forging. The last approach was to use a higher temperature glass coating (CRT). Although coatings can be applied in varying thicknesses, less than 3 mils is preferred for optimum surface conditions. The CRT was applied by dipping resulting in an approximate 4-mil coating. The first forging trials also indicated that the best forging response (lowest incidence of cracking) was found for material forged at 1121°C (2050°F); therefore, this temperature was selected for the second forge trial. The forging schedule used is shown in Table VIII. Information included in this table covers the material condition and orientation, the forging temperature and reduction, the method of reducing die chill, and comments concerning the forgings. The forgings for this second trial are shown in Figure 4. Based on the results, it appears that an insulator such as fiberfrax offers a solution to the cracking problem. The fine crazing observed for fiberfrax wrapped material may be attributed to tensile stresses developed during transverse flow which was allowed due to the slightly smaller preform width compared to the die cavity width.

Forging 29 is a restrike of Forging 4 made to determine response (tendency to crack) to additional work. Transverse edge cracks were observed, some of which were attributed to fine cracks initiated in the initial forging.

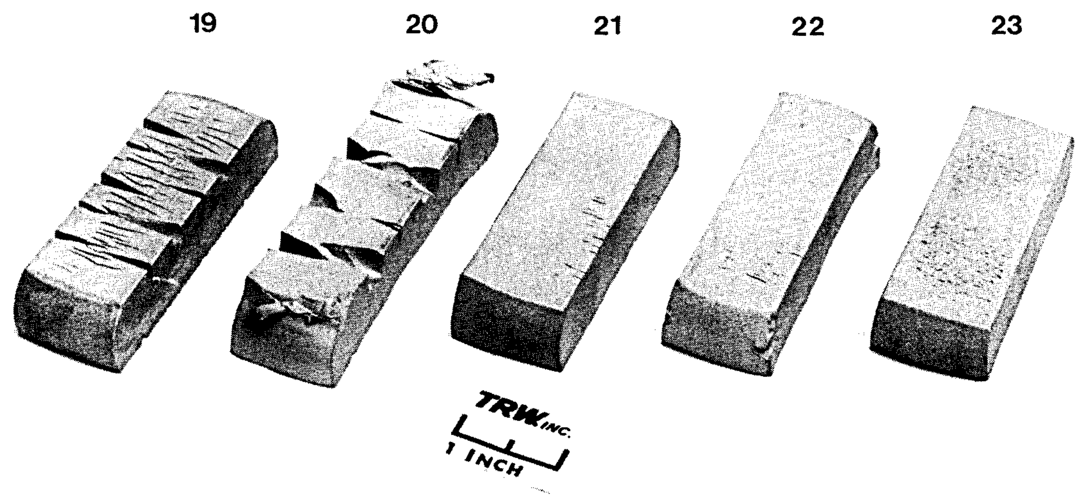
4.4.2 Directional Recrystallization Response

The evaluation of the response of the forged MA-6000 material to directional recrystallization was performed by IRDC. The forged pieces were cut lengthwise in half to produce two symmetrical pieces. One half was zone annealed; the other half was retained as a precaution against equipment malfunction. Two badly cracked pieces (Forgings 13 and 20) were not zone annealed. Zone annealing was performed in a single run of a traveling tube furnace zone annealing unit at 90 mm/h (3.5 in/h) with a peak temperature of approximately 1260°C (2300°F) and a thermal gradient of 21°C/mm (150°F/in) at 1190°C (2175°F). The zone annealing

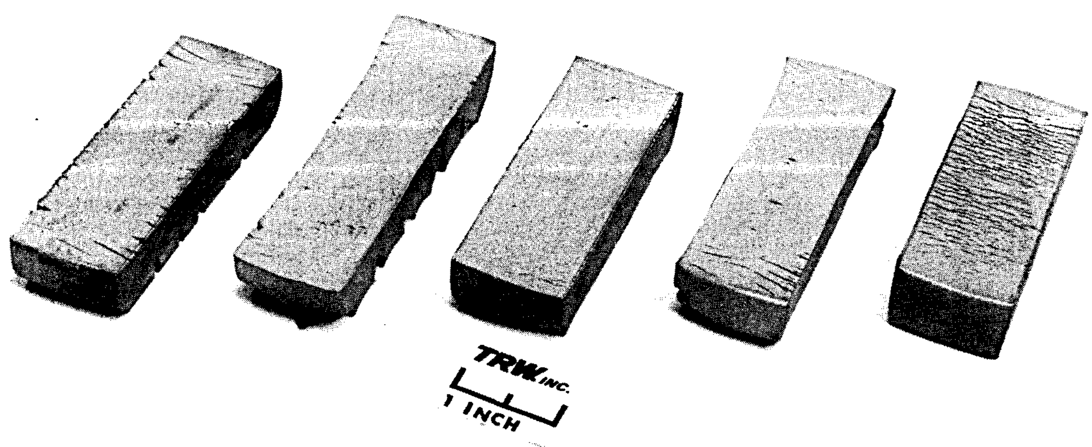
TABLE VIII

SECOND SERIES OF FORGING TRIALS

Forging Number	Processing Route - Orientation	Forging Temp. °C (°F)	Forge Reduction %	Comments
19	3 - L	1120 (2050)	35	CRT glass coating. Severe cracks on die side.
20	3 - L	1120 (2050)	35	Mild steel can. Severe transverse cracks on die side.
21	3 - L	1120 (2050)	35	Fiberfrax wrap. Few transverse cracks on die side.
22	3 - L	1120 (2050)	35	Stainless steel stand-off shims. Fine transverse crazing on punch and die side.
23	3 - L	1120 (2050)	35	Fiberglass wrap (not on top). Transverse cracks on punch side. Crazing on die side.
24	2 - L	1120 (2050)	35	CRT glass coating. Severe cracks on punch and die sides.
25	2 - L	1120 (2050)	35	Mild steel can. Fine surface tears.
26	2 - L	1120 (2050)	35	Fiberfrax wrap. Fine crazing on punch and die sides.
27	2 - L	1120 (2050)	35	Stainless steel stand-off shims. Transverse surface tears.
28	2 - L	1120 (2050)	35	Fiberglass wrap. Transverse die side cracks.
29	3 - L	1120 (2050)	35	Restrike of #4.

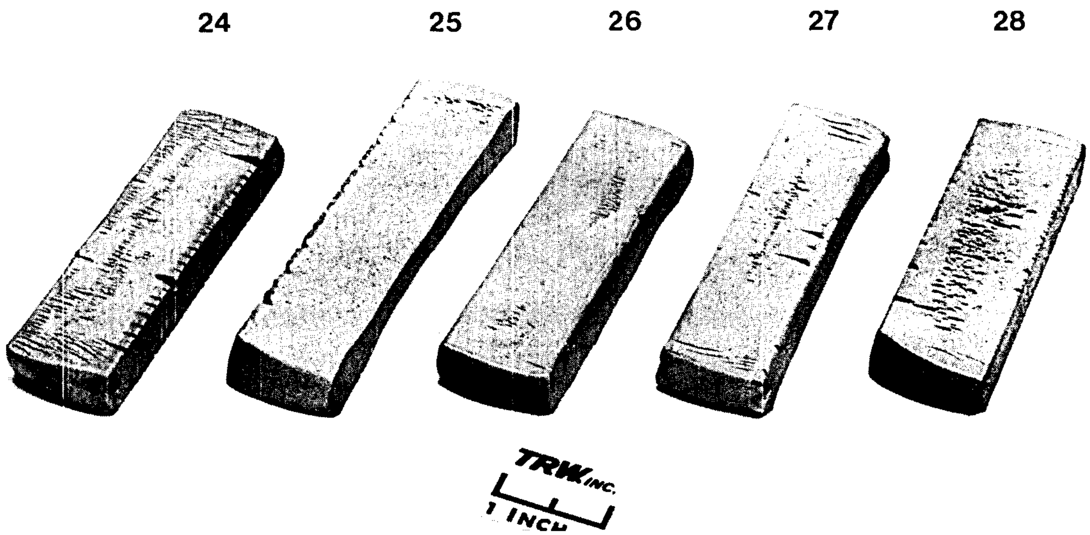


Die Side Up

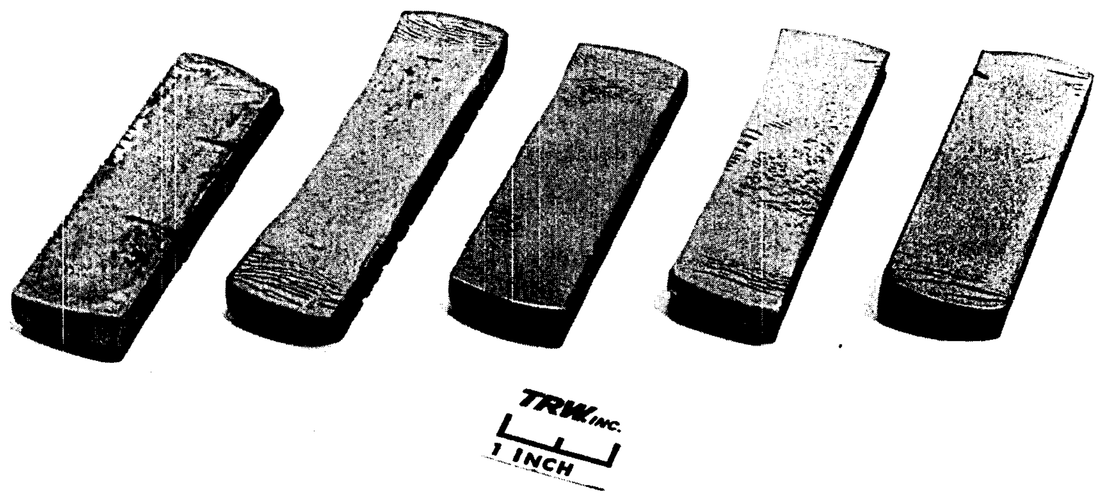


Punch Side Up

Figure 4(a). Second Series of Forging Trials - MA-6000 Forgings. See Table VIII for Forging Conditions.



Die Side Up



Punch Side Up

Figure 4(b). Second Series of Forging Trials - MA-6000 Forgings. See Table VIII for Forging Conditions.

direction was in all cases parallel to the extrusion direction. This procedure is identical to that normally employed in the laboratory manufacture of MA-6000 bar stock at IRDC.

After zone annealing, the pieces were sectioned as shown in Figure 5, then polished and etched (49% HCl, 49% H_2O, 2% H_2O_2) to reveal the grain structure in three orthogonal planes. Photographs were taken at 2X and appear in Figures 6, 7, and 8. In each photograph the upper, middle, and lower sections correspond to Sections 1, 2, and 3 of Figure 5. For Sections 1 and 2 note that one longitudinal cut edge and one longitudinal natural exterior edge appear in the photographs. The cut edges of both sections correspond to the longitudinal centerline of the forgings. The exterior edge of Section 1 was in contact with the punch during forging; the exterior edge of Section 2 was in contact with the die wall. For Section 3, the edge opposite the cut edge was in contact with the die wall; the placement of the other two edges can be deduced from their shape and/or the presence of flash on the punch side. In order to achieve high rupture strength, MA-6000 must recrystallize* to a coarse, elongated grain structure during zone annealing. Improper thermomechanical processing can result in a recrystallized structure having a low grain aspect ratio (GAR) or, for more extreme cases of improper processing, no recrystallization at all. Different areas of individual specimens may experience different processing histories, resulting in different DR responses.

An examination of the photographs of Figures 6, 7, and 8 reveals that, for forgings which did not properly recrystallize in all areas, the areas having the best DR response were towards the exterior surfaces; the poorest DR response was found in the interior. (The centerlines of the forgings do not correspond to the centerline of the starting bar stock except for Processing Route 1, suggesting that any improper processing causing such a pattern of poor structure occurred during forging. Improper zone annealing would have resulted in a pattern of poor structure centered in the annealed pieces rather than the center of the complete forgings, which had been cut in half prior to annealing.)

In the analysis that follows, two numbers are assigned to each forging to characterize its DR response. The first number is the percentage of area that recrystallized. The second number is the percentage of area that exhibits a high GAR (greater than about 10). GAR was judged by viewing Section 1 of each forging (see Figure 5) for which the apparent GAR is least sensitive to misorientation of the section plane with the grain orientation. The analysis is summarized in Table IX. Thus, a DR Response Factor (DRRF) of 20/0 (e.g., Forging 28, Figure 7) represents a very poor DR response; 100/100 (e.g., Forging 10, Figure 6) represents an excellent DR response; and 100/70 (e.g., Forging 2, Figure 6) represents a DR response that is good in most areas, but is unacceptable in others. The latter may be considered an example of a "near miss" in processing.

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* The term "recrystallize" is used here to mean the process by which the structure of MA-6000 changes from very fine grained to coarse grained during annealing. This has been described as secondary recrystallization[3].

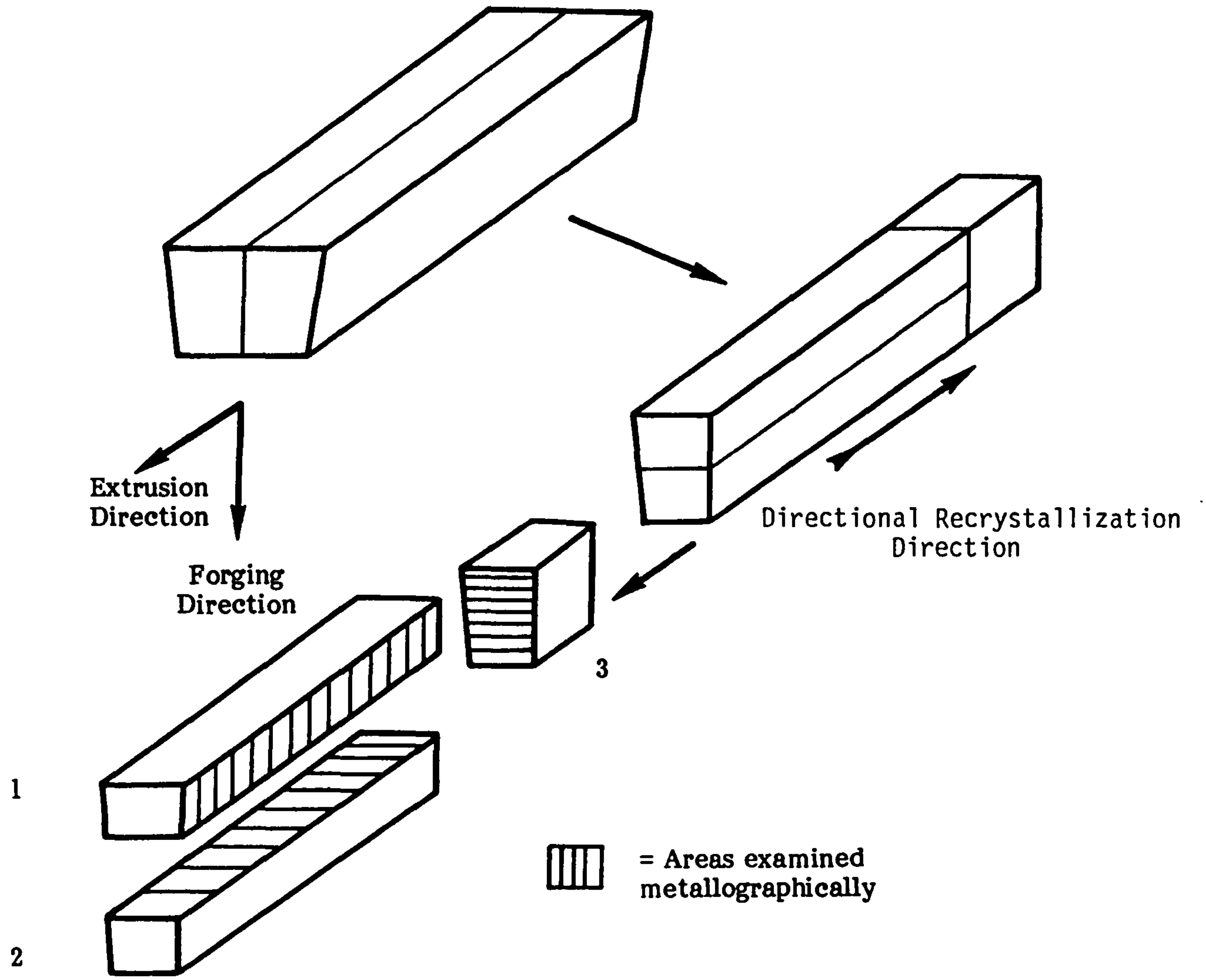
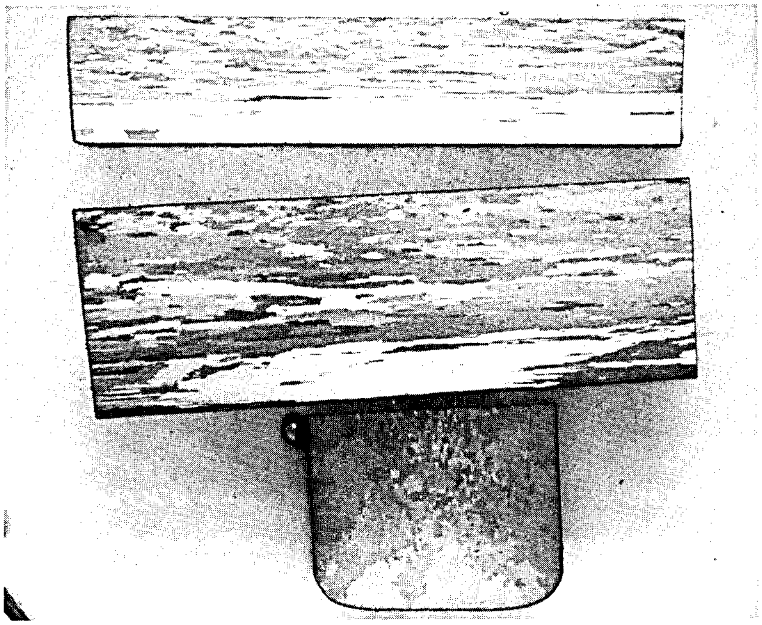
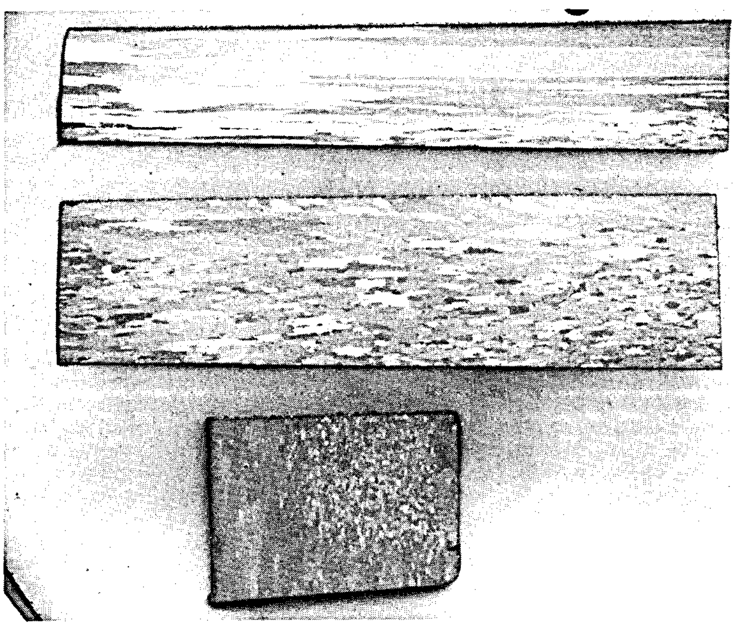


Figure 5. Sectioning of MA-6000 Forgings.

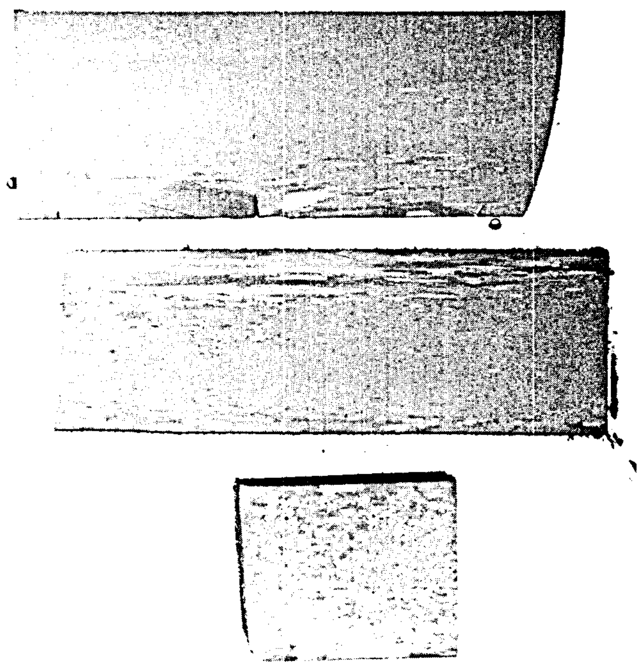


(a) Forging 1, Processing Route 1, Forged 10% at 1120°C (2050°F).

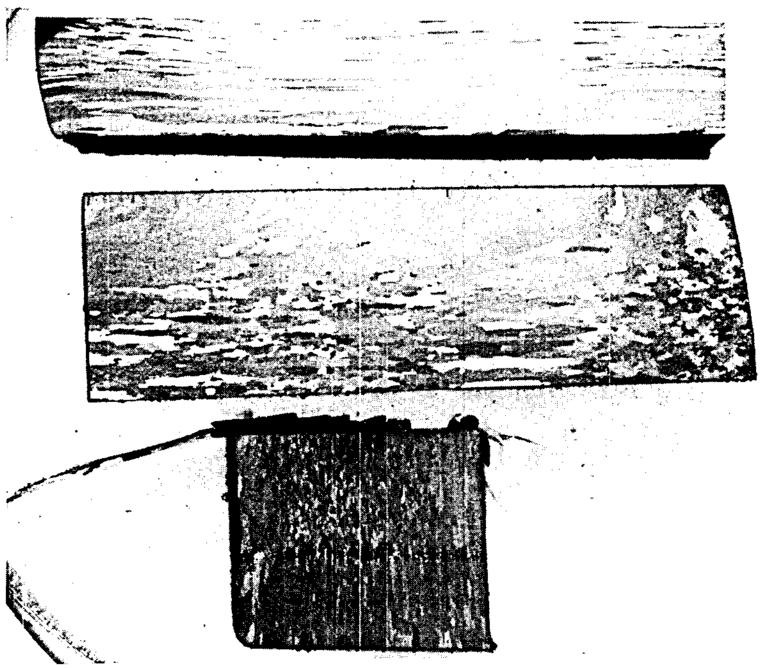


(b) Forging 2, Processing Route 2, Forged 10% at 1120°C (2050°F).

Figure 6. Polished and Etched Sections of MA-6000 Forgings. See Figure 5 for Identity of Sections.

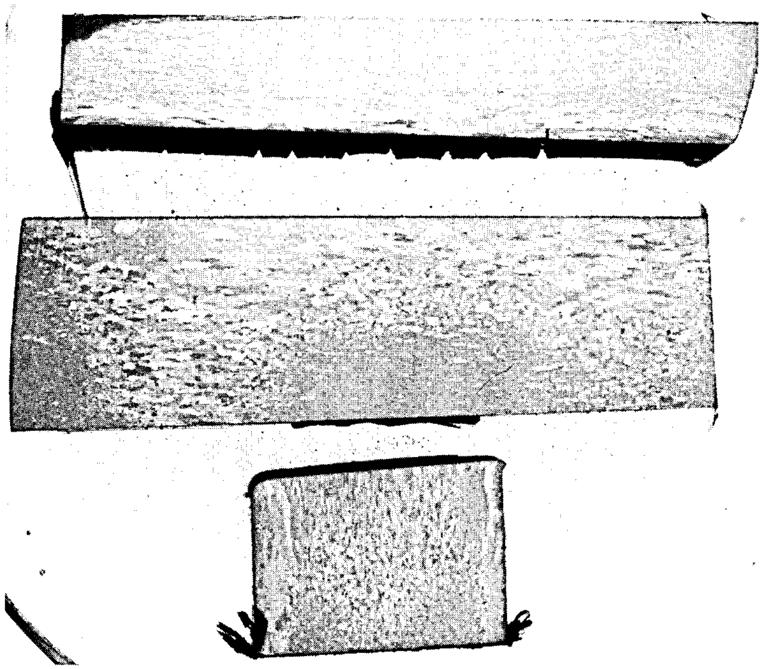


(c) Forging 4, Processing Route 3, Forged 35 + 20% at 1120°C (2050°F).

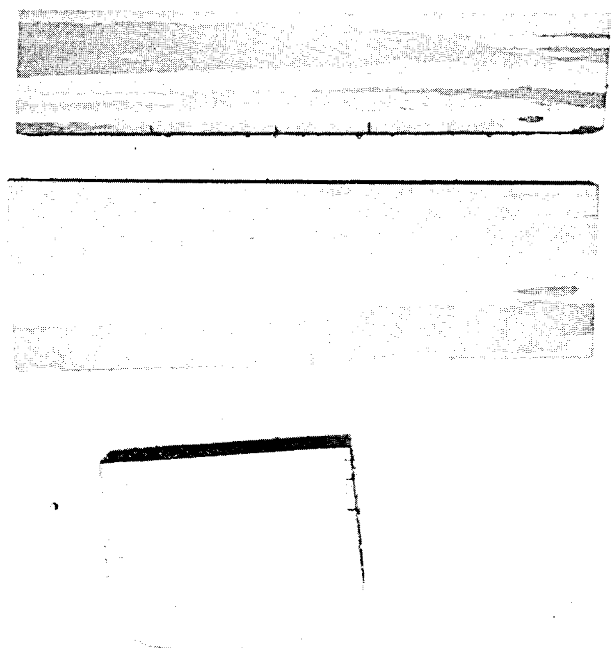


(d) Forging 5, Processing Route 3, Forged 35% at 1120°C (2050°F).

Figure 6. Cont'd.

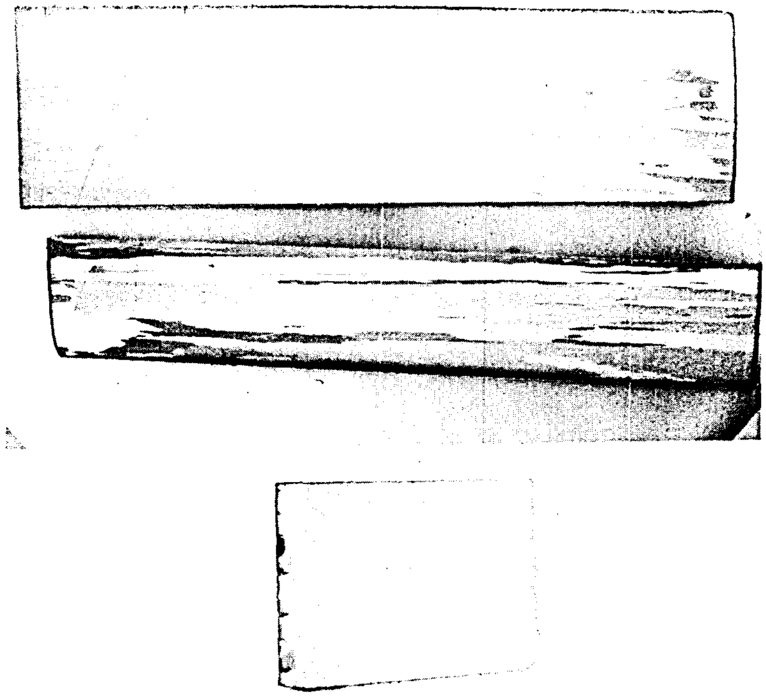


(e) Forging 7, Processing Route 4, Forged 35% at 1120°C (2050°F).

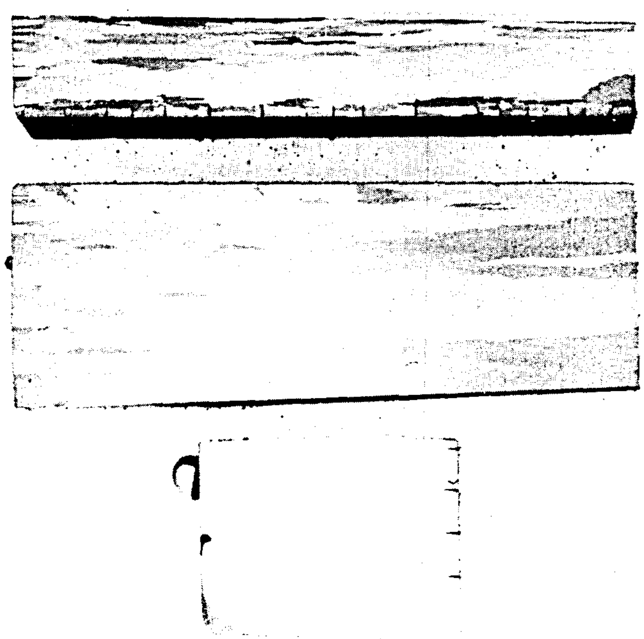


(f) Forging 8, Processing Route 1, Forged 10% at 1065°C (1950°F).

Figure 6. Cont'd.

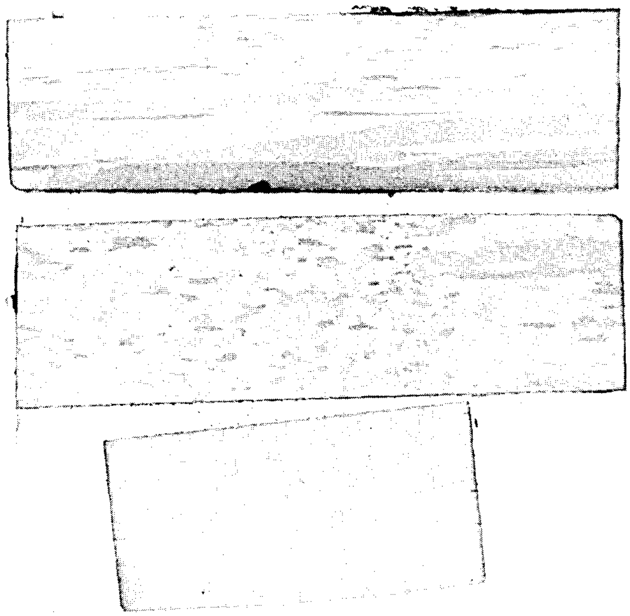


(g) Forging 10, Processing Route 2, Forged 10% at 1065°C (1950°F).

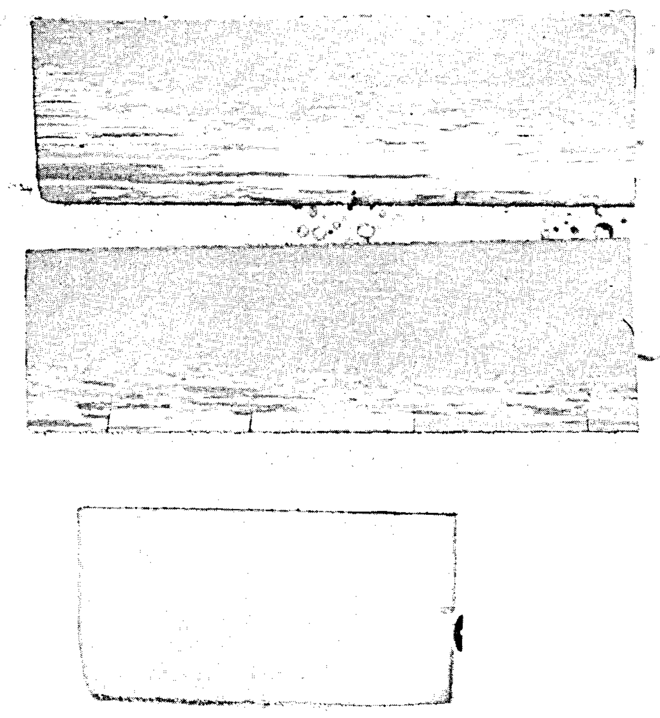


(h) Forging 14, Processing Route 2, Forged 10% at 1010°C (1850°F).

Figure 6. Cont'd.

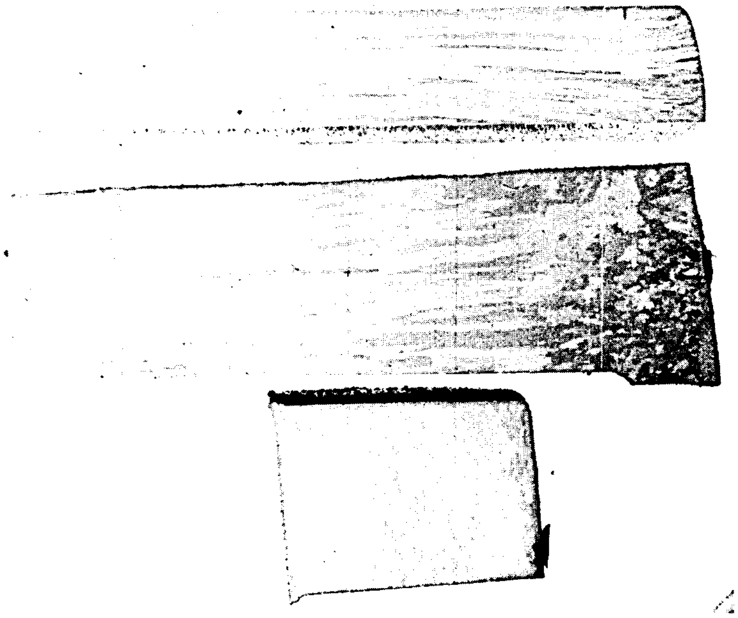


(i) Forging 17, Processing Route 3, Forged 10% at 1065°C (1950°F).

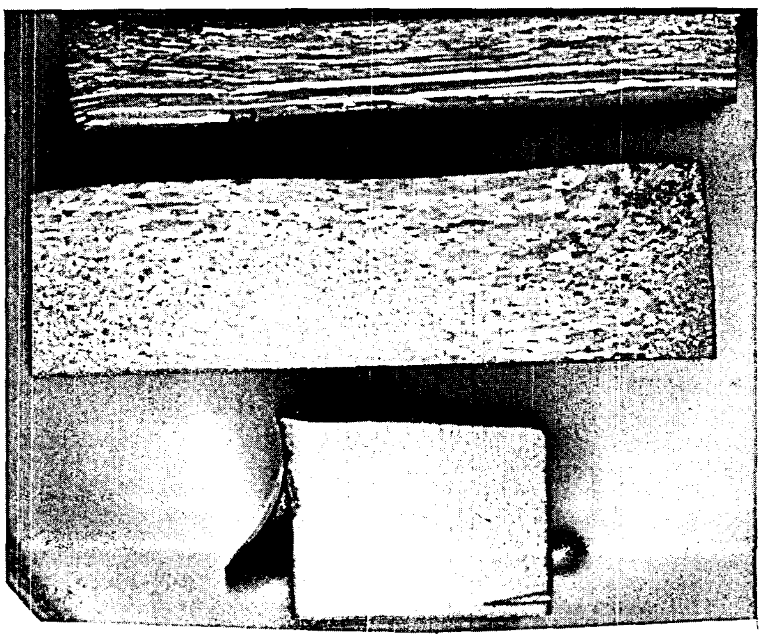


(j) Forging 18, Processing Route 4, Forged 10% at 1065°C (1950°F).

Figure 6. Cont'd.

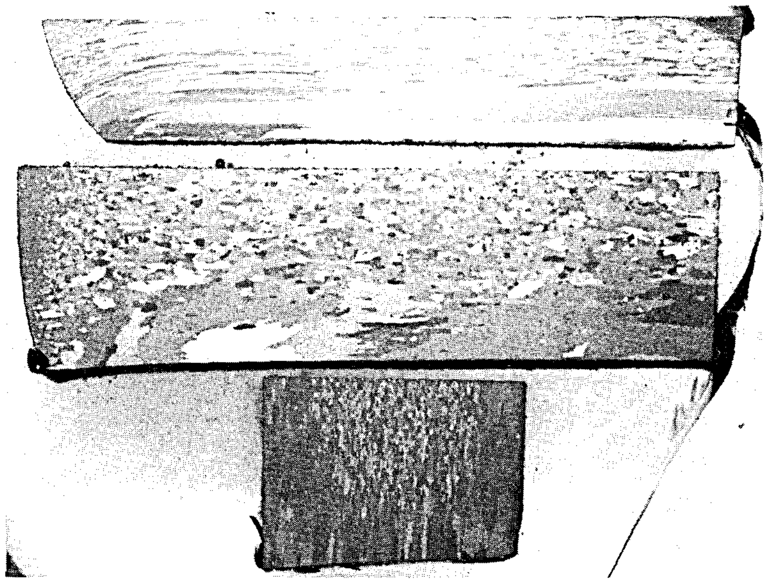


(a) Forging 19, Processing Route 3, Heavy Coating.

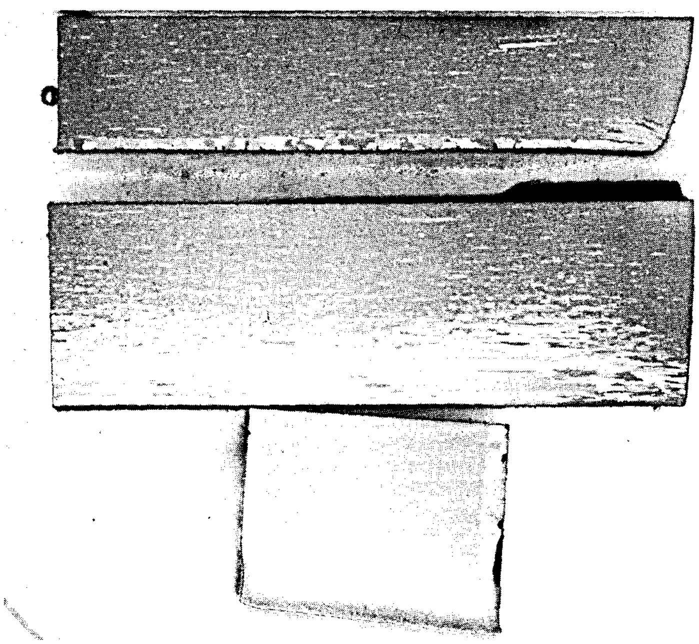


(b) Forging 21, Processing Route 3, Fiberfrax Insulation.

Figure 7. Forgings Used for Evaluation of Coatings and Insulators. All Pieces Forged 35% at 1120°C (2050°F).

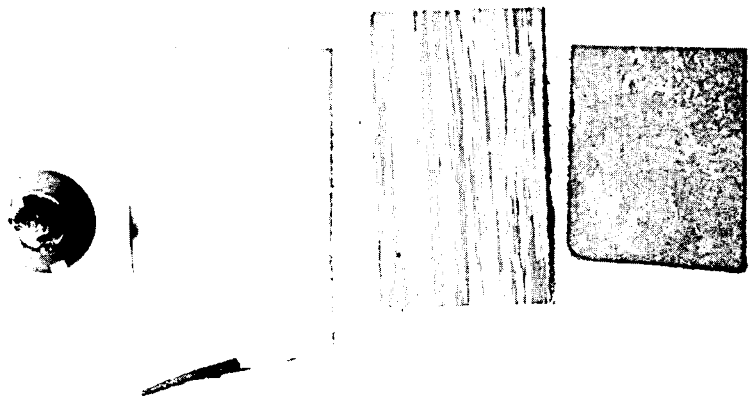


(c) Forging 22, Processing Route 3, Stainless Steel Clad.

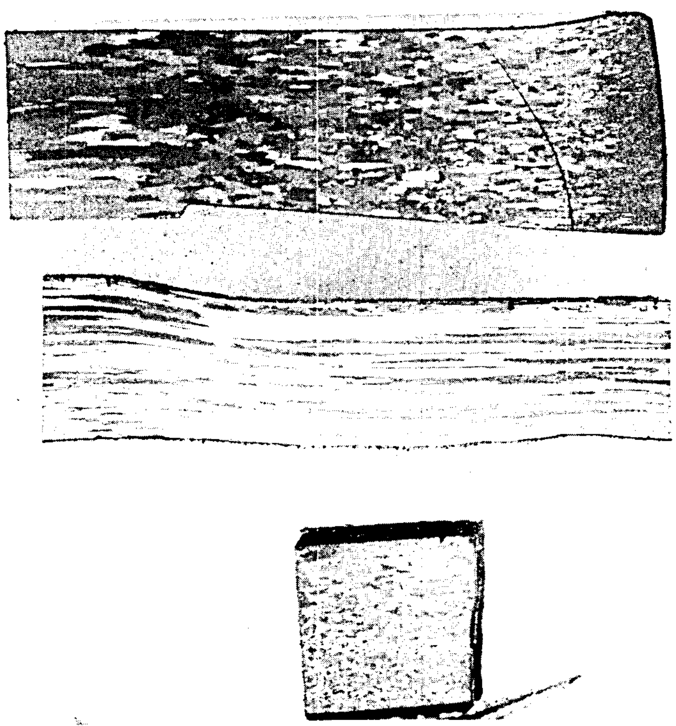


(d) Forging 23, Processing Route 3, Fiberglass Insulation.

Figure 7. Cont'd.

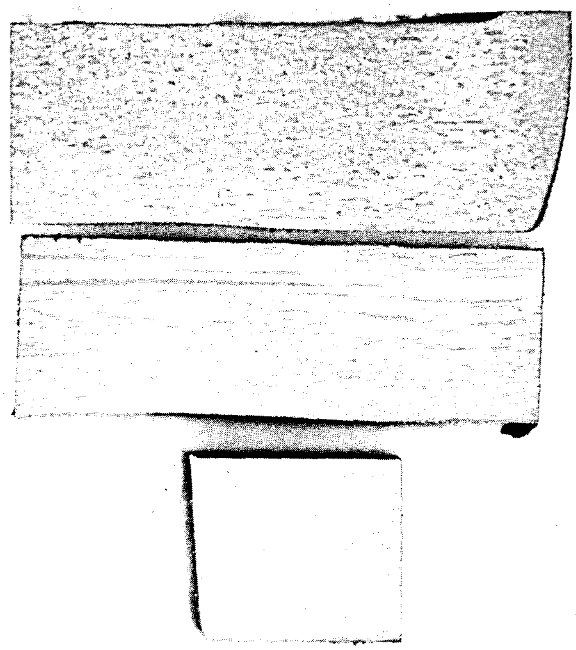


(e) Forging 24, Processing Route 2, CRT Glass Coating.

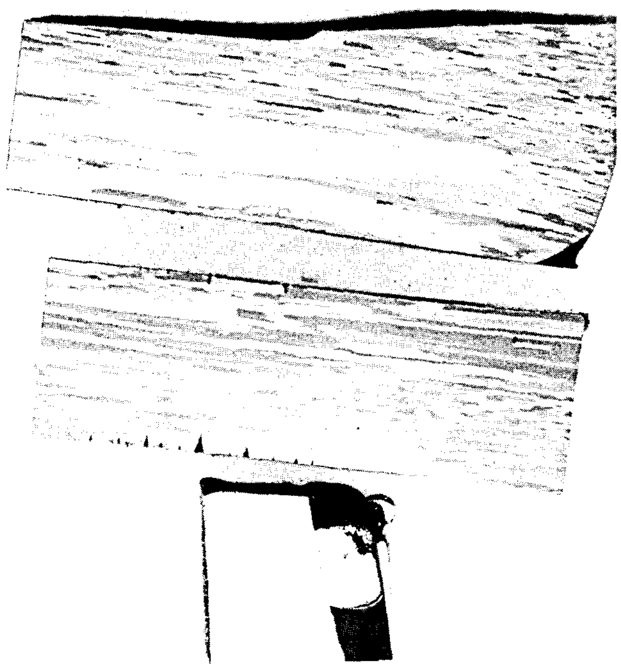


(f) Forging 25, Processing Route 2, Mild Steel Clad.

Figure 7. Cont'd.

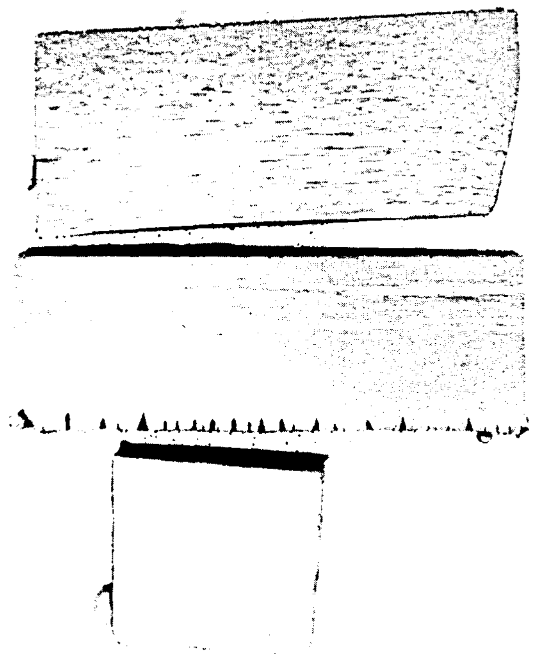


(g) Forging 26, Processing Route 2, Fiberfrax Insulation.



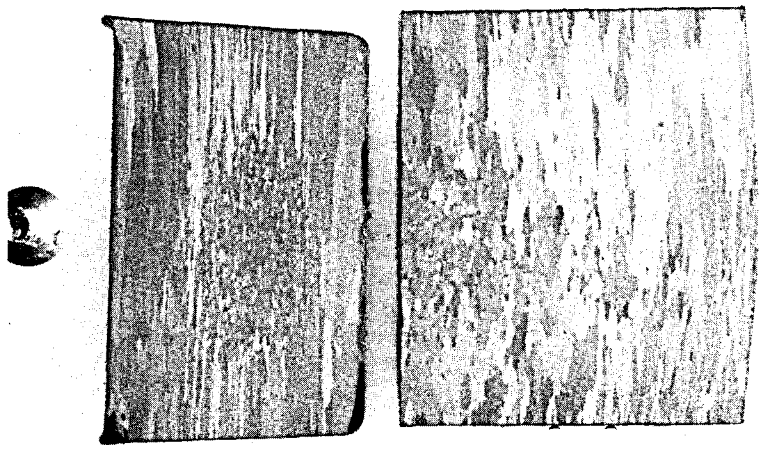
(h) Forging 27, Processing Route 2, Stainless Steel Clad.

Figure 7. Cont'd.

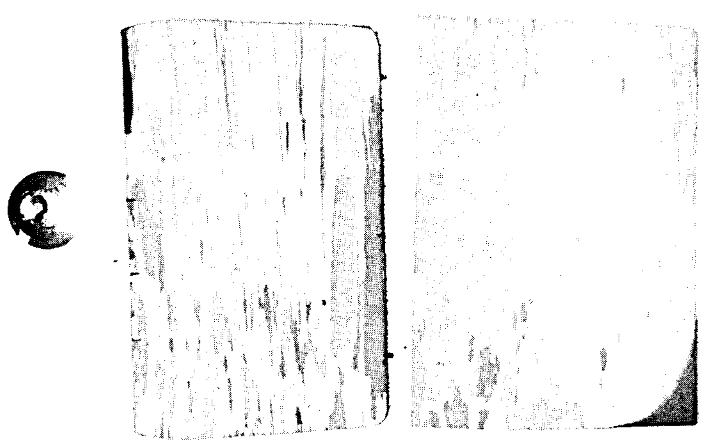


(i) Forging 28, Processing Route 2, Fiberglass Insulation.

Figure 7. Cont'd.



(a) Forging 6, Processing Route 3, Forged 35% at 1120°C (2050°F).



(b) Forging 12, Processing Route 2, Forged 10% at 1065°C (1950°F).

Figure 8. Forgings in Which Flow was Transverse to the Extrusion Direction.

1656-D

TABLE IX

PROCESSING DESCRIPTION AND DIRECTIONAL RECRYSTALLIZATION RESPONSE

Piece No.	Bar Identification	Processing Route No.	Temperature °C (°F)	Reduction %	Lubrication/ Insulation	Area of RX, %	Area of High GAR, %
1	T-86120-3	1	1120 (2050)	10	Regular*	100	25
2	T-86120-D	2	1120 (2050)	10	Regular	100	70
3	Not evaluated - duplicate						
4	T-86120-C1	3	1120 (2050)	35 + 20	Regular	20	10
5	T-86120-C1	3	1120 (2050)	35	Regular	100	90
6	T-86120-C3	3	1120 (2050)	35(trans)	Regular	100	80
7	T-86120-C2	4	1120 (2050)	35	Regular	40	10
8	T-86120-3	1	1065 (1950)	10	No Graphite	100	100
9	Not evaluated - duplicate						
10	T-86120-D	2	1065 (1950)	10	Regular	100	100
11	Not evaluated - duplicate						
12	T-86120-D	2	1065 (1950)	10(trans)	Regular	100	100
13	T-86120-3	1	1010 (1850)	10	Regular	Not DR'ed	
14	T-86120-D	2	1010 (1850)	10	Regular	100	100
15	T-84378-2	(DR)	1205 (2200)	10	Regular	(DR structure retained)	
16	T-84378-2	(DR)	1260 (2300)	10	Regular	(DR structure retained)	
17	T-86120-C1	3	1065 (1950)	10	Regular	100	80
18	T-86120-C2	4	1065 (1950)	10	Regular	40	20
19	T-86120-C1	3	1120 (2050)	35	CRT	100	100
20	T-86120-C1	3	1120 (2050)	35	Mild Steel Clad	Not DR'ed	
21	T-86120-C1	3	1120 (2050)	35	Fiberfrax	100	70
22	T-86120-C1	3	1120 (2050)	35	Stainless steel clad	100	50
23	T-86120-C1	3	1120 (2050)	35	Fiberglass	40	10
24	T-86120-D	2	1120 (2050)	35	CRT	100	100
25	T-86120-D	2	1120 (2050)	35	Mild Steel Clad	100	95
26	T-86120-D	2	1120 (2050)	35	Fiberfrax	100	20
27	T-86120-D	2	1120 (2050)	35	Stainless steel clad	100	50
28	T-86120-D	2	1120 (2050)	35	Fiberglass	20	0

* Regular = sprayed glass coating (1-2 mils) on preform.

4.4.2.1 Effect of Processing Route

The forgings evaluated here were made from MA-6000 blanks produced by four thermomechanical processing (TMP) routes (see Table IV), all of which were capable of good DR response prior to forging. Table X evaluates the four TMP routes by grouping the DR response results of pieces forged similarly. Each line entry in the table is for a similar set of forging parameters. By judging the best and worst responses on each line and noting the corresponding Processing Route, it can be determined that Processing Routes 1, 2, and 3 gave reasonable, and equivalent, DR responses, but that Processing Route 4 gave significantly poorer response. Processing Route 4 was similar to Route 3 except for a 55°C (100°F) higher rolling temperature, 1120°C (2050°F).

4.4.2.2 Effect of Forging Temperature

The effect of forging temperature is analyzed in Table XI which contains the data for pieces forged to a 10% reduction in thickness with "regular" lubrication (sprayed glass coating on workpiece, graphite spray on die). The limited data suggest that 1120°C (2050°F) is excessive for the forging of MA-6000. As will be noted in the next section, however, a greater reduction at this temperature was capable of yielding forgings with good DR response.

4.4.2.3 Effect of Lubrication/Insulation

Coating/insulation effects may be discerned from Table XII which contains data for pieces forged 35% at 1120°C (2050°F), at which temperature cracking was least severe. Processing Route 4 is excluded from this table. The photographs of the sectioned forgings being considered here are presented in Figure 7. Excellent DR response (100/100) was obtained for CRT glass frit coating. Reasonably good results (100/90) were also obtained for regular coating. However, attempts to insulate the bars to alleviate cracking due to die chill degraded the DR response to 100/50 typically, and to 40/10 or worse for fiberglass insulation. This degradation probably is due to enhanced retention of the 1120°C (2050°F) preheat temperature during transfer to the press. As discussed above, this preheat temperature is suspected to be excessive.

4.4.2.4 Effect of Orientation

Two pieces (Forgings 6 and 12) were forged so that flow was transverse to the extrusion direction, Figure 8. The section on the left in the photographs is the extrusion direction-forging direction plane. The right section is the extrusion direction-forging flow plane. Piece 12 was forged 10% at 1065°C (1950°F) and exhibits an excellent structure except for the DR sort-out zone. Piece 6 was forged 35% at 1120°C (2050°F) and exhibits good structure except towards the interior, a behavior similar to the other pieces forged at this temperature. Thus transverse flow does not appear to be harmful to the DR response of MA-6000.

4.4.2.5 Forging of Directionally Recrystallized MA-6000

Two pieces (Forgings 15 and 16) were supplied to TRW prepared by the standard procedure for the production of laboratory MA-6000 bar stock including

TABLE X

DIRECTIONAL RECRYSTALLIZATION RESPONSE: EFFECT OF PROCESSING ROUTE

Route 1		Route 2		Route 3		Route 4	
7:1 Extrusion (only)		14:1 Extrusion (only)		14:1 Extrusion +50%/1065°C (1950°F) Hot Roll		14:1 Extrusion +50%/1120°C (2050°F) Hot Roll	
Piece No.	DRRF	Piece No.	DRRF	Piece No.	DRRF	Piece No.	DRRF
8	100/100	10	100/100	17	100/80	18	40/20
1	100/25	2	100/70				
				5	100/90	7	40/10
		24	100/100	19	100/100		
		28	20/0	23	40/10		
		26	100/20	21	100/70		
		27	100/50	22	100/50		

NOTES: 1) Entries on each line are for similar forging parameters.
2) DRRF (DR Response Factor) is % recrystallized/% high GAR. See text for full explanation.

TABLE XI

DIRECTIONAL RECRYSTALLIZATION RESPONSE: EFFECT OF FORGING TEMPERATURE

1010°C (1850°F)/10%*		1065°C (1950°F)/10%		1120°C (2050°F)/10%	
Pc. No.	DRRF	Pc. No.	DRRF	Pc. No.	DRRF
14	100/100	8	100/100	1	100/25
		10	100/100	2	100/70
		17	100/80		

NOTES: * Thickness reduction.
1) Processing Route 4 not included.
2) DRRF (DR Response Factor) is % recrystallizaed/% high GAR. See text for full explanation.

TABLE XII

DIRECTIONAL RECRYSTALLIZATION RESPONSE:
EFFECT OF COATING/INSULATION

Regular		CRT		Fiberglass		Fiberfrax		Clad	
Pc. No.	DRRF	Pc. No.	DRRF	Pc. No.	DRRF	Pc. No.	DRRF	Pc. No.	DRRF
5	100/90	19	100/100	23	40/10	21	100/70	25(MS)	100/95
		24	100/100	28	20/0	26	100/20	22(SS)	100/50
								27(SS)	100/50

NOTES:
1) Processing Route 4 not included.
2) DRRF (DR Response Factor) is % recrystallized/% high GAR, see text.
3) MS = mild steel; SS = stainless steel cladding material.
4) All pieces forged 35% at 1120°C (2050°F).

zone annealing. These were forged 10% at 1205°C and 1260°C (2200°F and 2300°F), respectively. A coarse, elongated structure was retained by these pieces after forging, Figure 9. No internal grain boundary ruptures were found.

4.4.2.6 Summary of DR Response

Based on the DR analyses, several conclusions can be made of these initial forging efforts. Processing Routes 1, 2, and 3 all seem capable of good DR response after forging. These processing routes include small-scale, low-extrusion-ratio bar stock; large-scale, moderate-extrusion-ratio bar stock; and bar stock similar to the latter rolled 50% at the temperature normally employed for the production of large-scale MA-6000 bar stock. The failure of Processing Route 4, which involved a higher rolling temperature, suggests that, of the two primary factors in thermomechanical processing, temperature is the more critical for MA-6000. Although 1120°C (2050°F) appears to yield forgings with the least amount of cracking tendencies, the temperature is excessive and is very near a critical threshold for subsequent proper DR response. Some forging flow transverse to the extrusion direction does not appear to harm DR response.

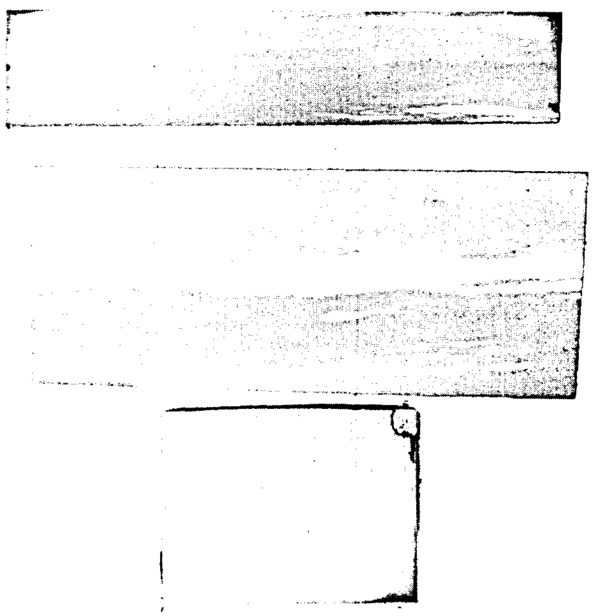
4.5 Third Forging Trial

Additional forging trials to evaluate the effects of forging zone-annealed material from Processing Routes 2, 3, and 4, as described in Table IV, were being planned at this time. However, a third forging trial was performed to evaluate some potentially insulative coatings to prevent die chill and subsequent cracking during forging. Table XIII lists the third forging trials.

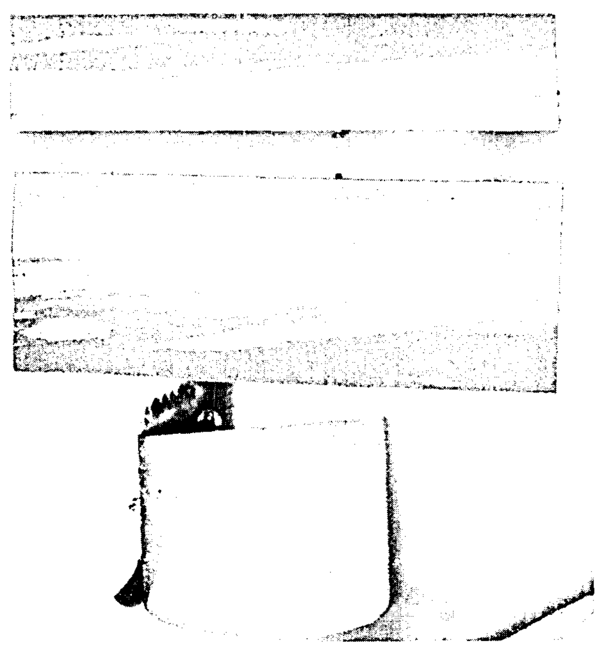
Most of the trials were conducted with material from Processing Route 4 since the material was previously found to be of little value because of its lack of response to directional recrystallization (DR) after forging. Forging of this material would indicate the direction in which to proceed for further trials. Pieces were charged into an electrically heated box furnace and heated at temperature for 25 minutes. The die was heated to about 260°C (500°F). Coating and lube practices are shown in Table XIII. Forging was conducted on a 700-ton mechanical press.

Results of these trials indicate that, for those preforms coated with glass, specimens 4-1 through 4-3, severe cracking on punch and die sides was observed on the forged pieces. Unrecrystallized material forged with at least two types of insulative material, specimens 4-4 through 4-6 and 4-9, showed significant improvements in surface condition. Only a few edge cracks were observed for each condition. Recrystallized material forged similarly, specimens 4-7 and 4-8, were found to have a craze cracking pattern on the surface. The MA-6000 forgings are shown in Figure 10.

The results again indicate that the better the insulative properties of the coating, the more promising the results; however, the more complex the coating practice becomes, the higher the processing costs. It was becoming quite obvious that conventional forging probably will not be appropriate for MA-6000 for producing a net-shape airfoil if heavy coatings or insulative materials are required; however, if the material could be formed to a near-net shape, significant improvements in material utilization and thus cost reduction could be



(a) Forging 15, Forged 10% at 1205°C (2200°F).



(b) Forging 16, Forged 10% at 1260°C (2300°F).

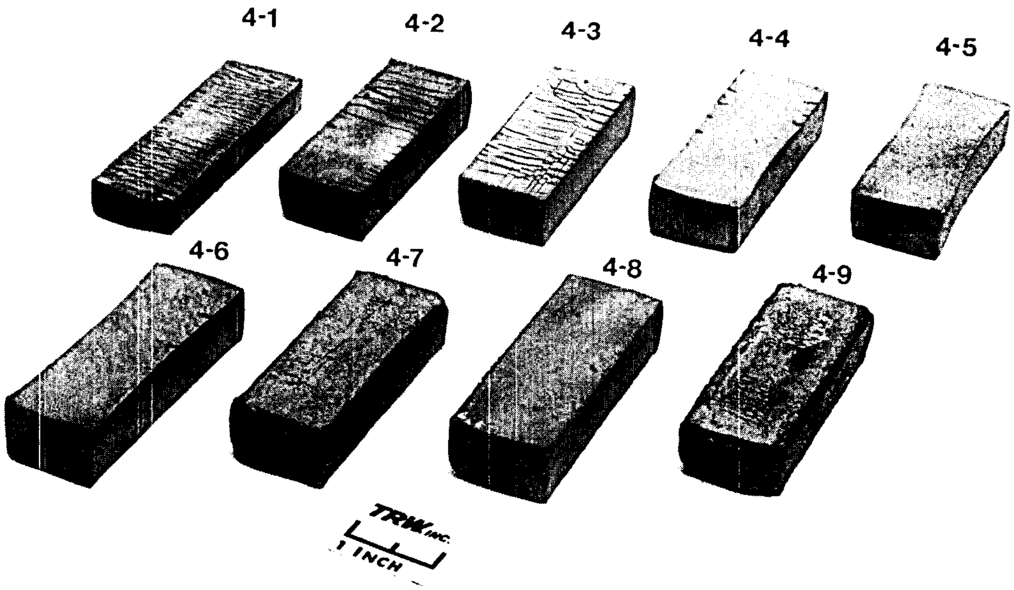
Figure 9. Pieces Forged from Directionally Recrystallized Barstock.

TABLE XIII

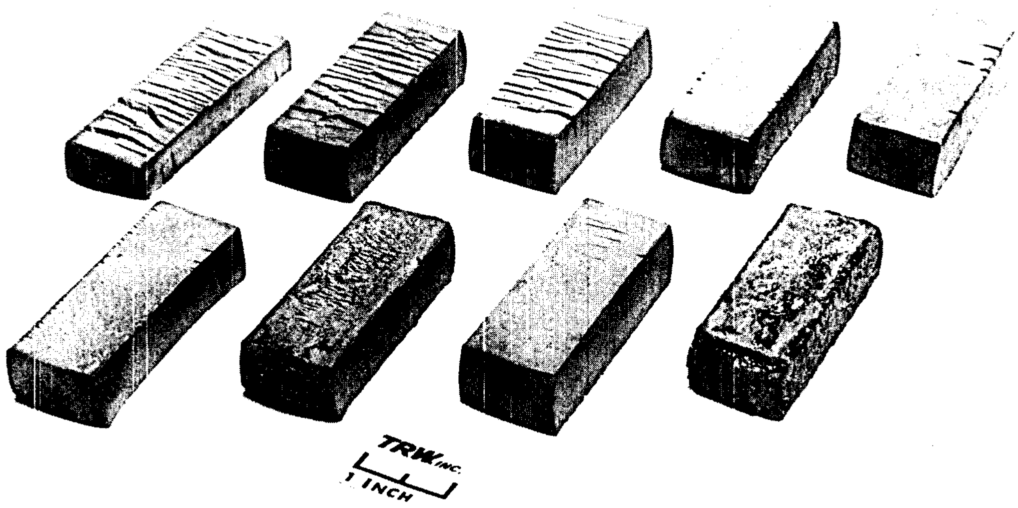
THIRD SERIES OF FORGING TRIALS*

Forging Number	Processing Route - Orientation	Forging Temp. °C (°F)	Comments
4-1	1 - L	1065(1950)	PK glass coating. Severe cracks on punch and die sides.
4-2	4 - L	1065(1950)	DM-1 glass coating (high-silica content). Severe cracks on punch and die sides.
4-3	4 - L	1065(1950)	CRT glass coating. Severe cracks on punch and die sides.
4-4	4 - L	1065(1950)	CRT/Fiberfrax/CRT. Some edge cracks.
4-5	4 - L	1065(1950)	Kaowool sheet/CRT. Some edge cracks.
4-6	4 - L	1065(1950)	Fiberfrax/Fiberfrax/CRT. Some edge cracks.
4-7	4 - L(DR)**	1205(2200)	Fiberfrax/CRT. Surface crazing.
4-8	4 - L(DR)	1260(2300)	Fiberfrax/CRT. Surface crazing.
4-9	4 - L	1065(1950)	Ceramic Slurry/CRT. Some edge cracks.

* Nominal reductions during forging 35%.
** (DR) - directionally recrystallized prior to forging.



Die Side Up



Punch Side Up

Figure 10. Third Series of Forging Trials - MA-6000 Forgings. See Table XIII for Forging Conditions.

achieved. The most obvious approach appeared to be to forge MA-6000 with the can material from the extrusion left intact. It was thought that the can material would be an ideal insulator because of IRDC's success in rolling the material with the can left intact. These observations led to the fourth forging campaign. Forging of recrystallized material as previously planned appeared to be of little value at this time.

4.6 Fourth Forging Trial

4.6.1 Forging Trials

At this time, TRW requested from IRDC an additional six pieces of MA-6000 with the mild steel material used to can the powder prior to extrusion left intact. The thickness of the mild steel was approximately 2 mm (0.1 in) for the six pieces supplied by IRDC.

Four of these pieces were processed similar to the Processing Route 1 material supplied previously (89 mm (3.5 in) diameter can), extruded to 1010°C (1850°F) through a 25 x 32 mm (1.0 x 1.25 in) die. IRDC reported that the material was virtually impossible to cut with abrasive wheels without cracking, as has been noted before for unrecrystallized MA-6000, particularly for unpickled bars. The shipped pieces (two labeled T-87092 and two labeled T-86378-4) contained cracks of undetermined depths at one or both ends, being more severe for the former heat listed. Two pieces (T-86378-4) were also supplied in the directionally recrystallized condition. Pieces cut after directional recrystallization appeared to be crack-free on the ends.

The fourth forging trial plan and results are shown in Table XIV. The MA-6000 forgings are shown in Figure 11 after pickling to remove the mild steel can. The average thickness of the mild steel after a forge reduction of 35% was 1.3 mm (0.051 in) and after a forge reduction of 60% was 0.9 mm (0.036 in). The surface condition after forging and pickling was found to be excellent except for some cracks observed near the ends of the forgings reduced 60%. It should be noted that these two preforms also exhibited cracks at the ends as a result of the abrasive cutting. The results were quite encouraging, and the forgings were sent to IRDC for zone annealing (if required) and macrostructure evaluation.

4.6.2 Directional Recrystallization Response

The forgings from the fourth forging campaign were directionally recrystallized by IRDC, and the resulting macrostructure was evaluated. The six forged pieces were cut transversely to yield two symmetrical halves. The furnace travel direction was such that the recrystallization front moved from the original end of the bar to the cut end (middle of forging). The pieces were then sectioned longitudinally to reveal the extrusion direction-forging direction plane. A transverse specimen was obtained from one half near the end of the complete forging. The transverse and longitudinal sections were mounted, polished, and macroetched (49% HCl, 49% H_2O, 2% H_2O_2).

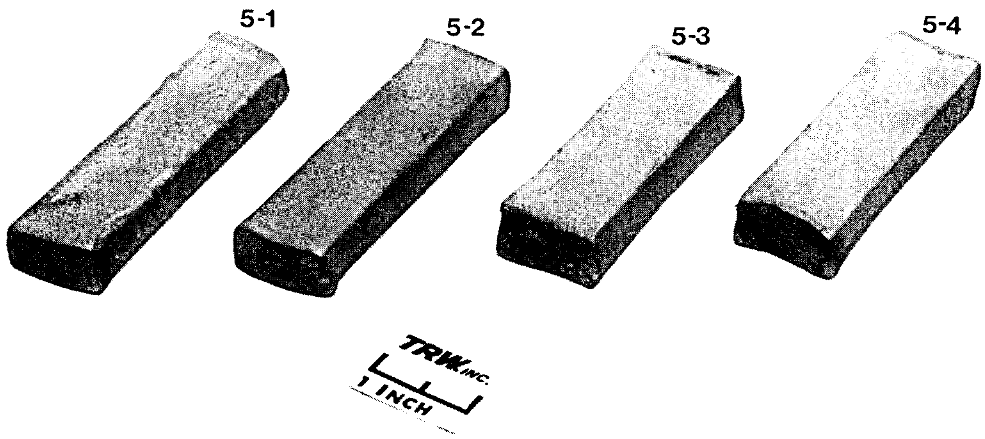
The four pieces forged in the unrecrystallized fine-grained condition were found to recrystallize completely upon directional recrystallization (DR). The macrostructures after DR are shown in Figure 12. Three recrystallized to the

TABLE XIV

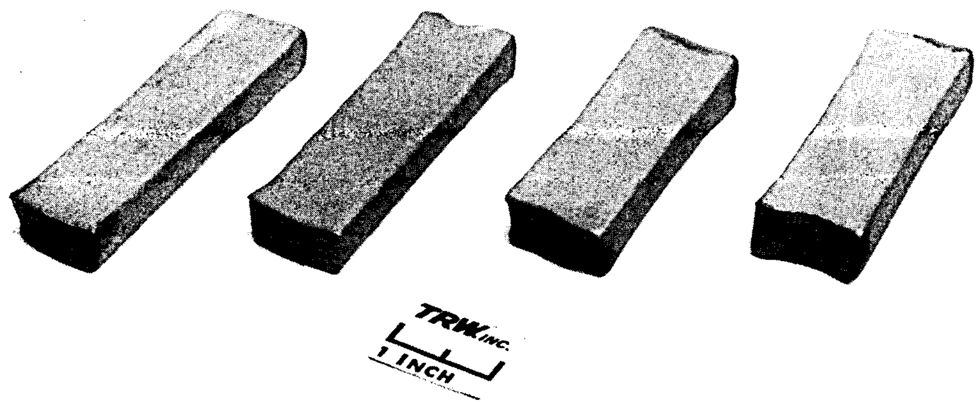
FOURTH SERIES OF FORGING TRIALS

Forging Number	Processing Route - Orientation	Forging Temp. °C (°F)	Nominal Reduction %	Comments
5-1	1 - L	1065(1950)	35	No cracks observed.
5-2	1 - L	1095(2000)	35	No cracks observed.
5-3	1 - L(DR)	1205(2200)	35	No cracks observed.
5-4	1 - L(DR)	1260(2300)	35	No cracks observed.
5-5	1 - L	1065(1950)	60	Surface cracks near ends on punch side.
5-6	1 - L	1095(2000)	60	Surface crack on end.

* All preforms forged with mild steel can left intact and coated with glass composition CRT.



Die Side Up



Punch Side Up

a. Forging Reduction 35%.

Figure 11. Fourth Series of Forging Trials - MA-6000 Forgings after Pickling. See Table XIV for Forging Conditions.

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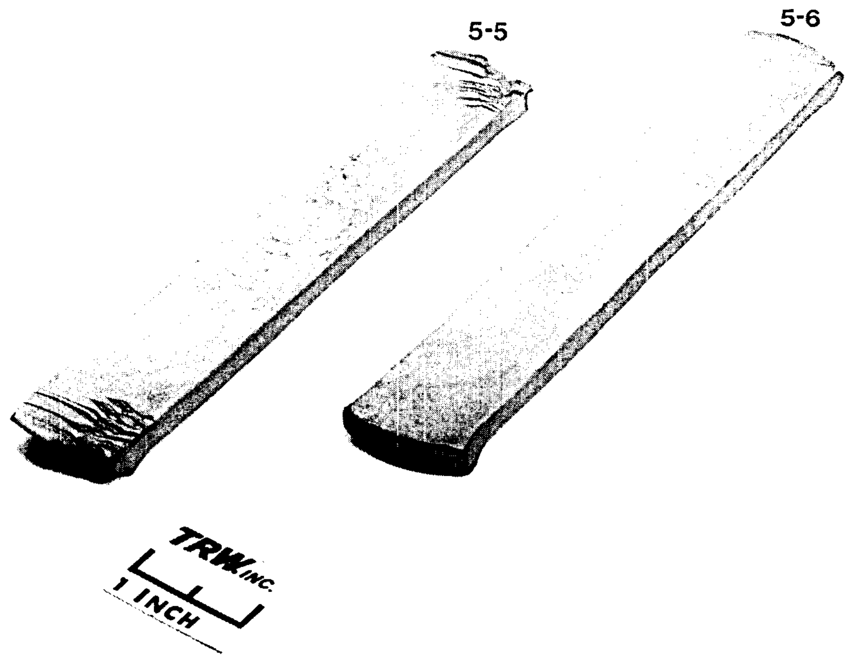
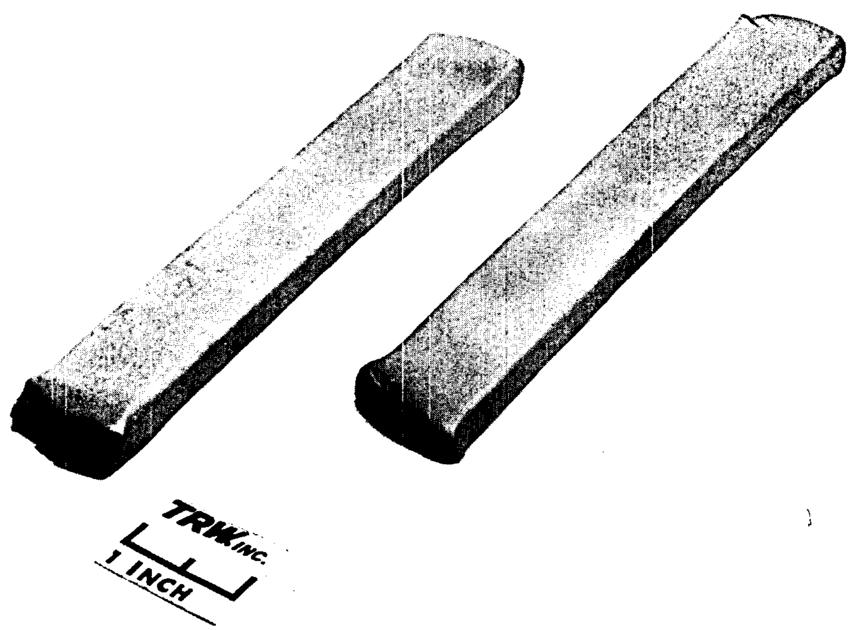


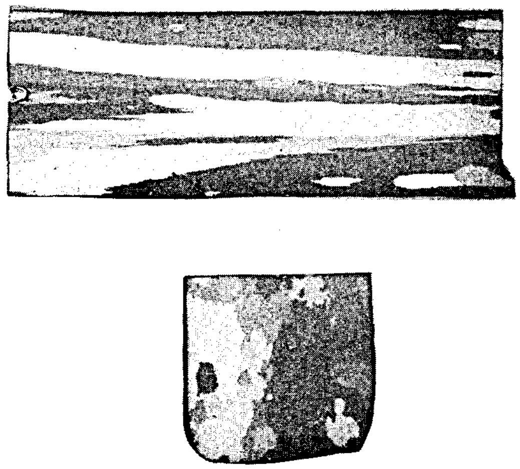
Die Side Up



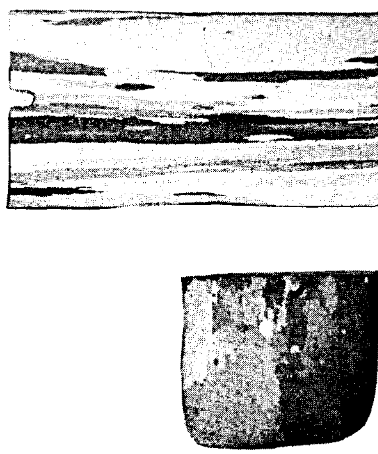
Punch Side Up

b. Forging Reduction 60%.

Figure 11. Cont'd.

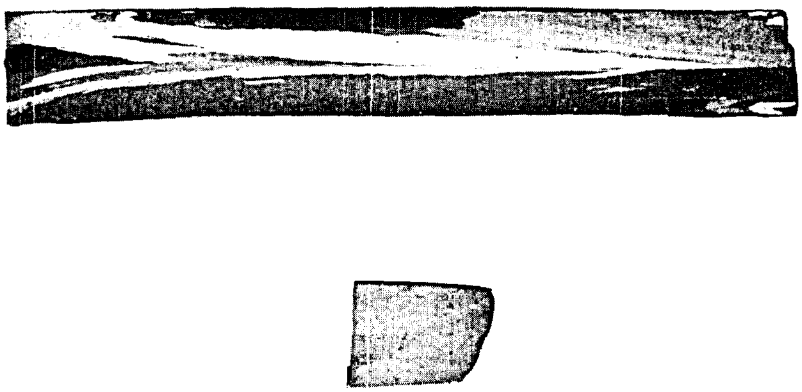


(a) 5-1, 35% Reduction at $1065^{\circ}C$ ($1950^{\circ}F$).

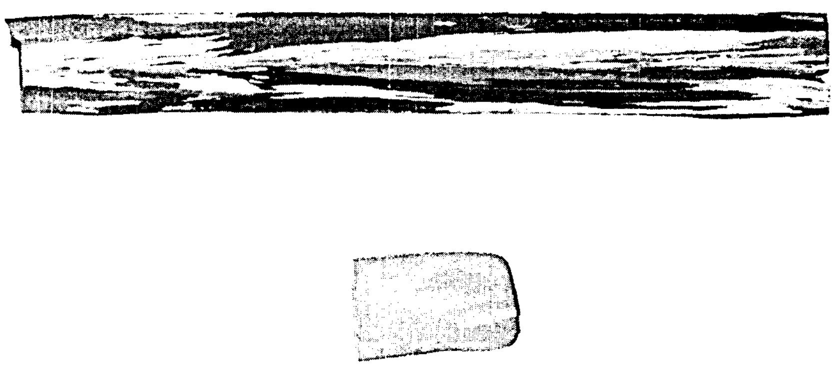


(b) 5-2, 35% Reduction at $1095^{\circ}C$ ($2000^{\circ}F$).

Figure 12. Longitudinal and Transverse Macrostructures of Canned MA-6000 Forged in Unrecrystallized Condition. Directional Recrystallization Proceeded from Notched End. ~2X



(a) 5-5, 60% Reduction at 1065°C (1950°F).



(b) 5-6, 60% Reduction at 1095°C (2000°F).

Figure 12. Cont'd.

desired coarse, elongated grain structure; a fourth (Forging 5-6) exhibited a relatively fine-grained structure having a generally low grain aspect ratio (GAR). The latter piece received the greater reduction (60%) at the higher forging temperature (1095°C (2000°F)). Adiabatic heating possibly could have raised the actual forging temperature to an excessive level. Previous results at higher forging temperatures were found to be unacceptable.

Some non-optimum features were observed for these forgings. The incidence of grains having low GAR is related mostly to powder quality and the low extrusion ratio used to produce these bars (7.2:1). The "flaring" of the grains of the pieces given a 60% reduction may also be related to powder quality and extrusion, but seems to reflect the forging deformation pattern.

Two canned pieces were forged in the recrystallized (zone annealed) state at 1205 and 1260°C (2200 and 2300°F). Unlike similar forgings at 10% reduction performed previously, these 35% forgings exhibit a degraded grain structure; transverse sections have a feathery appearance overlying what would appear to be as-directionally recrystallized grains. This feature suggests that additional recrystallization occurred during or shortly after forging. Moreover, a 3 mm (0.12 in) long crack is apparent in one of the transverse sections of Forging 5-3. Macrostructures of these forgings are shown in Figure 13.

4.6.3 Mechanical Property Response

Since the effect of the forging on mechanical properties was not known at this time, the remaining portion of Pieces 5-5 and 5-6 were machined into test specimens. As previously noted, these pieces were forged 60% at 1065 and 1095°C (1950 and 2000°F), respectively. Piece 5-6 had a poor grain structure (many low GAR grains) due to the high forging temperature. Piece 5-5 also had a non-optimum structure (flared grains).

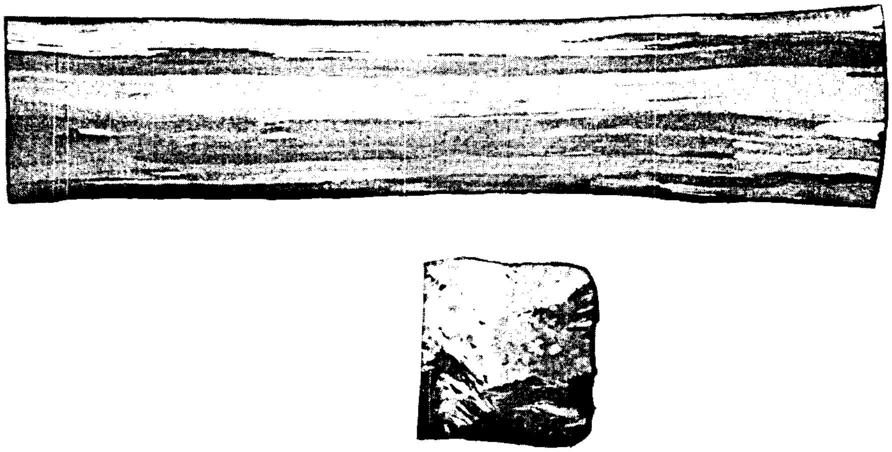
The stress rupture test specimens had gage dimensions of 3.48 mm (0.137 in) diameter and 20 mm (0.80 in) length. Tests were performed in air at 1095°C (2000°F). Results are presented in Table XV. As expected, Piece 5-5 had greater rupture strength than 5-6, but neither surpassed the normal acceptance criteria of 100 hours at 138 MPa (20 ksi). Piece 5-5 had an estimated 100-hour strength of 126 MPa (18.2 ksi), which is quite good considering the grain structure. Rupture ductility remained at normal levels for MA-6000.

The results of the fourth forging campaign indicated that forging of unrecrystallized canned MA-6000 appears promising; forging recrystallized, canned MA-6000 to high reductions appears to degrade the grain structure and may cause internal cracking; and forging temperatures for MA-6000 probably should not exceed 1065°C (1950°F).

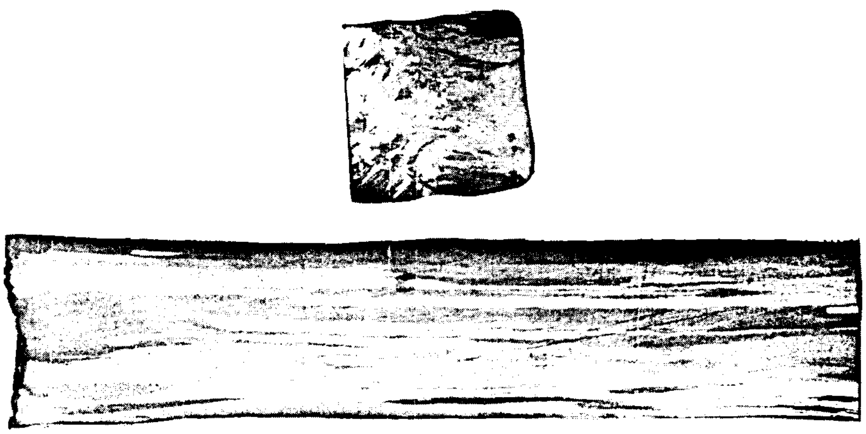
4.7 Fifth Forging Trial

4.7.1 Forging Trials

In preparation for proceeding into the blade forging task, a fifth and final forge campaign was conducted to identify additional processing guidelines. Variables considered were multiple strike (with reheat), step-forge (interface



(a) 5-3, 35% Reduction at 1205°C (2200°F).



(b) 5-4, 35% Reduction at 1260°C (2300°F).

Figure 13. Longitudinal and Transverse Macrostructures of Canned MA-6000 Forged in Recrystallized Condition. ~2X

TABLE XV

1093°C (2000°F) RUPTURE STRENGTH OF CANNED FORGINGS

Test No.	Piece No.	Forging Temperature °C	(°F)	Forging Reduction %	Stress MPa	(ksi)	Life Hours	% El	% RA
40477	5-5	1065	(1950)	60	138	(20)	17.5	3.8	12.2
40478	5-5	1065	(1950)	60	124	(18)	120.7	2.5	11.0
40479	5-6	1095	(2000)	60	138	(20)	1.6	5.0	23.1
40480	5-6	1095	(2000)	60	124	(18)	36.2	3.8	15.0

with different degrees of work), thick 2.5 (0.1) versus thin 0.5 (0.02) mm (inches) mild steel can condition, single reductions as high as 70% and forging temperatures as low as 1038°C (1900°F). The fifth forging trial schedule is shown in Table XVI. Forging was conducted using conditions similar to those previously discussed. There was no evidence of surface tearing or cracking as was observed for material forged previously without the mild steel can. The forgings are shown in Figure 14. Restrikes, step-forging, forging material with a thin can, higher reductions, and lower forging temperatures had no obvious effect on material processibility. After forging and removal of the mild steel can, it was apparent that material with reduced can thicknesses degraded surface quality, but did not lead to cracking.

4.7.2 Directional Recrystallization Response

The four forgings given uniform reductions were cut transversely into two halves. The forgings that were placed halfway into the die, resulting in a non-uniform reduction with gradual transitions from the reduced sides to the sides left unstruck (referred to as step-forged), were not cut for DR.

All six forgings were directionally recrystallized (DR). The recrystallization direction was from the original ends inward for the case of the simple forgings and from the unstruck ends inward of the step forgings. The latter was meant to be analogous to recrystallization starting at the root section of a forged blade. For the latter, it would seem preferable to have grains blend into the airfoil section rather than have new grains nucleating along the sides of the transition, which conceivably might occur if DR proceeded from the airfoil into the root. After DR, each forging was sectioned lengthwise to reveal the forging direction/extrusion direction plane from which grain aspect ratio is best judged. All six forgings recrystallized completely to reasonably good structures except as noted below.

Piece 6-3 received two 35% reductions at 1065°C (1950°F) for a total of 60% reduction. The structure after DR is similar to Piece 6-4 that received a single 60% reduction, except for an apparent "renucleation boundary" near the end, Figure 15(a). This type of feature will be discussed further below.

The can of Piece 6-4 was deliberately reduced to 0.5 mm (0.02 in) at TRW to determine the effect of can thickness. One side of all of the pieces used in the fifth forging campaign were already thin due to an extrusion problem at IRDC. For Piece 6-4, both sides, rather than just one, exhibited a degraded surface after forging to a 60% reduction at 1065°C (1950°F). No cracking occurred except at the very ends and at an apparent blemish. The DR'd structure, Figure 15(b), shows a tendency towards inward flaring plus a few "bulbous" grains. The latter was observed to some extent in all the forgings performed at 1065°C (1950°F). This is probably attributable to the low extrusion ratio employed and the absence of a hot rolling operation in the production of the blanks.

Piece 6-6 was forged 60% at a lower temperature than the others (1038°C (1900°F)). After DR, the structure consisted of larger grains than the others, with a reduced tendency for flared or bulbous grains, Figure 15(c).

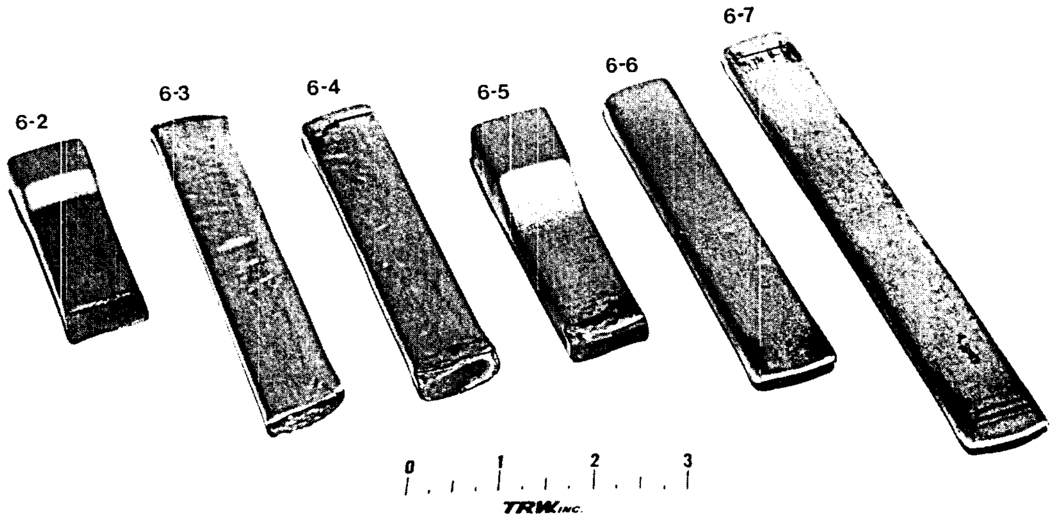
A 70% reduction in one strike was performed on Piece 6-7. A high grain

TABLE XVI

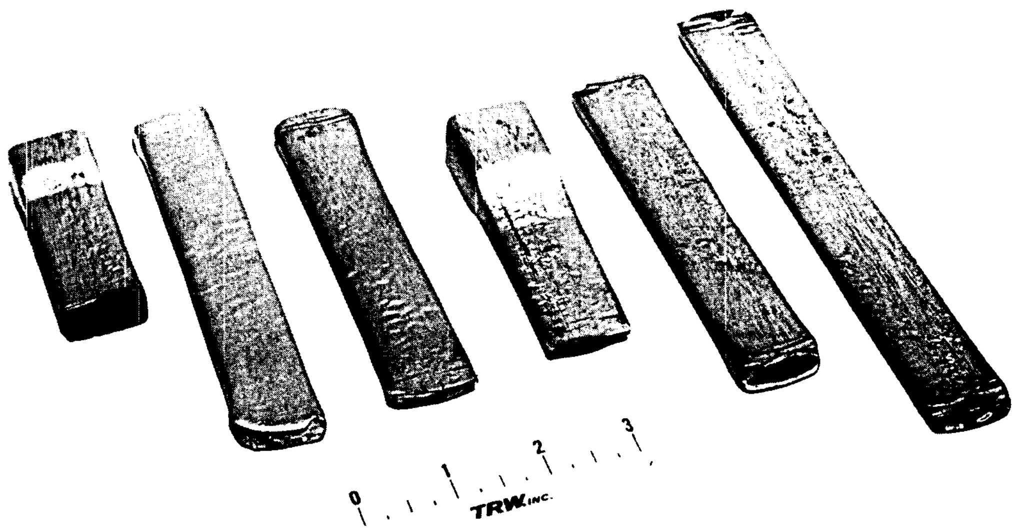
FIFTH SERIES OF FORGING TRIALS*

Forging Number	Processing Route - Orientation	Forging Temp. °C (°F)	Nominal Reduction %	Comments
6-1	1 - L	1065(1950)	35	See 6-3.
6-2	1 - L	1065(1950)	35	Step-forged.
6-3	1 - L	1065(1950)	60	Restrike of 6-1 60% total reduction.
6-4	1 - L	1065(1950)	60	0.020 inch thick can.
6-5	1 - L	1065(1950)	60	Step-forged.
6-6	1 - L	1038(1900)	60	
6-7	1 - L	1065(1950)	70	No surface cracks observed.

* All preforms forged with mild steel can left intact and coated with glass composition CRT.



Die Side Up



Punch Side Up

Figure 14. Fifth Series of Forging Trials - MA-6000 Forgings. See Table XVI for Forging Conditions.

(a) 6-3, 60% Total Reduction at 1065°C (1950°F)

(b) 6-4, 60% Reduction at 1065°C (1950°F)

(c) 6-6, 60% Reduction at 1038°C (1900°F)

(d) 6-7, 70% Reduction at 1065°C (1950°F)

Figure 15. Macrostructure of MA-6000 Forgings. Recrystallization Direction was Left to Right. 1X

aspect ratio structure was obtained after DR, see Figure 15(d). However, a "wavy" appearance not observed in hot rolled bar is apparent.

All forgings discussed above, except for the 70% reduced forging, have multiple low aspect ratio grains near the cut ends, which were originally the center of the forgings. It is not known whether this is due to a dead zone of deformation or due to the reduction of thermal gradient and increase of recrystallization front velocity that occurs at the end of a bar being zone annealed.

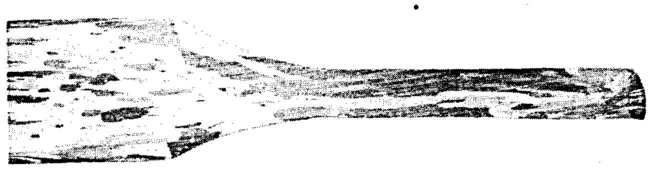
Pieces 6-2 and 6-5 were step-forged to 35% and 60% reductions, respectively (Figure 16). While all areas of each recrystallized to coarse, elongated grains, an interesting feature is observed at what appears to be a boundary separating the forging deformation zone and the parent extrusion deformation zone. An entirely new set of grains nucleated at this boundary, implying that the boundary is a set of connected transverse grain boundaries. It is thought that this feature arises from slightly different recrystallization temperatures on either side of the boundary (lower on the forged side). Thus, as the recrystallization front proceeded toward this boundary from the as-extruded side, the recrystallization temperature of the forged side was reached before the arrival of the original front. By the time the latter reached the boundary, a new front had nucleated and grown. According to this theory, the boundary would not be observed if DR were performed in the opposite direction. An alternative explanation is that the deformation zone boundary itself somehow impedes the growth of recrystallized grains. In any case, a renucleation boundary might be discouraged by including a finish forge operation that deformed the entire workpiece. The forging route planned for would have a total workpiece deformation during preform and finish forge operations, although the degree of deformation would vary along the blade length.

4.8 Acceptable Forging Process Practice

The results of the five forging campaigns led to a set of forging guidelines for use in the blade forging task. These results indicated that the following forging process variables should be used by TRW for IRDC supplied MA-6000 bar:

Preform Material:	As-extruded and rolled MA-6000 bar processed by IRDC's current practice.
Coatings:	Mild steel can, left intact from IRDC processing, and preform coated with a commercial glass recommended for the proposed forging temperature.
Tooling:	Hot work tool steel heated to a range of 150-260°C (300-500°F).
Forge Temperature:	The forge temperature shall not exceed 1065°C (1950°F).
Forge Reduction:	Forging reductions up to 70% per blow are currently acceptable.

(a) 6-2, Right Side Reduced 35%.



(b) 6-5, Right Side Reduced 60%.

Figure 16. MA-6000 Step-Forged by Placing Only Half of Blank into Straight-Sided Die. Forging Temperature was 1065^{o}C (1950^{o}F). Recrystallization Direction was Left to Right. 1X

2162-0

5.0 TASK II - TURBINE BLADE FORGING DEVELOPMENT

The task objective was to fabricate blade shapes having mechanical properties approaching those found in extruded, hot-rolled bar after both have been recrystallized and heat treated. The thermal-mechanical-processing schedule developed in Task I was to be applied to the fabrication of turbine blade hardware.

5.1 Turbine Blade Design Selection

The blade design selected to demonstrate the capability of hot forging turbine blades from MA-6000 was General Electric's first stage CF6-80 air-cooled turbine blade. Some of the design features are shown in Figure 17. The blade has an overall length of 109 mm (4.29 in), the maximum chord width is 39 mm (1.54 in), and the span is 59 mm (2.34 in). The blade, normally a casting, is shown in Figure 18.

5.2 Forged Blade and Tooling Designs

The preform and finish forge blade design considerations included allowance of a 1.57 mm (0.062 in) envelope for the blade to insure enough stock was available for removal of the mild steel can after forging and finish machining of the airfoil by a conventional or non-conventional (electrochemical machining) process. The tooling designs also did not allow any lateral flow in the airfoil section in order to retain the desired grain structure established during processing of the starting slug material. This design is unique compared to standard airfoil forging practices which allow flash to be formed at the leading and trailing edges. To accommodate small variances in slug volume, the material was allowed to flow freely and directionally along the blade axis towards the blade tip. Essentially, the excess airfoil length can be considered as flash.

Based on the excellent workability of the MA-6000 with the can left intact, a two-step processing sequence was established. Volume calculations performed indicated that a starting slug of 127 cu. cm (7.76 cu. in) would be required to produce the selected blade design. The slug dimensions are shown in Figure 19. The initial forging step, preform forge, reduced the slug a maximum of 50% in the airfoil section. The second and final forging step reduced the preform to the required finished forged blade dimensions. A sketch of the forging sequence is shown in Figure 20.

5.3 MA-6000 Blade Material

TRW requested IRDC to roll 60-90 cm (2-3 ft) of MA-6000 material for initial tool trials. Required material 38 mm (1.5 in) in height by 43 mm (1.7 in) in width was supplied along with some off-dimension material 39 mm (1.54 in) in height by 40 mm (1.57 in) in width to be used for die setup. Enough material was received from IRDC to cut eight preforms of each size. Preform blanks of the required size had been previously machined from low carbon steel by TRW for the first tool setups and forging trials.

After the first forging trial, TRW requested IRDC to finish roll the

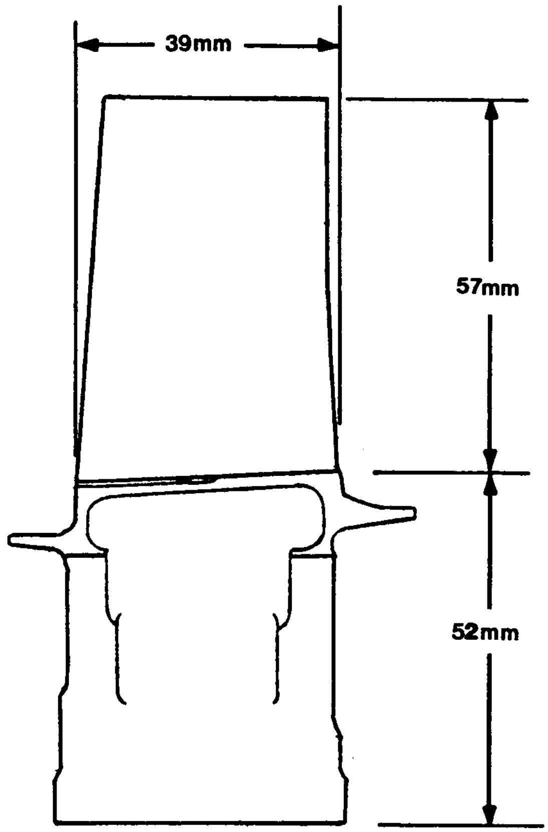


Figure 17. External Contour of Demonstration Blade - First Stage CF6-80.

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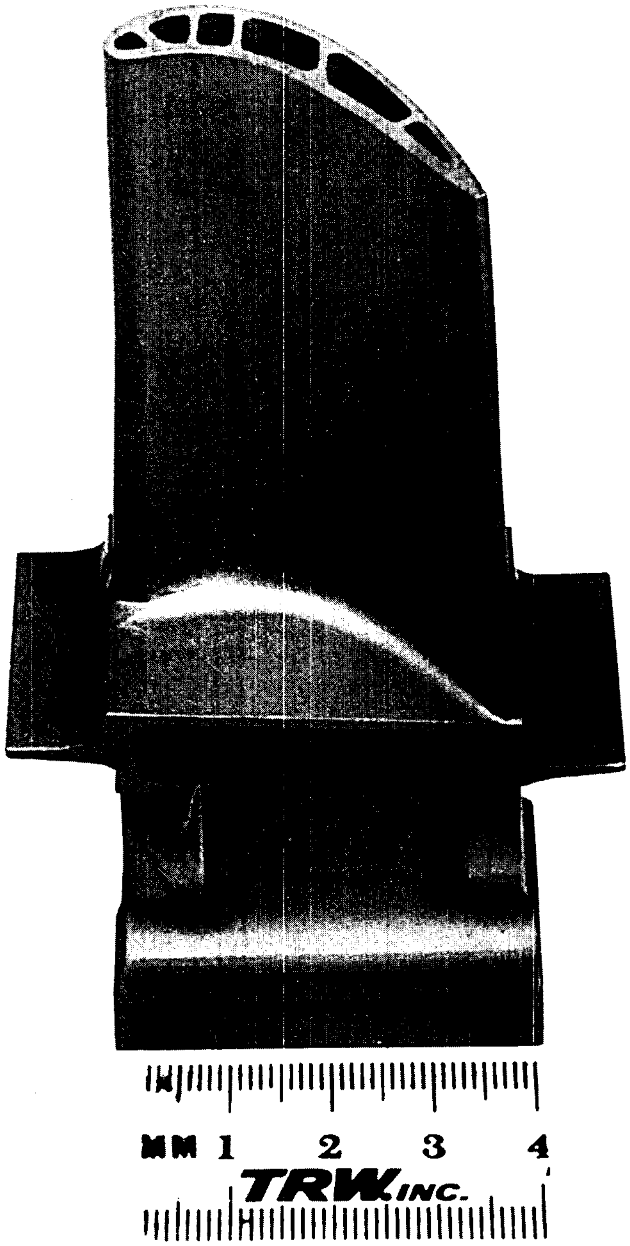


Figure 18. Blade Design Selected for Blade Forging Task.

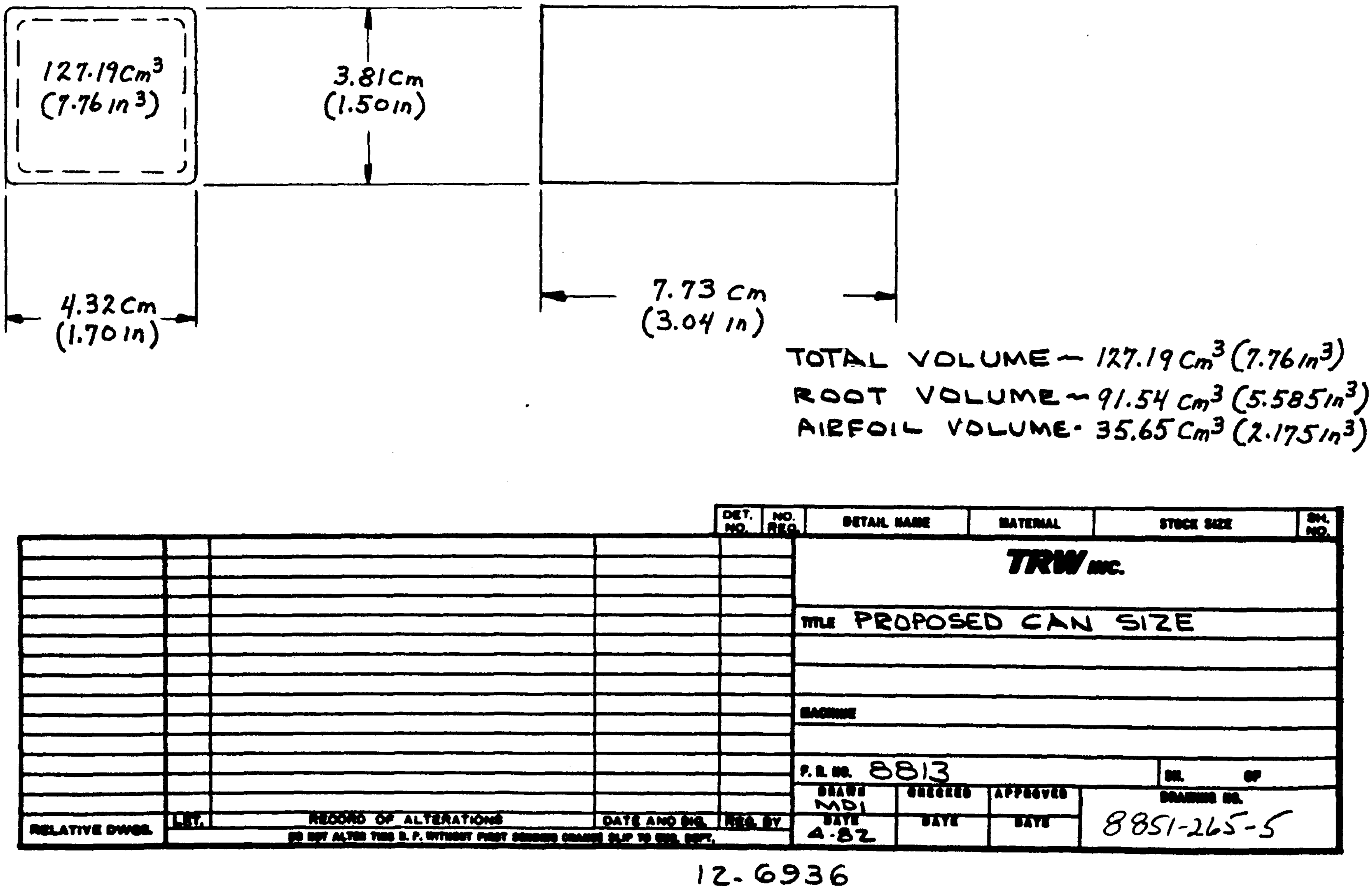


Figure 19. Starting MA-6000 Slug Preform for Blade Forging Task.

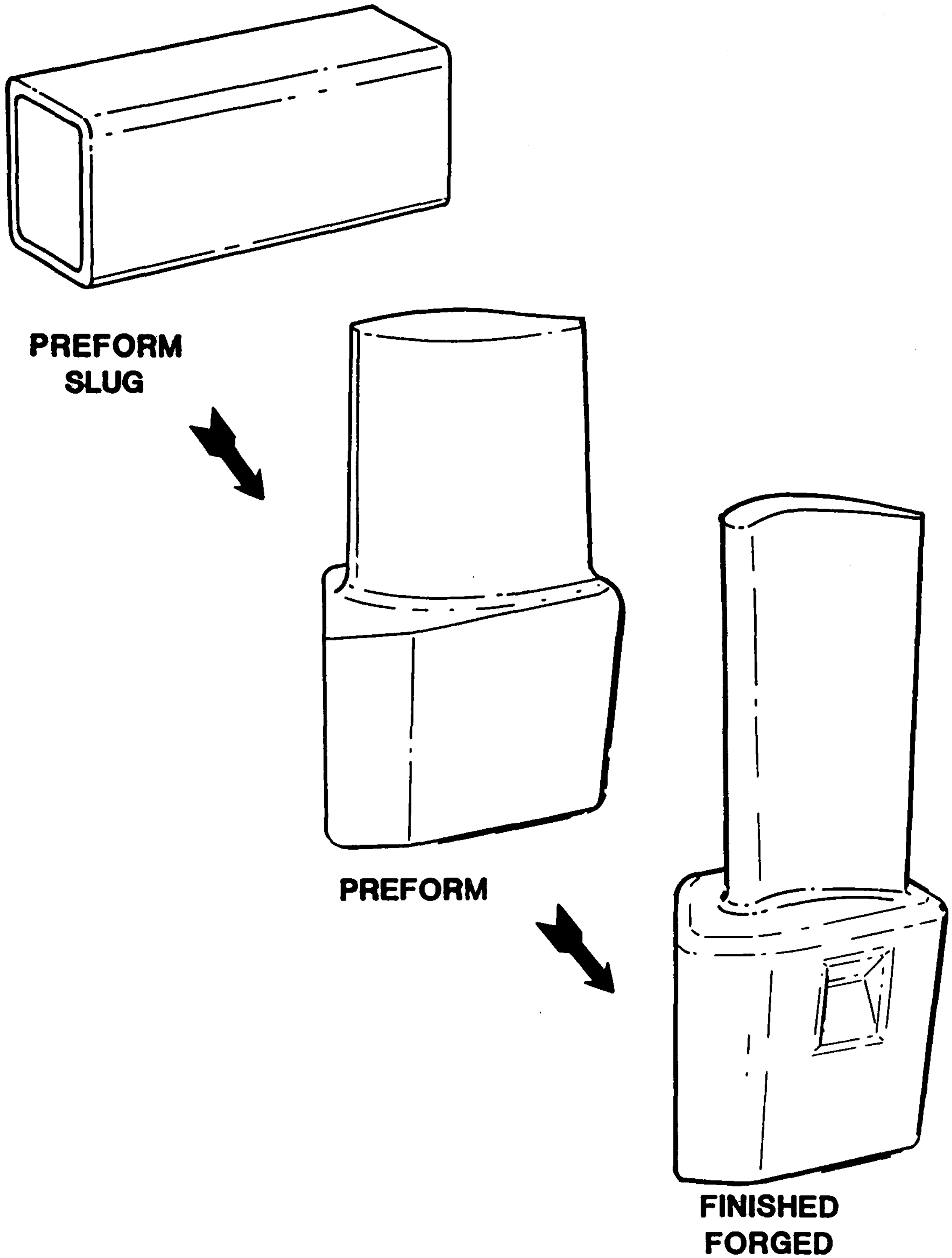


Figure 20. Forging Sequence Sketch for MA-6000 Blade Forging Task.

2624-D

remaining MA-6000 material to the required preform bar dimensions such that a total of 100 preforms were available for the blade forging effort. Material for this effort was prepared by IRDC as discussed in Section 4.1.

5.4 Blade Forging Trials - First Campaign

5.4.1 Preform Forging

The preform dies were set up in a 700-ton mechanical press. The dies were heated by gas torch to about 204°C (400°F). A graphite lubricant was sprayed onto the dies prior to each forging. Initial die setup was achieved with the low carbon steel preforms. The preforms were coated with a protective glass coating and heated for 20 minutes at 1066°C (1950°F). Die setup was achieved after forging four steel preforms. It was assumed that the setup was correct when the maximum pitch thickness in the airfoil after forging was 15.2 mm (0.600 in). Using identical forging conditions, three MA-6000 preforms were forged as shown in Table XVII. These preforms were reduced to the required size in one forging blow. Several observations were made with respect to the forgings. It appears that material on the punch side is moving at a faster velocity than the material on the die side since there is no can material left on the die side of the airfoil near the tip. There is also a lack of can material after forging in the shelf area and on the leading edge on the punch side of the forging. In an effort to alleviate the problems with incomplete can material coverage, a two and three-blow forging sequence was planned for the remaining preforms. The intent was to improve metal flow of the can by improved lubrication - preforms were recoated, and dies were relubed between restrikes. Another change for the remaining preforms was furnace preheat time was increased to 30 minutes. The fourth preform was forged to 28.4 mm (1.120 in) maximum pitch, conditioned, recoated, preheated, and forged to the 15.2 mm (0.600 in) requirement. There was no obvious difference in surface condition between the one-blow and two-blow sequences. The remaining preforms were forged using a three-blow sequence; maximum pitch after the first blow was 28.4 mm (1.120 in); after the second blow was 21.6 mm (0.850 in); and after the third blow as 15.2 mm (0.600 in). The appearance of the forgings did not differ much from those forged with a one or two-blow preform forge sequence. Examples of forged preforms are shown in Figure 21. Note the lack of can at the tip of the airfoil on the die side and at the shelf (difficult to see from photograph) and leading edge on the punch side. The phenomena of the punch side material moving faster than the die side is shown in the Figure 22 photomacrograph of a longitudinal cross-section of the airfoil after forging. Some shallow cracks are evident in all areas that are worked where the can is not present. There was no evidence of cracks in forged material where the can was retained.

5.4.2 Finish Forging

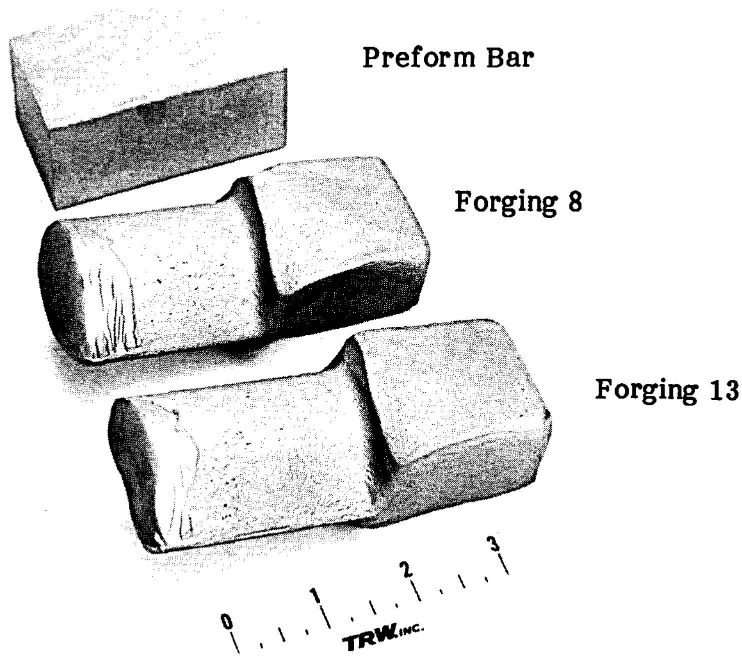
The finish forge dies were installed also in the 700-ton mechanical press. Forging procedures were essentially identical to those used for preform forging with respect to coating and lubrication practices, die temperature, forging temperature, and heating times. Setup was again achieved by forging low carbon steel preforms. Setup was assumed correct when the maximum pitch at Section F-F was 10.6 mm (0.418 in). Only four of the fourteen available preformed MA-6000 blades were finish forged, and all were finish forged in one blow from the preform. Examples of two of the finish forged blades are shown in Figure 23 with

TABLE XVII

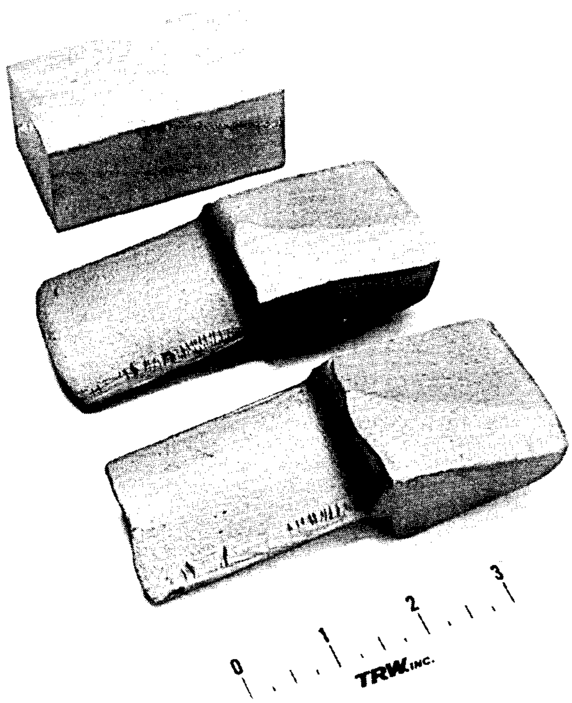
BLADE FORGING TRIALS - FIRST CAMPAIGN

Forging	Preform[a]	Coating	Forge[b] Sequence	Preform Pitch Thickness mm	Preform Pitch Thickness inches	Finish Forge Pitch Thickness mm	Finish Forge Pitch Thickness inches
1	A	D841	1	15.4	0.605	10.4	0.409
2	B	D841	1	15.2	0.600	10.4	0.410
3	B	CRT-HA	1	15.3	0.601	-	-
4	B	D841	2	15.3	0.603	10.5	0.412
5	A	D841	3	15.1	0.596	10.4	0.408
6	B	D841	3	15.3	0.601	-	-
7	A	D841	3	15.3	0.601	-	-
8	A	D841	3	15.3	0.601	-	-
9	A	D841	3	15.2	0.597	-	-
10	B	D841	3	15.2	0.598	-	-
11	A	D841	3	15.3	0.602	-	-
12	A	D841	3	15.3	0.602	-	-
13	A	D841	3	15.2	0.598	-	-
14	B	D841	3	15.2	0.600	-	-

(a) A = 38mm x 43mm; B = 39mm x 40mm. Cross-section dimensions.
(b) 1 = one-blow sequence; 2 = two-blow sequence; 3 = three-blow sequence. See text.



Die Side

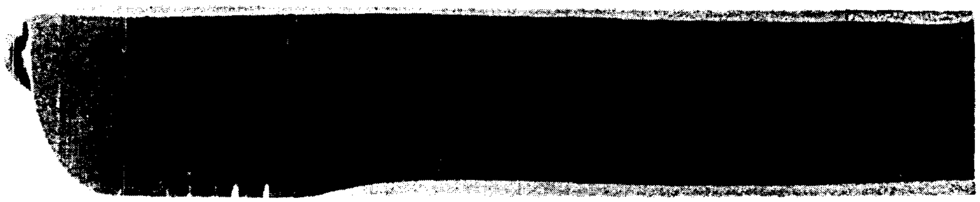


Punch Side Up

Figure 21. Typical As-Forged MA-6000 Preforms.

2850-D

Punch Side



Can End

Die Side

Figure 22. Longitudinal Section of As-Forged MA-6000 Preform Airfoil Indicating the Lack of Can on Die Side Airfoil Tip.

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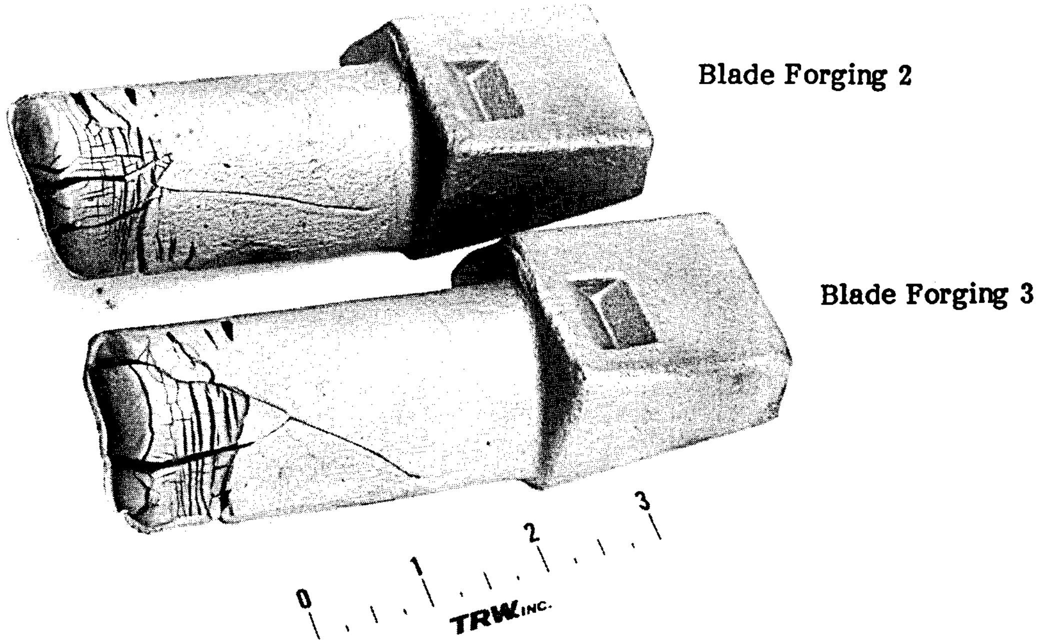
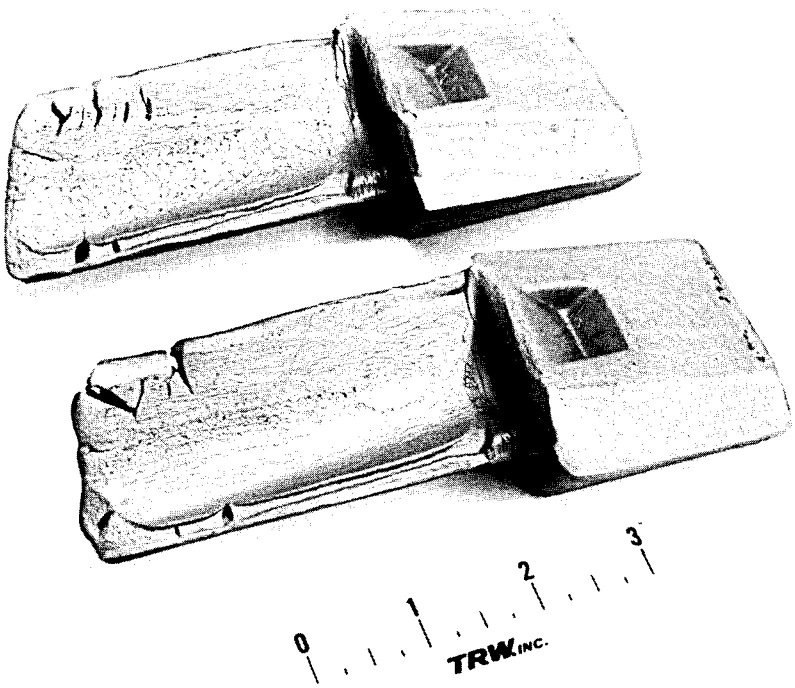


Die Side Up



Punch Side Up

Figure 23. Typical As-Forged MA-6000 Warm Coined Blades.

2852-D

the can left intact. Although the material has been shown to have excellent flow characteristics, areas where there was no can left after preforming cracked extensively resulting in some severe crack propagation. It was also observed that additional material is needed in the airfoil after preforming to properly fill the leading and trailing edges after finish forging.

5.4.3 Directional Recrystallization Response

Two MA-6000 forged preforms (10 and 11) and one finish forged blade (Blade 2) were sent to IRDC to evaluate the response of the material to recrystallization heat treatments. At IRDC, the three pieces were pickled to remove the can material and were ground at the corners in order to fit within a 51 mm (2.0 in) I.D. tube for zone annealing. This tube and a matching traveling furnace, larger than customarily used, were constructed for this project. After a conditioning run, the three pieces were loaded into the tube behind two similarly sized pieces of MA-6000 scrap. The two scrap pieces were instrumented with thermocouples to record their peak temperatures, allowing adjustment after each. Preform 10, also instrumented with a thermocouple, was oriented so that the furnace passed over the root section first, which is desirable from the standpoint of blending the grains of the root into the airfoil. However, the completed forging study task of this project found a potential problem with this orientation due to mismatched grain growth temperatures between area of sharply different deformation histories. Therefore, Preform 11 was oriented in the opposite way so that grains would grow into the root from the airfoil. The finish forged Blade 2 was oriented so that the root was heated first, i.e., the same as the first preform. This piece was also instrumented with a thermocouple.

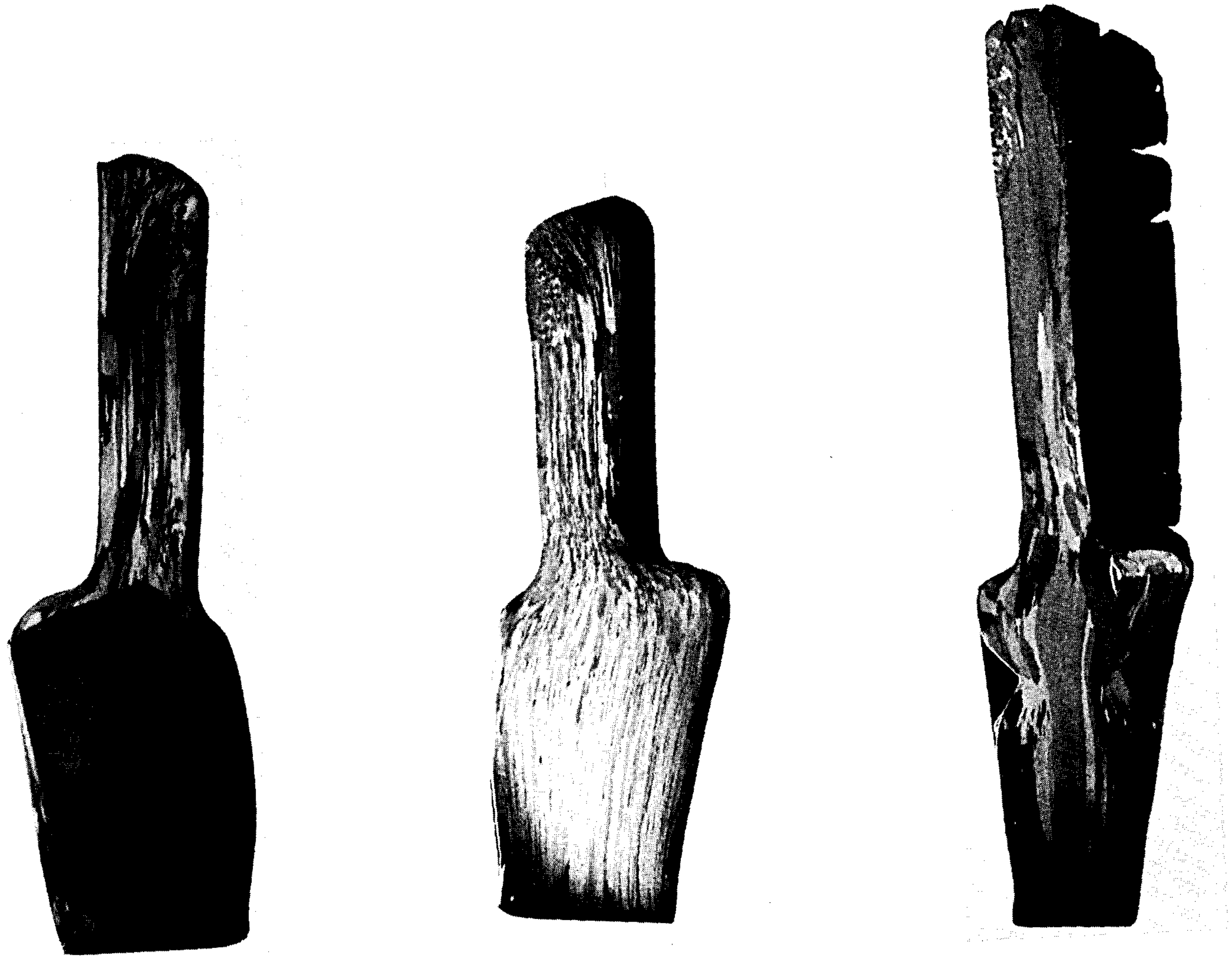
Temperature control for this run was difficult at IRDC probably due to incomplete conditioning of the furnace (furnace was new, and more trial runs should have been performed). Furnace setpoint was reduced several times, once during passage over Preform 10. Actual temperatures were nevertheless within the range normally allowing complete transformation to a coarse, elongated grain structure.

Following zone annealing, each piece was sectioned longitudinally, polished, and macro-etched to reveal the grain structure. Transformation to a coarse grain structure was observed in all areas of all forgings except for the root section of Preform 10, Figure 24.

All of the pieces exhibited excellent grain structures (high grain aspect ratio) in the airfoil and root sections (except 11). This is a very promising result since it was thought that MA-6000 was extremely sensitive to thermomechanical processing, which would prevent the achievement of good grain structure in both airfoil and root. The failure of the root section of Preform 10 to transform may have resulted from a low peak temperature during zone annealing due to the aforementioned problems with the furnace.

Poor structure was obtained at the extreme airfoil tips of all three forgings. This probably was associated with the extensive cracking in these areas. In any event, the poor structure was mainly confined to the excess length of airfoil that would be trimmed during finishing.

A problem in grain structure was revealed in the transitions between



Preform #10

Preform #11

Finish Forged Blade #2

Figure 24. Macrostructures of Zone Annealed MA-6000 Blade Forgings.

airfoil and root, where discontinuities in grain structure were produced. There is a large degree of grain termination in the one area which could be deleterious to mechanical properties. The discontinuities are apparently related to the differing levels of deformation received in these areas.

5.5 Blade Forging Trials - Second Campaign

5.5.1 Tooling Modifications

The results of this first forging campaign effort had indicated that there was insufficient material in areas of the airfoil cross-section after preforming to fill the airfoil die cavity during finish forging. Cracks found in the shelf area were attributed to preform die design in this area. Prior to proceeding into a second series of forging trials, several tooling modifications were made to the preform die. Because of lack of fill on the leading and trailing edges, the preform punch airfoil section was opened up to retain a greater volume of material before going into the finish forge operation. In addition, the radius between the airfoil and root on the punch preform tooling was increased from 4.7 mm (0.187 in) to 12.7 mm (0.5 in). The intent was to minimize any shearing action in this area and reduce the velocity of the metal in forming the punch side of the airfoil.

5.5.2 Preform Forging

A second series of forge trials was conducted with the modified preform tooling. The preform dies were set up in a 700-ton mechanical press. The dies were heated by gas torch to about 204^{o}C (400^{o}F). A graphite lubricant was sprayed onto the dies prior to each forging. Initial die setup was achieved with low carbon steel preforms. The preforms were coated with a protective glass coating and heated for 30 minutes at 1065^{o}C (1950^{o}F). Die setup was achieved after forging four steel preforms. It was assumed that the setup was correct when the maximum pitch thickness in the airfoil after forging was 15.2 mm (0.600 in). Using identical forging conditions, eight MA-6000 preforms were forged as shown in Table XVIII. The first four blades were preformed in one blow prior to finish forging while the remaining four blades were preformed in a three-blow sequence prior to finish forging. The advantage of the three-blow preform sequence appears to be the ability to recondition the forged preform to remove any small cracks or can flash as the part is being produced. The incidence of cracks at the tip was not as great compared to the first forge trial; however, the lack of can material on the die side of the airfoil was still apparent.

5.5.3 Finish Forging

The finish forge dies were installed also in the 700-ton mechanical press. Forging procedures were essentially identical to those used for preform forging with respect to coating and lubrication practices, die temperature, forging temperature, and heating times. Setup was again achieved by forging low carbon steel preforms. Setup was assumed correct when the maximum pitch at section F-F was 10.6 mm (0.418 in). All eight preformed blades of MA-6000 were finish forged. The forged blades are shown in Figure 25 with the can still left intact, while Figure 26 shows one blade with the can removed. The results of the second forge trial are promising. The incidence of cracks in the shelf radius and

TABLE XVIII

BLADE FORGING TRIALS - SECOND CAMPAIGN

Forging	Preform[(a)]	Coating	Forge[(b)] Sequence
15	A	CG-11	1
16	A	CG-11	1
17	A	CG-11	1
18	A	CG-11	1
19	A	CG-11	3
20	A	CG-11	3
21	A	CG-11	3
22	A	CG-11	3

(a) A = 38mm x 43mm. Cross-section dimensions.
(b) 1 = one-blow sequence; 2 = two-blow sequence; 3 = three-blow sequence.

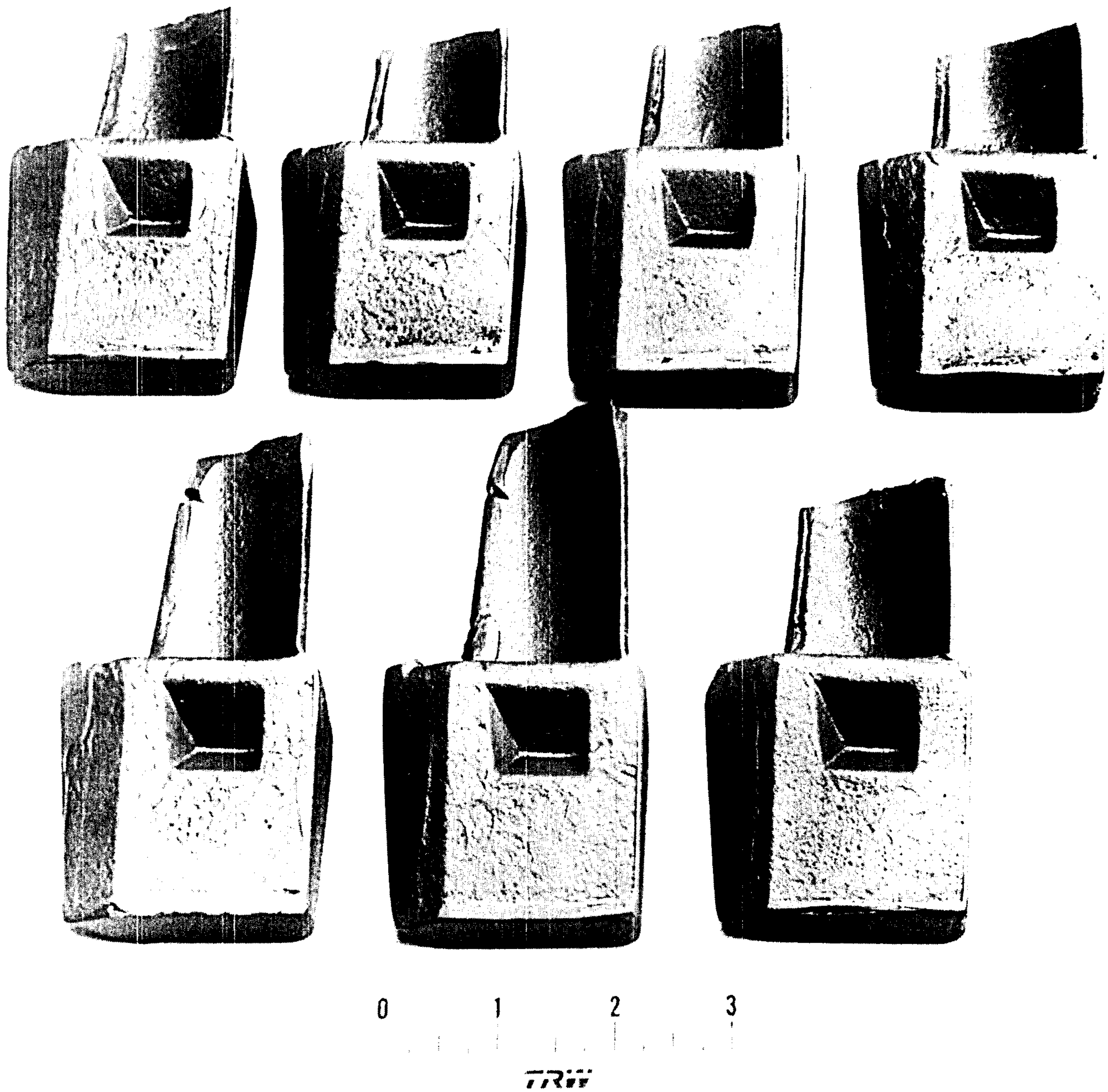


Figure 25. Examples of Finish Forged MA-6000 Blades with Can Intact - Second Forge Campaign.

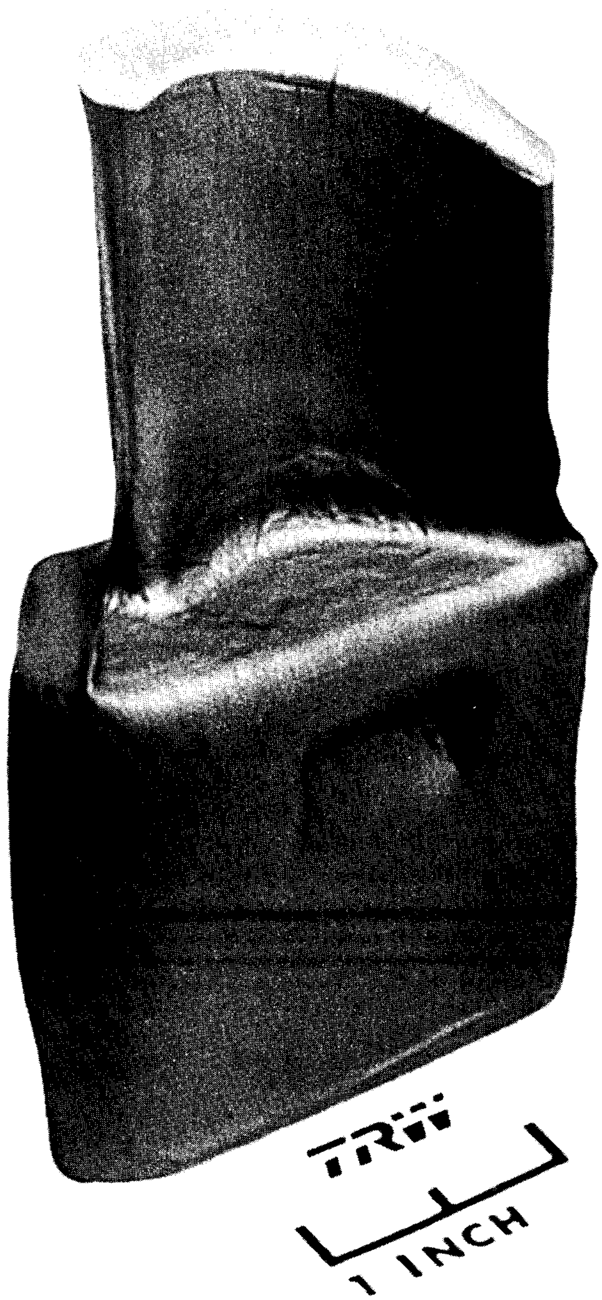


Figure 26. Example of Finish Forged MA-6000 Blade with Can Removed - Second Forge Campaign.

2992-0

blade tip have been reduced to one or two due to the change in the airfoil-to-shelf radius in the preform tooling. Changing the preform cross-section has also allowed complete filling in the finish forging die. It is still apparent, however, that too much mild steel can is lost as flash because of the 3° draft of the side walls of the die (both preform and finish forge).

5.5.4 Directional Recrystallization Response

The only evaluations performed with this lot of forged blades was to determine the effect of zone annealing in the airfoil-to-root direction compared to zone annealing in the root-to-airfoil direction.

The effect of zone annealing direction can be seen by comparing Figures 27 and 28, which show the grain structures of two forgings produced similarly in the original finish forge dies. The two were zone annealed in opposite directions. The part in Figure 27 was zone annealed in the root-to-airfoil direction, which resulted in a sharply defined discontinuity in the platform area. None of the grains of the root survived past the line of discontinuity. The part in Figure 28 was zone annealed in the airfoil-to-root direction. This did not entirely suppress the discontinuity, but increased its width so that grains of the airfoil are interleaved with the grains of the root. At the relatively low temperature of this area of a blade in service, such a structure would probably be acceptable.

5.6 Blade Forging Trials - Third Campaign

5.6.1 Tooling Modifications

Based on the results of the second blade forge campaign, tool rework was found to be necessary. Rework consisted of changing the draft angle from 3° to 0.5° and also changing the airfoil-to-shelf radius in the finish forge die to 12.7 mm (0.5 in). Changing the draft angle was an attempt to restrict the loss of can material as flash along the die walls. Increasing the radius in the airfoil-to-shelf area was performed to minimize cracking tendencies in this area and to more gradually change the degree of deformation from airfoil to root. It was thought that a more gradual change in deformation may minimize or eliminate grain termination found in this area after zone annealing.

5.6.2 Preform Forging

A third series of forge trials was conducted with the modified tooling. The preform dies were set up in a 700-ton mechanical press. The dies were heated by gas torch to about 204°C (400°F). A graphite lubricant was sprayed onto the dies prior to each forging. Initial die setup was achieved with low carbon steel preforms. The preforms were coated with a protective glass coating and heated for 30 minutes at 1065°C (1950°F). Die setup was achieved after forging four steel preforms. It was assumed that the setup was correct when the maximum pitch thickness in the airfoil after forging was 15.2 mm (0.600 in). Using identical forging conditions, four MA-6000 preforms were forged as shown in Table XIX.

Preforming was accomplished in one blow. Visual examination of the forged preforms indicated no apparent cracks at the tip (although the can material

Figure 27. Grain Structure of Forging 15 after Zone Annealing in the Root-to-Airfoil Direction. 2X

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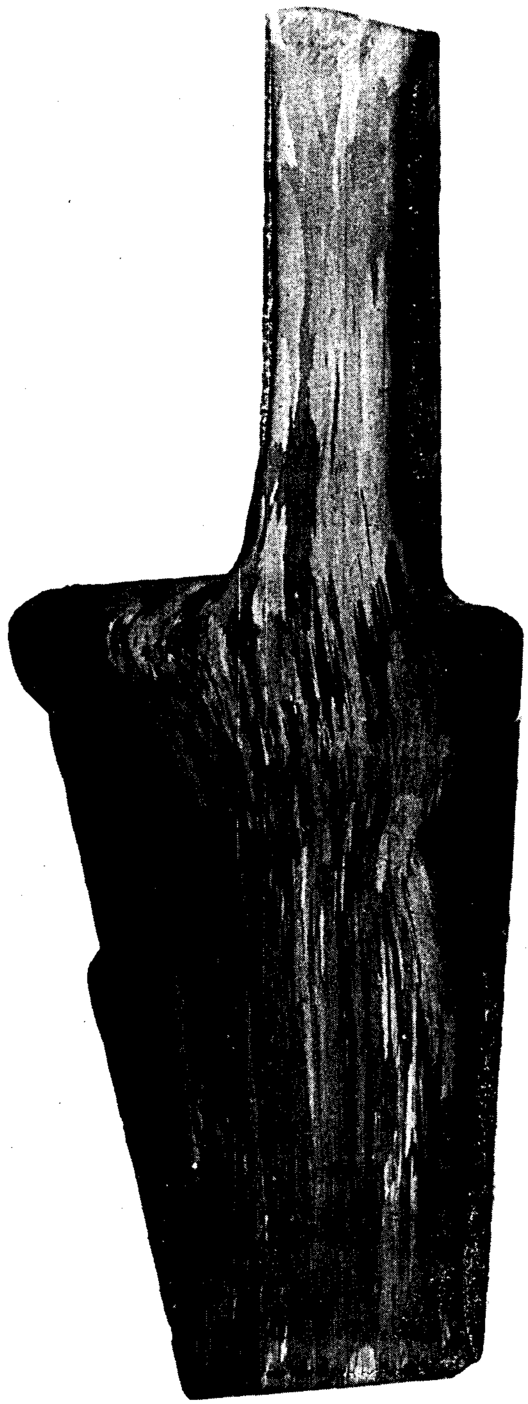

Figure 28. Grain Structure of Forging 17 after Zone Annealing in the Airfoil-to-Root Direction. 2X

TABLE XIX

BLADE FORGING TRIALS - THIRD CAMPAIGN

Forging	Preform[a]	Coating	Forge[b] Sequence
23	A	CG-11	1
24	A	CG-11	1
25	A	CG-11	1
26	A	CG-11	1

(a) A = 38mm x 43mm. Cross-section dimensions.
(b) 1 = one-blow sequence; 2 = two-blow sequence; 3 = three-blow sequence.

was still being stripped on the die side). Very little can flash was observed along the edges, a result of the change in tooling draft angles.

5.6.3 Finish Forging

After preforming, the finish forge dies were installed in the 700-ton mechanical press. Forging procedures were essentially identical to those used for preform forging with respect to coating and lubrication practices, die temperature, forging temperature, and heating times. Setup was again achieved by forging low carbon steel preforms. Setup was assumed correct when the maximum pitch at section F-F was 10.6 mm (0.418 in). The four forged preforms were finish forged and decanned. Cracks again appeared in the tip area because of the lack of can on the die side after preforming. Some of these cracks propagated along the airfoil. Since these blades were only to be used for mechanical property evaluation, this effort of tooling trials was now considered complete. Possible solutions to compensate for the stripping of can material on the die side which eventually leads to cracking would involve developing a method to recan the preforms prior to finish forging or the design and build of a new set of tooling which would allow a more uniform distribution of work in forming the airfoil. The cost to the current program for accomplishing these tasks was considered unacceptable; however, it was also known that the current program results would demonstrate that the directional blade forging approach was feasible and would answer questions with regards to the effect of material deformation on mechanical properties.

Other approaches were evaluated to eliminate the crack propagation problem from the tip. One such approach was to finish forge some of the blades with a two-blow sequence. Repair of the blade tip could be performed as required between each of the blows in the finish forge die. A second approach taken to eliminate the crack propagation problem was to strip the mild steel can off after preforming, plate with nickel (approximately 0.075 in/side) and then finish forge. These approaches were applied to the blades forged for the final mechanical property evaluation effort of this program and are described in the next section.

5.6.4 Directional Recrystallization Response

All of the blades forged in this trial responded well to DR. Of importance was the significant reduction in the severity of the discontinuity when the transition radii of the platform-airfoil transition were increased to 12.7 mm (0.5 in). The blade section in Figure 29 was zone annealed in the "wrong" direction (root-to-airfoil), but nevertheless exhibited a continuous grain structure through the suction side of the transition. The pressure side showed an extended discontinuity near the airfoil and a sharp discontinuity further out on the platform area.

5.7 Forging of Blades for Mechanical Property Evaluations

Based on the results of the tool trials during the third forge trial, a forge schedule was planned as shown below:

- 34 blades - single-blow preform plus double-blow finish forge

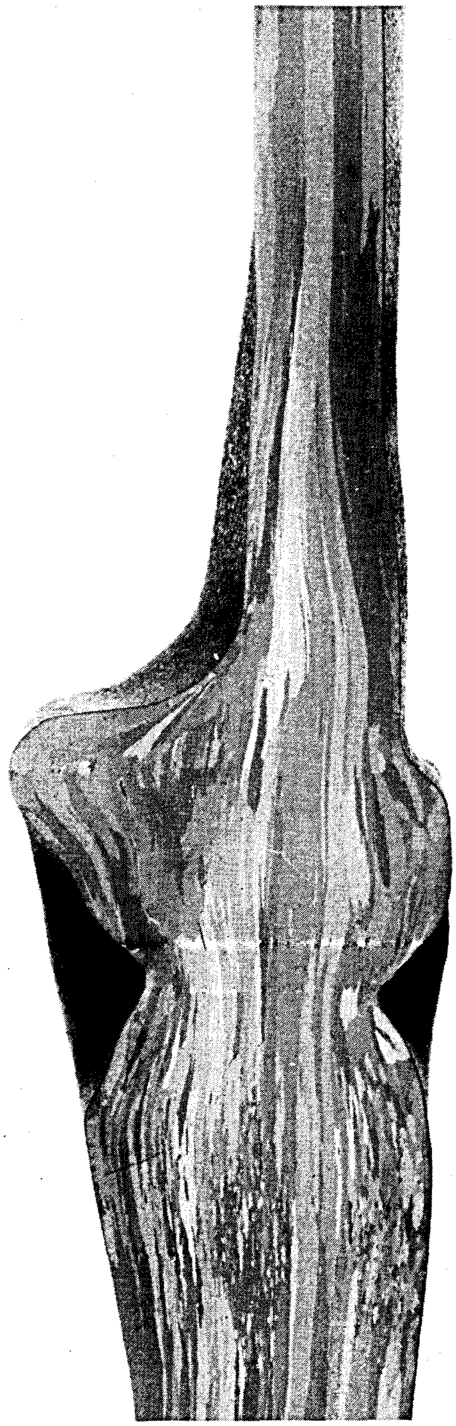

Figure 29. Grain Structure of Forging 23 Which was Forged in Finish Forging Dies with Increased Transition Radii. 2X

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- 31 blades - single-blow preform plus single-blow finish forge
- 9 blades - single-blow preform, strip mild steel can and plate with nickel, single-blow finish forge

All of the 74 blades were forged using identical forging conditions as described in Section 5.6. After forging, the mild steel can was removed by immersion in a hot water-nitric bath. Those blades plated with nickel were left as-forged. Visual examination after removal of the mild steel can indicated that there was less tendency for crack propagation (emanating from the tip) when only one finish forging blow was employed. Those MA-6000 preforms plated with nickel and finish forged were found to be free from any large cracks that have propagated through the airfoils.

IRDC initiated zone annealing of twenty-nine (29) randomly selected blades. Initially, only a few of the blades were zone annealed by IRDC to evaluate whether the blades should be zone annealed tip or root first. These blades were sectioned and examined metallographically. It was found that the blades showed only partial recrystallization near the surface. Several more blades that were processed at different times during the forging schedule at TRW were zone annealed and again evaluated metallographically. Similar results were obtained. A typical blade is shown in Figure 30. Small areas of coarse grains can be seen at the base of the root, the two "dimples" of the root, and along the airfoil surfaces. Otherwise, the blade did not undergo abnormal grain growth and remains in the fine-grained condition. This pattern suggests that an over-temperature condition existed during processing.

Currently, the best explanation for this behavior was that the bar was either rolled or forged at too high a working temperature. After rolling the bar, IRDC sent all rolled material to TRW without any evaluation of their rolled product. Since they had performed considerable evaluation of previously rolled material for this effort, IRDC was confident of their rolling schedule. At TRW, all rolled material was cut into preform lengths and forged. TRW measured the furnace temperature at the beginning of the forging run and found it to be 1065°C (1950°F). No material remains at IRDC or TRW after rolling to check out the response of the rolled bar to zone annealing.

The blades forged and zone annealed at the end of the forging run were to be used for the mechanical property study. Fortunately, a sufficient quantity of forged blades produced during the forging tooling trial effort was available to complete the mechanical property evaluations. These blades were sent to IRDC where they were zone annealed and returned to TRW.

Two separate blade halves were sectioned transversely in order to check for complete through-thickness recrystallization at four locations, Figure 31. The forging on the right side of the figure has a generally finer grain structure than the left; but considered individually, all sections showed similar grain diameter except the mid-root locations, which had more variable grain diameter (left) or simply finer grains (right). Most importantly, there is no suggestion that there is any significant effect of transverse location within these forgings on grain structure.

Figure 30. Grain Structure of One of the Forgings Forged in the Third Forging Campaign that Failed to Recrystallize after Zone Annealing. 1X

Figure 31. Transverse Grain Structures at Four Locations of Two Blade Halves. 2X. Locations are Base of Root, Platform, Base of Airfoil, and Tip of Airfoil.

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5.8 Mechanical Property Evaluations

Extensive mechanical property tests were performed on material sectioned from the forged blades produced during the first and second forge trial. After the directional recrystallization, all test blank material sectioned from the blades was given the following heat treatment:

1230°C (2246°F)/30 minutes/AC+
955°C (1751°F)/2 hours/AC+
845°C (1553°F)/24 hours/AC

Test specimens were machined to a gage diameter of 2.87 mm (0.113 in) and a gage length of 19.05 mm (0.750 in) except those required for the tests in the airfoil and short transverse in the platform. The gage diameter was 2.18 mm (0.086 in), and the gage length was 12.7 mm (0.500 in) for these test requirements. Property evaluations included tensile and stress rupture.

5.8.1 Tensile Test Results

The results of the tensile tests of material taken from the airfoil, platform, and root are shown in Table XX. The tensile properties determined in various sections of the blade compare favorably with published data (4,5) for hot-rolled MA-6000 bar. The tensile properties are not sensitive to various amounts of deformation from the forging process. Although there is some dropoff in tensile properties in the transverse direction, the tensile properties are not as sensitive to the direction of testing as was found in the stress rupture properties. These results are discussed in the following section.

The other significant point in the data shown in Table XX is the inconsistency in the ductility values. Quite a few of the tests show that the material has little ductility at the temperatures tested. Reported literature values indicate that MA-6000 has more ductility than these tests have shown.

5.8.2 Stress Rupture Test Results

The results of the stress rupture tests of material taken from the airfoil, platform, and root are shown in Table XXI. The data is also plotted in Figure 32 to show a better comparison of properties in the sections of a blade at three operating temperatures. Based on published data (4,5) on MA-6000, the stress rupture properties found in the forged blades appear to be not as good as those found in hot-rolled bar. It is not surprising that some property degradation has occurred in the airfoil and platform area. A minimum deformation in excess of 70% has occurred in the airfoil because of the forging operation. The deformation in the root section (between 30 and 40%) is significantly less.

The property degradation at 2000°F in the longitudinal direction of the airfoil appears to be about 10%; that is, the stress capability of the alloy for a 100-hour life has dropped from the published 135 MPa (20 ksi) stress level to about 124 MPa (18 ksi). There are other factors that should also be considered. The specimen is of a sub-compact design because of the size and shape of the airfoil. It is quite easy to machine off-axis specimens; the degree of off-axis would not exceed 10° because of the manner the specimens were sectioned from the

TABLE XX

ELEVATED TEMPERATURE TENSILE TEST DATA OF FORGED MA-6000

Blade No.	Location	Test Direction	Test Temp. °C	Test Temp. °F	UTS MPa	UTS Ksi	YS* MPa	YS* Ksi	% El	% RA
6	Root	L	650	1200	1248	181.0	1169	169.6	1.3	2.6
6	Root	L	650	1200	1222	177.3	1145	166.0	1.8	3.5
19	Platform	L	760	1400	903	131.0	886	128.5	0.8	0.9
19	Platform	L	760	1400	936	135.8	928	134.6	1.1	0.9
1	Airfoil	L	760	1400	1036	150.3	985	142.8	2.6	1.2
17	Airfoil	L	760	1400	974	141.2	-	-	3.9	6.9
6	Airfoil	T	760	1400	923	133.9	-	-	0.5	1.2
6	Airfoil	T	760	1400	982	142.4	978	141.9	2.5	1.2
17	Airfoil	L	1010	1850	289	41.9	279	40.5	5.6	2.3
17	Airfoil	L	1010	1850	316	45.8	310	44.9	1.8	1.1
1	Airfoil	L	1100	2000	179	25.9	-	-	-	-
23	Airfoil	L	1100	2000	221	32.1	216	31.3	18.9	26.5
6	Airfoil	T	1100	2000	150	21.7	-	-	1.9	-
6	Airfoil	T	1100	2000	186	27.0	-	-	1.9	-
	Baseline (Ref.5)	L	538	1000	1156	167.6	1011	146.6	5.5	4.0
		L	760	1400	976	141.6	781	113.3	5.5	12.5
		T	760	1400	897	130.1	804	116.6	3.5	2.5
		L	982	1800	407	59.0	344	49.9	12.5	35.0
		L	1100	2000	222	32.2	192	27.8	9.0	31.0
		T	1100	2000	177	25.7	170	24.7	2.0	1.0

* Values reported for yield strength for platform and root specimens are at 0.2% offset. The size of the gage section did not allow this type measurement for specimens from the airfoil.

TABLE XXI

STRESS RUPTURE PROPERTIES OF FORGED MA-6000

Blade No.	Location	Test Direction	Test Temp. °C	Test Temp. °F	Stress MPa	Stress Ksi	Life Hours	% El	% RA
6	Root	L	650	1200	758	110	39.0	1.9	4.3
6	Root	L	650	1200	724	105	75.0	9.5	22.4
6	Root	L	650	1200	724	105	141.0	2.7	6.9
6	Root	L	650	1200	724	105	246.7	2.2	3.5
24	Root	T	650	1200	552	80	2.0	0.5	1.8
24	Root	T	650	1200	483	70	10.1	1.6	2.6
24	Root	T	650	1200	414	60	17.3	1.2	2.6
23	Platform	L	760	1400	552	80	12.5	1.2	2.6
23	Platform	L	760	1400	517	75	35.9	2.7	4.3
15	Platform	L	760	1400	483	70	36.9	0.7	1.8
15	Platform	L	760	1400	448	65	65.3	1.1	1.8
24	Platform	T	760	1400	276	40	190.8	0.6	-
24	Platform	T	760	1400	276	40	58.0	1.1	-
6	Platform	ST	760	1400	276	40	120.0	-	-
6	Platform	ST	760	1400	276	40	61.3	0.6	-
1	Airfoil	L	760	1400	552	80	0.9	0.3	0.9
1	Airfoil	L	760	1400	483	70	4.5	-	-
1	Airfoil	L	760	1400	414	60	20.2	3.5	2.3
15	Airfoil	L	760	1400	345	50	495.9	-	4.6
6	Airfoil	T	760	1400	276	50	160.9	0.3	1.1
6	Airfoil	T	760	1400	276	40	583.4	1.6	1.1
3	Airfoil	L	1100	2000	138	20	2.0	6.7	8.6
3	Airfoil	L	1100	2000	124	18	16.8	4.7	8.6
24	Airfoil	L	1100	2000	124	18	82.9	3.7	6.1
24	Airfoil	L	1100	2000	124	18	22.6	4.4	5.2
23	Airfoil	L	1100	2000	124	18	111.5	6.5	6.6
23	Airfoil	L	1100	2000	124	18	16.3	6.8	4.5
6	Airfoil	T	1100	2000	41	6	22.8	-	-
6	Airfoil	T	1100	2000	38	5.5	78.2	0.6	2.3

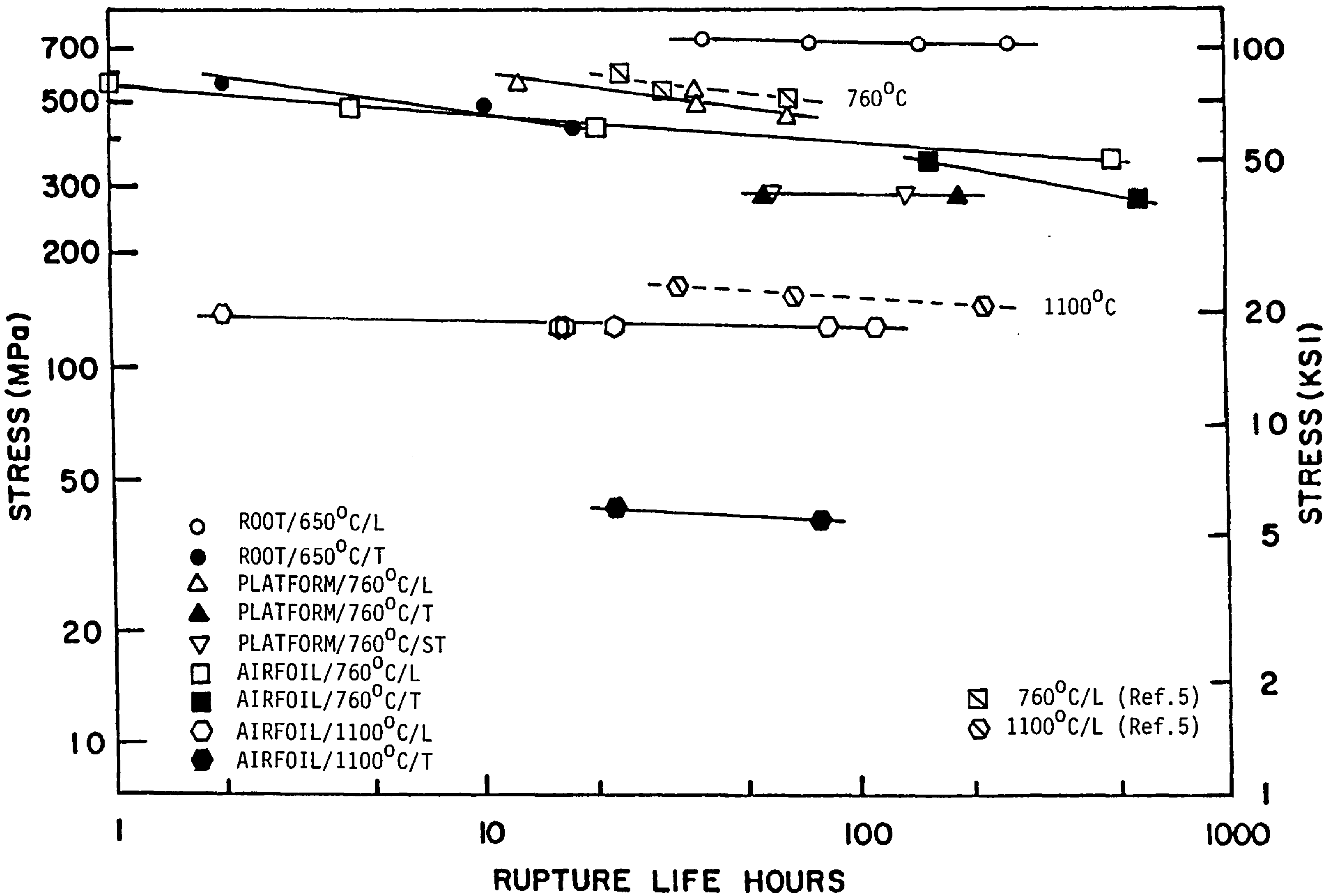

Figure 32. Comparison of Stress Rupture Properties at Several Areas on the Forged Blade.

blade. This degree of off-axis would affect the stress capability a few percent. There was also some degradation of the stress capability at 760°C (1400°F) for both the airfoil and platform tests, although the stress capability of MA-6000 in the platform area seemed to be greater. Of real significance is the fact that the gage section of the platform test specimens was in the transition area between the platform and airfoil, an area that saw significant metal flow in several directions. The stress rupture properties were still quite reasonable after this type of deformation and metal flow.

It should be noted that stress rupture testing in the platform area was performed on blades produced from two tooling designs. Early tooling designs with sharp radii in the platform area produced blades (Blade 15) that when recrystallized had a significant degree of grain discontinuities in this section (see Figure 27). More continuous grains were observed after recrystallization when the radii were opened up in the platform regions (see Figure 29, Blade 23). The stress rupture properties in the platform found in Table XXI for these blades show a trend of better properties for Blade 23 produced from the modified tooling.

5.9 Hollow MA-6000 Turbine Blades

Because of the nature of the process (hot worked wrought material) to produce MA-6000, casting cannot be used to produce hollow turbine blades. There are basically two approaches which could be used, forming a hollow blade by bonding two hollowed halves or machining a hollow cavity through the airfoil section. To demonstrate the latter approach, several of the forged MA-6000 blades were made hollow by electrical discharge machining an airfoil cavity starting from the root section up through the airfoil. Some examples are shown in Figure 33. This technology is well established, but is most practical for simple hollow sections. The second approach, bonding of two halves, would require development in processing and the determination of processing on properties. Bonding of two halves does allow for more complex cooling schemes to be used in the airfoil.

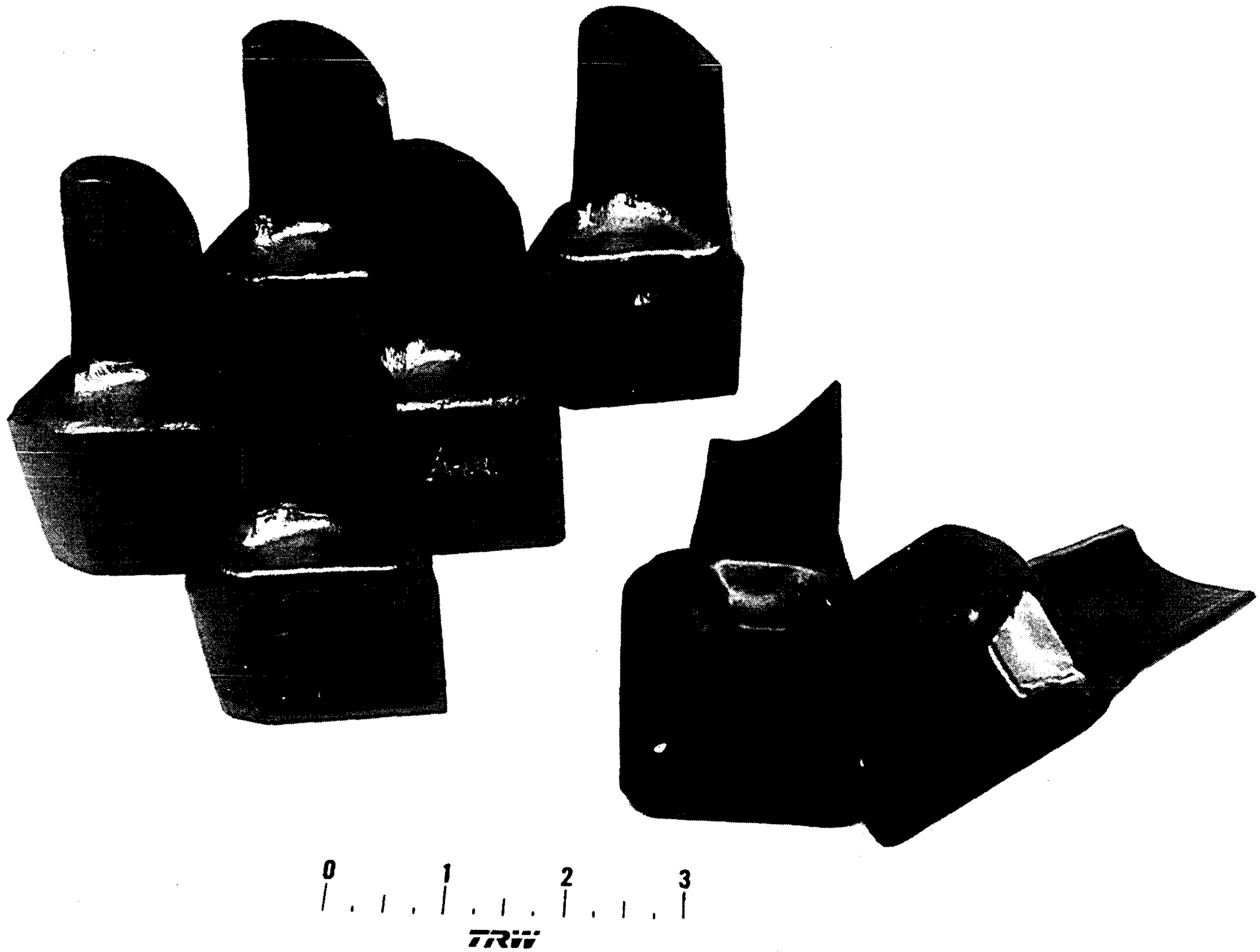

Figure 33. Typical Forged MA-6000 Blades Showing Hollow Section Electrical Discharge Machined.

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6.0 CONCLUSIONS

The objective of this program was to develop a thermal-mechanical-processing approach for the conventional hot forging of MA-6000. Several conclusions can be drawn from this effort and are presented below:

1. Conventional hot forging of MA-6000 can yield an optimum grain structure provided that the following conditions are observed:

   - The starting material should be capable of being recrystallized to an elongated grain structure.
   - Material should have an adherent coating such as the original canning material to prevent cracking during forging.
   - Forging should be performed in the temperature range 1010-1065°C (1850-1950°F). A temperature of 1038°C (1900°F) is probably preferred because of workability at a temperature significantly below where non-optimum grain structures after recrystallization could occur because of processing.
   - MA-6000 can be forged to very large (70%) amounts of deformation and still respond to recrystallization.

2. When forging turbine blades, it was found that:

   - Only near-net shapes are achievable because of the requirements for a can material.
   - Large, smooth radii are preferred to sharp radii in forged blade designs because they minimize the tendency to form discontinuous grains at the transition areas.
   - Designs should consider approaches which minimize or eliminate flash so as to retain the mild steel canning material on the blade surfaces for subsequent forge operations. Stripping of the canning material during forging can lead to crack-type defects.

3. The following property results were noted:

   - Tensile properties of forged material are equivalent to those reported in the literature for hot-rolled bar.
   - Stress rupture properties of forged material were somewhat degraded for material undergoing large deformations in the blade.

4. Generally speaking, conventional forging of canned MA-6000 is a viable approach for the manufacture of near-net shape turbine blades. The cost effectiveness will have to be determined based on each blade design. Forging versus machining the program component selected saves approximately 900 gms (2 pounds) of material. Forging costs are significantly less than the value of the MA-6000 material that would be saved by the near-net forging process established.

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