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SOME EFFECTS OF COLD WORKING BY HYDROSTATIC EXTRUSION ON MECHANICAL PROPERTIES OF HIGH-STRENGTH STEELS

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16. Abstract

A 300-grade maraging steel and AISI 4340 were cold worked in various heat-treated conditions by hydrostatic extrusion. Maximum extrusion pressures ranged from 260 to 300 ksi (1795 to 2070 MN/m^2) for 50-percent reductions in area. Cold working and reaging increased the strength of the fully aged maraging steel about 50 ksi (345 MN/m^2). AISI 4340, initially heat treated to R_c 44, showed a 60-ksi (415-MN/m^2) increase in strength after cold working and retempering. In both steels, resolution and reprecipitation as a result of cold working and reaging or retempering contributed to the strength increases noted.

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SUMMARY

A 300-grade maraging steel and AISI 4340 were cold worked in the heat-treated condition by hydrostatic extrusion. The maraging steel was extruded in the partially and fully aged conditions. The AISI 4340 samples were extruded in the quenched and tempered condition at hardness levels of R_c 42 and 44. For a 50-percent reduction in area, an extrusion pressure of 280 ksi (1930 MN/m^2) was required for the maraging steel in the fully aged condition. The AISI 4340 samples were extruded against a back pressure (fluid-to-fluid extrusion) to produce sound extrusions, and they required differential pressures of at least 260 ksi (1795 MN/m^2). Post-extrusion heat treatments included reaging at 900° F (480° C) for the maraging steel and retempering at 400° F (200° C) for the AISI 4340.

Cold working and reaging increased the yield strength of the maraging steel from 280 ksi (1930 MN/m^2) (as heat treated) to 330 ksi (2280 MN/m^2). Samples cold worked in the partially aged condition gave intermediate increases in strength. A slight decrease in tensile ductility was associated with the higher strength, cold worked samples. The process of resolution and reprecipitation as a result of cold working and reaging appeared to be the major cause for the strength increases noted.

For the AISI 4340 the highest strength was obtained with samples having an initial hardness of R_c 44. Cold working and retempering increased the yield strength from 200 to 260 ksi (1380 to 1790 MN/m^2) and increased the tensile strength from 208 to 270 ksi (1435 to 1865 MN/m^2). Tensile ductility (elongation) decreased from about 15 to about 10 percent. About half of the strength increase resulted from strain hardening. The remainder probably resulted from resolution and reprecipitation of carbon and/or carbides upon retempering.

INTRODUCTION

This report describes some effects of cold working and heat treatment on the mechanical properties of a 300-grade maraging steel and AISI 4340. Both steels were cold worked in various heat-treated conditions by hydrostatic extrusion. Relatively large amounts of cold working can be introduced in the heat-treated steels by hydrostatic extrusion primarily because the large deformation force available and the highly compressive state of stress developed in the deformation zone. Also, the billets can be extruded into a pressurized fluid (fluid-to-fluid extrusion) to provide an additional compressive stress on the material. This tends to reduce the tensile stresses that introduce cracking during deformation. Both hydrostatic extrusion and other hydrostatic forming processes have been described in detail in the literature (refs. 1 to 3).

In the solution-treated condition, the maraging steels can be subjected to large amounts of cold working by conventional processes such as rolling (ref. 4). However, the relatively low rate of work hardening (attributed to the extra low carbon content of these steels) results in modest strength increases as a result of cold work. As a means of obtaining higher increases in strength, cold working after aging was suggested by Mihalism and Bieber (ref. 5). Nolan and Davidson (ref. 6) reported a slight increase in strength for a 250-grade maraging steel cold worked in the fully aged condition by hydrostatic extrusion. However, a 30-percent increase in strength was obtained by cold working in the fully aged condition and reaging. Enhanced precipitation as a result of cold working and reaging was suggested as the reason for the strength increase. In the study reported herein, one objective was to examine the effects of several aging treatments combined with cold working on the mechanical properties of a 300-grade maraging steel. Cold working was done in the partially and fully aged conditions at reductions in area of 20 and 50 percent. Reaging after cold working was done at 900° F (480° C).

Heat-treated, low alloy steels such as AISI 4340 have exhibited appreciable strength increases as a result of cold working and retempering (refs. 7 to 9). This thermomechanical treatment is usually referred to as strain tempering. Both strain hardening and reprecipitation of carbon and/or carbides during retempering contribute to the increase in strength. In most studies, cold working has been achieved by either drawing or straining tensile specimens. The relatively low ductility and high rate of strain hardening limits the amount of cold work that can be introduced by these techniques. About a 10-percent reduction in area can be achieved by drawing or about a 3-percent elongation can be produced in tensile specimens. Thus, another objective of this study was to examine the effect of greater amounts of cold work on the mechanical properties of strain-tempered AISI 4340. Two heat-treated hardness levels were selected, R_C 42 and 44. Most of the cold working by hydrostatic extrusion was limited to 50-percent reduction in area. Retempering was done at 400° F (200° C).

Cold working the high-strength steels was done in a 450-ksi (3100-MN/m^2) hydrostatic extrusion press. The salient features of the laboratory press are described herein.

EXPERIMENTAL PROCEDURE

Material and Heat Treatment

Maraging steel. - The 300-grade maraging steel used in this study was obtained from a commercial vendor in the form of vacuum melted, hot rolled bar stock. Results of a chemical analysis are as follows:

Element	Ni	Co	Mo	Ti	Al	C	Ca	Si	S	B	Fe
Weight, percent	18.9	9.1	5.05	0.64	0.10	0.015	0.03	0.08	0.005	0.001	Balance

Extrusion billets conforming to figure 1 were machined from the 1.25-inch- (3.18-cm-) diameter bar stock. After machining, the billets were solution treated at 1500° F (820° C) for 1 hour and air cooled. Aging prior to extrusion was done at 700°, 800°, or 900° F (379°, 430°, or 480° C) for 1 hour or at 900° F (480° C) for 3 hours. The 3-hour age at 900° F (480° C) is referred to herein as the fully aged condition. After extrusion most of the samples were reaged at 900° F (480° C) for 3 hours. The other samples were tested in the as-extruded condition. Samples in the unworked condition, used for comparison of mechanical properties, were given a conventional heat treatment consisting of a 3-hour age at 900° F (480° C) after solution treating at 1500° F (820° C) for 1 hour. All of the heat treatments were done in a salt bath furnace.

AISI 4340. - Aircraft quality, air melted AISI 4340 steel was obtained from a commercial source in the form of hot rolled bar. Results of a chemical analysis are as follows:

Element	Ni	Cr	Mn	Mo	Si	C	Fe
Weight, percent	1.78	0.82	0.79	0.25	0.23	0.43	Balance

Extrusion billets conforming to figure 1 were machined from the 1-inch- (2.54-cm-) diameter bar. After machining, the billets were heated to 1550° F (840° C) in a salt bath and oil quenched. Tempering was done at either 800° or 900° F (430° or 480° C) for 1 hour. After extrusion, the samples were retempered at 400° F (200° C) for 1 hour in a salt bath. Tensile specimens machined from the bar were given similar heat treatments for comparison of as-heat-treated properties to those obtained by cold working and re-tempering.

Extrusion Equipment and Procedure

Extrusion press. - The hydrostatic extrusion press used in this study is shown in figure 2. Extrusion is accomplished in the tapered pressure tube (extrusion chamber) that has a 1.5-inch- (3.8-cm-) diameter bore. Radial support of the pressure tube is obtained by forcing it into the support rings using the lower piston. Simultaneously, a carbide stem, attached to the upper piston (ram), forces the plunger into the bore of the tube to generate pressure in the fluid surrounding the billet and die. Die and plunger seals consist of a O-ring/mitre-ring combination as illustrated in the inset of figure 2. The receiver chamber has a 1-inch- (2.54-cm-) diameter bore, and it was pressurized with a carbide stem attached to the driving piston. It was used to provide back pressure in the fluid-to-fluid extrusion of the heat treated AISI 4340 steel samples.

The extrusion chamber is designed for and has been operated at pressures up to 450 ksi (3100 MN/m^2). Pressures in the monobloc receiver chamber are limited to 200 ksi (1380 MN/m^2). Both chambers were fabricated using Vasco-Jet 1000 tool steel heat treated to R_c 52/54. An electrically driven, hydraulic pump was used to drive the pistons. The fixed displacement pump limited ram speed to about 1/2 inch per minute (1.27 cm/min) at the higher pressures. Pressure magnification ratios (piston area/chamber bore area) are approximately 60 and 25 for the extrusion and receiver chambers, respectively.

The extrusion dies used in this study had a 40° included angle, and they were made from cold working die steels such as AISI A2. The die orifices were 0.71 inch (1.80 cm) for the 1-inch- (2.54-cm-) diameter billets and 0.68 inch (1.73 cm) for the 3/4-inch- (1.91-cm-) diameter billets.

Extrusion Procedure

Maraging steel. - For the maraging steel samples, a silver plating (~0.0003 in., 0.001 cm, thick) was applied to the billets for lubrication. In addition, a lead nose cone was placed at the die-billet interface to aid in starting the extrusion. Either castor oil or a mixture of castor oil and gasoline was used as the pressuring fluid. All of the maraging steel billets were extruded into atmospheric pressure at either 20- or 50-percent reductions in area.

AISI 4340. - A castorwax coating (~0.001 in., 0.002 cm, thick) containing about

20 weight percent molybdenum disulfide was used as a lubricant for most of the AISI 4340 billets. This lubricant was reported to give good results in the cold extrusion of this steel in the annealed condition (ref. 10). One billet was extruded bare, and the others were coated with lead (~0.005 in., 0.001 cm, thick). A mixture of either mineral oil and gasoline, mineral oil and varsol, or castor oil and gasoline was used as the pressurizing medium. Because of the high rate of work hardening and relatively low ductility of the heat-treated AISI 4340, a back pressure (fluid-to-fluid extrusion) was used to provide an added compressive stress component to reduce tensile stresses and thereby minimize the possibility of cracks initiating during the extrusion process. Most of the billets were extruded at a 50-percent reduction in area

Extrusion data. - Pressure and ram displacement were recorded simultaneously during extrusion on an x-y recorder. The pressure signal was generated by a transducer in the hydraulic line, and ram displacement was indicated by a linear transducer. The extrusion pressures were calculated from the hydraulic pressure and the magnification ratio. The effect of friction is included in the reported extrusion pressures. Friction losses in the system were estimated to be about 3 to 5 percent of the reported pressures. The estimate was based on the hysteresis observed in cyclic pressure - displacement data obtained in pressurization tests.

Mechanical Properties

Mechanical properties of the extrusions were determined by tensile tests. After the final heat treatment, tensile specimens conforming to ASTM E8 were machined from the extrusions. The specimens had a 1/4-inch- (0.64-cm-) gage diameter and a 1-inch- (2.54-cm-) gage length. Testing was done at ambient temperatures using a crosshead speed of 0.05 inch per minute (0.13 cm/min).

RESULTS AND DISCUSSION

Maraging Steel

Hydrostatic extrusion. - Even though the yield strength of some of the specimens was near 280 ksi (1930 MN/m^2), no difficulties were encountered in obtaining up to 50-percent reductions in area by hydrostatic extrusion. The extrusion data are summarized in table I. Recorded maximum and minimum pressures are given for each extrusion. For most of the extrusions, the maximum pressure does not represent the breakthrough pressure. Often, the maximum pressure was reached when the lead coating from the nose cone terminated as illustrated in figure 3(a).

Figure 3(b) shows a stick-slip pressure - ram displacement trace typical of the extrusions receiving 20-percent reductions in area. The stick-slip phenomenon has been attributed to large differences in the static and dynamic friction along the die-billet interface (ref. 10). Initially, the much larger static friction causes the pressure to reach a higher level than normally required for steady-state extrusion conditions. The overpressure caused extrusion of the billet to proceed at a rate faster than the ram could maintain pressure. The pressure dropped below that required for steady-state conditions and the extrusion stopped. The process was repeated until the extrusion was completed. Usually stick slip has little effect on extrusion quality or properties unless there is excessive overheating during the high velocity part of the cycle.

In addition to possible differences in the static and dynamic friction, the ratio of the billet diameter to the diameter of the pressure chamber may have some effect on stick slip. Stick slip was observed in only one of the 1-inch- (2.54-cm-) diameter billets. But all of the 3/4-inch- (1.91-cm-) diameter billets (used for the 20-percent reductions) exhibited stick slip. This observation suggests that the smaller annulus between the billet and chamber bore for the 1-inch- (2.54-cm-) diameter billets provides more restraint to billet movement through the fluid medium (particularly at the higher pressures). Restraint to rapid billet movement would decrease the tendency for stick slip.

The general increase in strength with aging temperature is reflected in the higher extrusion pressures required for billets aged at the higher temperatures. From these limited test results, there appeared no appreciable difference in extrusion quality or pressure requirements using either castor oil or the castor oil - gasoline mixture. Typical samples of the extruded maraging steel are shown in figure 4.

Mechanical properties. - Results of tensile tests conducted on samples receiving a conventional heat treatment and on samples preaged, extruded, and reaged are given in table II. The effects of preaging temperature (aged for 1 hr) and of percent cold working on tensile properties are presented graphically in figure 5. As shown, the highest tensile and yield strengths are associated with the highest preaging temperature used (900° F, 480° C) and the greatest amount of cold working (50-percent reduction).

Figure 6 shows the increase in strength as a function of cold working for samples fully aged, extruded, and reaged at 900° F (480° C) for 3 hours. The strength increase appears to reach a maximum at about 50-percent cold working. Negligible increases in strength would be expected for greater amounts of cold working.

The tensile and yield strength advantage of the 50-percent cold worked and reaged samples over samples in the standard heat-treated condition is about 50 ksi (345 MN/m^2) or about a 17-percent increase in strength. Only a modest decrease in tensile ductility was associated with the increase in strength (fig. 6 and table II).

Samples tested after extrusion in the fully aged condition without subsequent reaging (table II, tests 18 and 19) showed only a slight increase in strength compared to samples aged after extrusion (table II, tests 17 and 18). Assuming that no stress relief annealing occurred in the 900° F (480° C) reaging treatment, the results indicate that only 16 percent of the total yield strength increase can be attributed to strain hardening. Similar results were reported for a 250-grade maraging steel (refs. 6 and 11). The small increase in strength after cold working is due to the lack of strain hardening, even in the fully aged condition. The increase in strength upon reaging could be related to several factors, such as transformation of retained or reverted austenite by cold working with subsequent aging of the transformed martensite, or enhanced precipitation as a result of cold working, as suggested by Nolan and Davidson (ref. 6).

Resolution and reprecipitation as a result of cold working and reaging have been suggested by Kula and Hickey (ref. 11) as the bases for the strength increase. Carbon extraction replicas of the precipitates in the 300 grade maraging steel samples from this study showed evidence of resolution and reprecipitation (fig. 7). The thin, flakelike precipitates were difficult to resolve, particularly, in the extruded and reaged samples. Positive identification of the precipitates could not be made. They are probably Ni_3Mo which has been identified as the primary precipitate in the maraging steels receiving a 900° F (480° C), 3-hour aging treatment (ref. 12). In the as-extruded condition (after a 3-hr age at 900° F, 480° C), fig. 7(a), the precipitates were generally larger and not as numerous as those in the extruded and reaged samples, figure 7(b). Since the extruded and reaged samples were exposed to the aging temperature for a longer period of time, the precipitate size should be larger and probably not as finely dispersed. Apparently, some resolution and reprecipitation occurred during reaging. Presumably, the finer and more closely spaced precipitate present after reaging contributed to the strength increases noted by offering greater resistance to plastic flow.

It should be noted that the Ni_3Mo precipitate is metastable; after longer times at the aging temperature (900° F, 480° C) or aging at higher temperatures, the Ni_3Mo is replaced by Fe_2Mo or sigma (ref. 12). Cold working and reaging might initiate the change in the precipitate from Ni_3Mo to Fe_2Mo or sigma. Therefore, the finer precipitate present after cold working and reaging could be different in chemistry as well as having a different morphology than the precipitate formed by aging alone.

AISI 4340

Hydrostatic extrusion. - Extrusion data for the AISI 4340 billets are summarized in table III. Maximum and minimum pressure differentials and the back pressures used are given for each extrusion. At a hardness of R_c 44, extrusion pressures ranged from 260 to 290 ksi (1795 to 2000 MN/m^2) for a 50-percent reduction. Except for sample 3-44, sound extrusions were obtained with back pressures of 50 to 75 ksi (345 to 520 MN/m^2). The minor surface cracks noted in 3-44 and in the samples extruded with back pressures less than 50 ksi (345 MN/m^2) were circumferential and about 0.01 inch (0.02 cm) deep.

Billets heat treated to R_c 42 were subjected to a 50-percent reduction without surface cracking using back pressures of 77 and 50 ksi (530 and 345 MN/m^2). A back pressure of 25 ksi (174 MN/m^2) was not adequate to prevent surface cracking of the type previously described.

In general, the AISI 4340 billets were difficult to cold extrude. Only three of the billets extruded at a fairly uniform pressure (3-44, 4-44, and 7-42). The other billets exhibited either minor stick slip or a continuous increase in pressure during extrusion (8-42 and 9-42). None of the variation noted could be related directly to the lubricant, to the different fluids used, or to differences in billet hardness. However, the lead billet coating used with a varsol - mineral oil pressurizing fluid appeared to give the best overall results. Two of the better extrusions are shown in figure 8.

Samples 8-42 and 9-42 were reextruded at a reduction of 33 percent for a total reduction of 66 percent. Reextrusion pressures were about the same as those required for a 50-percent reduction. Minor surface cracking was noted in both extruded products even though a 50 ksi (345 MN/m^2) back pressure was used.

Mechanical properties. - Tensile properties of the AISI 4340 samples in the as-heat-treated condition, after cold working, and in the cold worked and retempered conditions are summarized in table IV. The test results show that combined cold working and heat treatment (retempering) increased the yield and tensile strength about 30 percent for samples having an initial hardness of R_c 42 or 44 and cold worked 50 percent. As shown, about half of the strength increase was associated with strain hardening. The additional strength increase when retempering is probably related to resolution and reprecipitation of carbides. Conventional strain-tempering studies have shown the reprecipitated carbides are much finer than in those found in the as-tempered or strained condition (ref. 7). For samples having an initial hardness of R_c 42 and cold work 67 percent, most of the strength increase appeared to be associated with strain hardening. Highest strengths were obtained from samples having an initial hardness of R_c 44 (table IV). The strength increase obtained by cold working and by cold working and retempering samples heat treated to R_c 44 is shown graphically in figure 9. Tensile ductility, as measured by the percent elongation, was decreased from about 14 to 15 percent to about 8 to 10 percent by cold working and retempering.

Several differences were noted between the results of this study and those reported by Stephenson and Cohen (ref. 7) for AISI 4340 subjected to a more conventional strain tempering treatment using similar tempering and retempering temperatures. In their conventional strain tempering study, the deformation was limited to about 3 percent strain (tensile test), and they found no change in sample hardness. But in this study, hardness increased as much as 5 R_c points as a result of cold working and retempering (table IV). However, the strength increases were about the same in both studies. Also, mechanical instability (maximum tensile load at yielding with the load decreasing to fracture) usually associated with strain tempering was not observed in this study. Stephenson and Cohen found mechanical instability, which they attributed to dislocation pinning by the redistribution of carbides and/or carbon during retempering.

A more extensive study is required to relate the differences noted. Competing strain-softening and strain-hardening effects associated with the larger deformations in this study may account for the strength levels being similar to those obtained at the more modest deformations. The absence of mechanical instability suggests that the greater dislocation density present with the larger amounts of deformation precluded complete dislocation pinning by carbon and/or carbides. Also, it appears that hardness is not an accurate measure of the effects associated with strain tempering.

SUMMARY OF RESULTS

A 300-grade maraging steel and AISI 4340 were cold worked in various heat-treated conditions by hydrostatic extrusion. The effects of cold working and subsequent aging treatments on mechanical properties were evaluated. The results are summarized below.

1. A 300-grade maraging steel was cold worked successfully in the partially aged (700° to 900° F, 370° to 480° C, 1 hr) and fully aged (900° F, 480° C, 3 hr) condition by hydrostatic extrusion. Even though the yield strength in the fully aged condition was 280 ksi (1930 MN/m^2), no difficulties were encountered in obtaining a 50-percent reduction in area. For this condition, the maximum pressure required for extrusion was about 280 ksi (1930 MN/m^2).

2. The yield strength of maraging steel samples cold worked in the fully aged condition and then reaged was about 330 ksi (2280 MN/m^2). In comparison, the yield strength of this steel in the unworked, fully aged condition was 280 ksi (1930 MN/m^2). Samples cold worked in the partially aged condition and then reaged gave intermediate increases in strength over those in the as-heat-treated condition. A slight decrease in tensile ductility was associated with the higher strength, cold worked samples.

3. The process of resolution and reprecipitation as a result of cold working and reaging appears to be the major cause of the strength increases noted for the maraging steel. Even in the fully aged condition, very little change in strength was observed from cold working alone.

4. AISI 4340 samples, heat treated to R_c 42 or 44, were hydrostatically extruded against back pressures as high as 77 ksi (530 MN/m^2) at a 50-percent reduction in area. Back pressures of 50 to 75 ksi (345 to 520 MN/m^2) were required to prevent minor surface cracking in the extruded products. Differential pressures of at least 260 ksi (1795 MN/m^2) were required for extrusion at both hardness levels.

5. The highest strength increase was obtained with the AISI 4340 samples having a hardness of R_c 44 and retempered at 400° F (200° C). Cold working and retempering increased the yield strength from 200 to 259 ksi (1380 to 1790 MN/m^2) and the tensile strength from 208 to 270 ksi (1435 to 1865 MN/m^2). About half of the strength increase resulted from strain hardening. The remainder probably resulted from resolution and reprecipitation of carbon and/or carbides upon retempering. Tensile ductility (elongation) decreased from about 15 to about 10 percent as a result of cold working and retempering.

6. Mechanical instability, usually associated with conventional strain tempering of steels (deformation ~3 percent), was not observed in this study. Hardness increases as much as 5 R_c points after hydrostatic extrusion and retempering. The strength increases were similar to those reported for AISI 4340 subjected to conventional strain tempering.

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TABLE I. - HYDROSTATIC EXTRUSION DATA FOR A 300-GRADE MARAGING STEEL

[Solution treated at 1500° F (820° C) prior to aging treatment indicated.]

Extrusion number	Billet diameter, in. (cm)	Reduction in area, percent	Pressure media	Billet lubricant	Extrusion pressure, max/min, ksi (MN/m^2)	Extruded length, in. (cm)
Aged: 700° F (370° C); 1 hr; R_c 38						
M7-12	$\frac{3}{4}$ (1.91)	20	CO[a]	Silver plating (0.0003 in., 0.0007 cm) with lead nose cone	[b]92/83 (635/570)	4 (10.2)
M7-15	1 (2.54)	50	CO		213/193 (1470/1330)	$6\frac{3}{4}$ (17.2)
M7-25	1 (2.54)	50	CO		201 (1390)	$7\frac{1}{2}$ (19.1)
Aged: 800° F (430° C); 1 hr; R_c 45						
M8-12	$\frac{3}{4}$ (1.91)	20	CO	Silver plating (0.0003 in., 0.0007 cm) with lead nose cone	[b]122/92 (845/635)	$5\frac{3}{4}$ (14.6)
M8-15	1 (2.54)	50	CO		255/230 (1760/1590)	$4\frac{1}{2}$ (11.4)
M8-25	1 (2.54)	50	CO		[b]247/220 (1705/1520)	6 (15.2)
Aged: 900° F (480° C); 1 hr; R_c 50						
M9-12	$\frac{3}{4}$ (1.91)	20	CO	Silver plating (0.0003 in., 0.0007 cm) with lead nose cone	[b]134/110 (925/760)	$6\frac{1}{4}$ (15.9)
M9-15	1 (2.54)	50	COG[c]		270/259 (1865/1790)	$6\frac{1}{4}$ (15.9)
M9-25	1 (2.54)	50	CO		262/278 (1810/1920)	$4\frac{1}{2}$ (11.4)
Aged: 900° F (480° C); 3 hr; R_c 52						
M9-32	$\frac{3}{4}$ (1.91)	20	CO	Silver plating (0.0003 in., 0.0007 cm) with lead nose cone	[b]144/121 (995/835)	$6\frac{1}{4}$ (15.9)
M9-35	1 (2.54)	50	COG[c]		280/248 (1930/1710)	6 (15.2)
M9-45	1 (2.54)	50	COG[c]		282/253 (1945/1750)	$6\frac{1}{4}$ (15.9)

[a]Castor oil.
[b]Stick slip during extrusion.
[c]Castor oil - 25 vol.% gasoline.

TABLE II. - TENSILE PROPERTIES OF A 300-GRADE MARAGING STEEL IN CONVENTIONALLY HEAT TREATED CONDITION AND DIFFERENT COLD WORKED AND REAGED CONDITIONS

Test	Sample condition						Yield strength (0.2 percent), ksi (MN/m^2)	Tensile strength, ksi (MN/m^2)	Elongation, percent	Reduction in area, percent
	Preage		Percent cold work	Final age						
	Temperature, ^{o}F (^{o}C)	Time, hr		Temperature, ^{o}F (^{o}C)	Time, hr	Hardness, R_c				
1	--------	-	--	900 (480)	3	53/54	276 (1910)	289 (1995)	10.6	55
2	--------	-	--			53/54	282 (1945)	293 (2020)	10.0	54
3	900 (480)	3	--			53/54	284 (1960)	294 (2030)		54
4	700 (370)	1	20			-----	294 (2030)	299 (2060)		54
5	700 (370)		50			56/57	303 (2090)	307 (2120)		50
6	700 (370)		50			56/57	306 (2110)	308 (2125)		51
7	800 (430)		20			-----	300 (2070)	311 (2150)		50
8	800 (430)		50			57/58	312 (2155)	319 (2200)	8.6	48
9	800 (430)		50			57/58	314 (2170)	320 (2210)	8.6	49
10	900 (480)		20			-----	326 (2250)	330 (2280)	9.3	50
11			20			-----	328 (2265)	332 (2290)	9.3	48
12			50			58/59	333 (2300)	337 (2325)	8.6	46
13			50			58/59	331 (2290)	335 (2310)	6.0	46
14		3	20			-----	319 (2200)	325 (2240)	9.3	48
15			20			-----	318 (2195)	324 (2235)	9.3	48
16			50			58/59	328 (2265)	334 (2305)	8.6	47
17						58/59	330 (2280)	334 (2305)	5.3	47
18				--------	-	-----	288 (1990)	303 (2090)	9.3	50
19				--------	-	-----	288 (1990)	305 (2105)	10.6	50

TABLE III. - HYDROSTATIC EXTRUSION DATA FOR FLUID-TO-FLUID EXTRUSION OF AISI 4340

STEEL AT 50-PERCENT REDUCTION IN AREA

[Austenitized at 1550° F (840° C); oil quenched; tempered at 800° or 900° F (430° or 480° C); billet diameter, 1 in. (2.54 cm).]

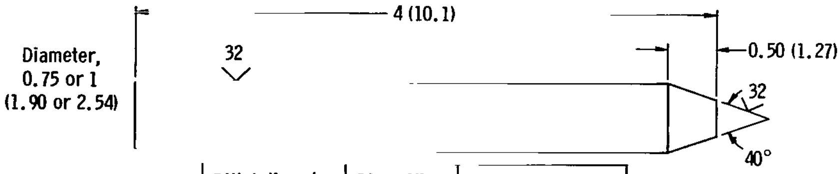
Extrusion number, R_c hardness	Pressure media	Billet lubricant	Extrusion[a] pressure, max/min, ksi (MN/m^2)	Back pressure, ksi (MN/m^2)	Extruded length, in. (cm)	Remarks
1-44	[b]MOG	----------	290/264 (2000/1820)	2.5 (17)	4 (10.2)	Minor surface cracks[c]
2-44	[d]COG	[e]CW-MoS_2	290/260 (2000/1795)	25 (172)	6 (15.2)	Minor surface cracks[c]
3-44	COG	[e]CW-MoS_2	264/248 (1820/1710)	50 (345)	$4\frac{1}{2}$ (11.4)	Minor surface cracks
4-44	[f]VMO	[g]Pb	275/255 (1900/1760)	75 (517)	$7\frac{1}{8}$ (18.1)	Sound extrusion
5-44	VMO	Pb	260/243 (1795/1680)	50 (345)	$5\frac{1}{4}$ (13.3)	Sound extrusion[c]
6-44	VMO	Pb	269/235 (1860/1620)	75 (517)	6 (15.2)	Sound extrusion[c]
7-42	COG	[e]CW-MoS_2	258/232 (1780/1600)	77 (531)	$7\frac{1}{2}$ (19.1)	Sound extrusion
8-42	MOG	[e]CW-MoS_2	316/268 (2180/1850)	50 (345)	3 (7.6)	Sound extrusion
9-42	COG	[e]CW-MoS_2	315/230 (2175/1590)	25 (172)	6 (15.2)	Minor surface cracks

[a]Pressure differential across die.
[b]Mixture of mineral oil and gasoline (equal volumes).
[c]Minor stick slip.
[d]Mixture of castor oil and gasoline (equal volumes).
[e]Castorwax with 20 volume percent MoS_2.
[f]Varsol with 10 volume percent mineral oil.
[g]Lead coating, ~0.0005 in. (0.001 cm) thick.

TABLE IV. - TENSILE PROPERTIES OF AISI 4340 IN PRETEMPERED, COLD WORKED, AND RETEMPERED CONDITIONS

Test	Sample condition								Yield strength (0.2 percent), ksi (MN/m^2)	Tensile strength, ksi (MN/m^2)	Elongation, percent	Reduction in area, percent
	Pretemper			Cold work		Retemper						
	Temperature, °F (°C)	Time, hr	Hardness, R_c	Percent	Hardness, R_c	Temperature, °F (°C)	Time, hr	Hardness, R_c				
1	800 (430)	1	44	--	--	--------	-	--	200.5 (1385)	208.5 (1440)	14.0	54.4
2				--	--	--------	-	--	194.5 (1344)	208.5 (1440)	14.0	54.6
3				50	47	--------	-	--	229.0 (1580)	239.0 (1650)	8.6	46.7
4						400 (200)	1	49	259.0 (1790)	268.0 (1850)	10.0	47.7
[a]5									258.0 (1780)	270.2 (1865)	7.0	47.3
6									258.6 (1785)	268.4 (1855)	12.0	47.3
7									259.0 (1790)	270.0 (1865)	11.0	50.2
8	900 (480)	1	42	--	--	--------	-	--	182.5 (1260)	189.2 (1305)	15.5	56.8
9				--	--	--------	-	--	181.5 (1255)	188.0 (1300)	15.0	55.6
10				50	43	--------	-	--	211.0 (1455)	229.0 (1580)	9.3	48.9
11				50	43	400 (200)	1	46	227.0 (1565)	240.0 (1590)	10.0	48.3
[a]12				67	--	--------	-	--	225.0 (1555)	239.0 (1650)	8.3	46.3
13					--	--------	-	--	225.0 (1555)	254.0 (1755)	7.5	41.5
14					--	400 (200)	1	--	230.5 (1590)	256.0 (1765)	9.5	41.5
15					--	400 (200)	1	--	237 (1635)	258 (1780)	7.5	40.8

[a]Failed outside gage section.



Billet diameter, in. (cm)	Die orifice, in. (cm)	Reduction in area, percent
1 (2.54)	0.707 (1.80)	50
0.75 (1.91)	.680 (1.73)	20

Figure 1. - Steel extrusion billet. Dimensions are in inches (cm).

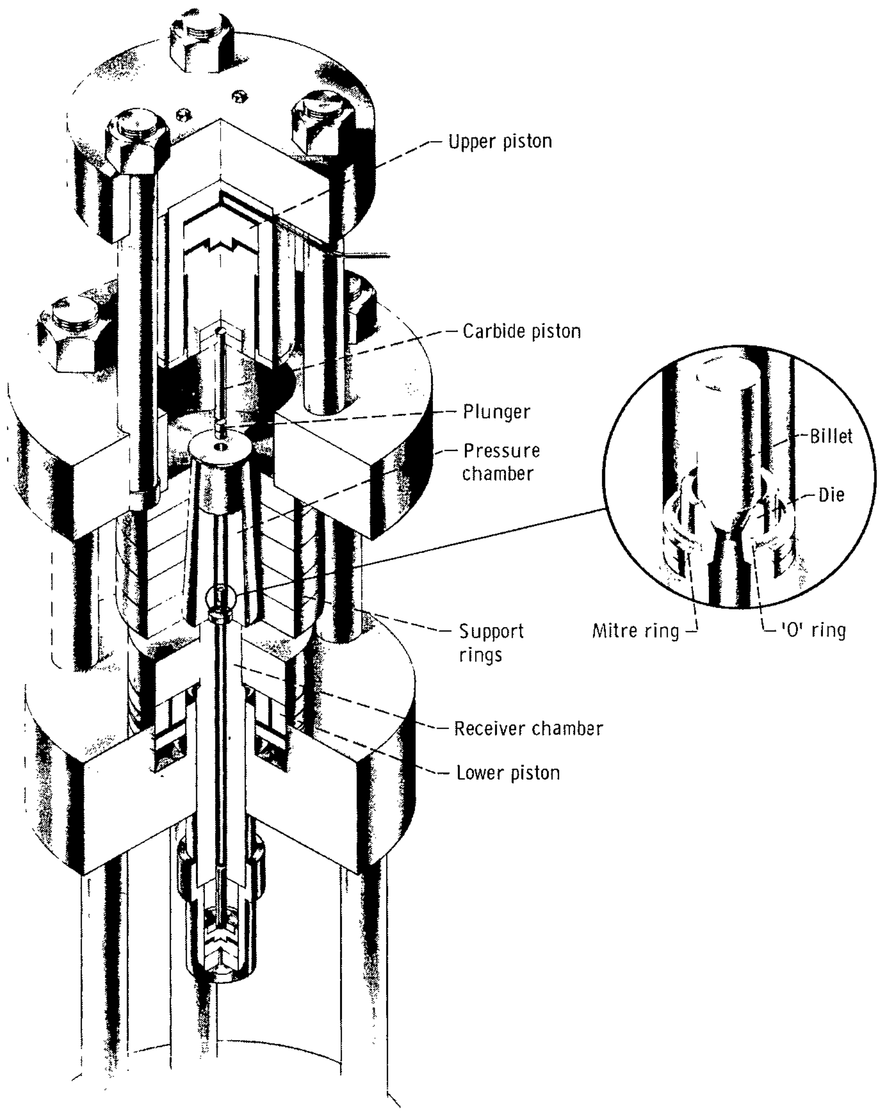
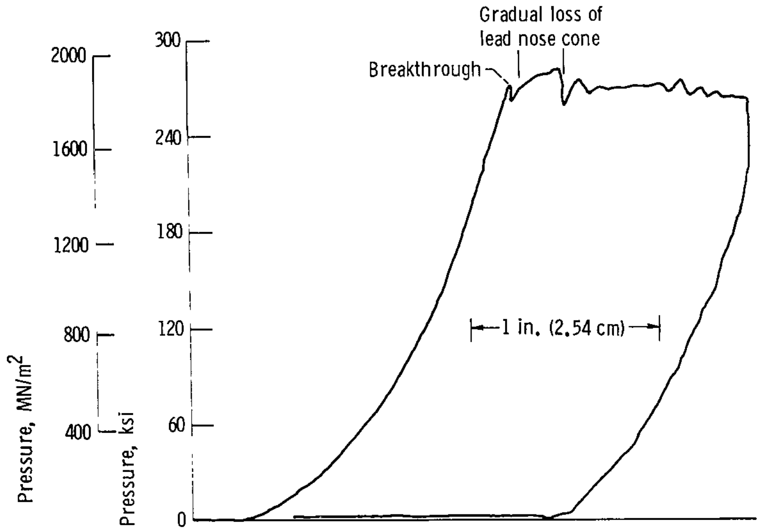
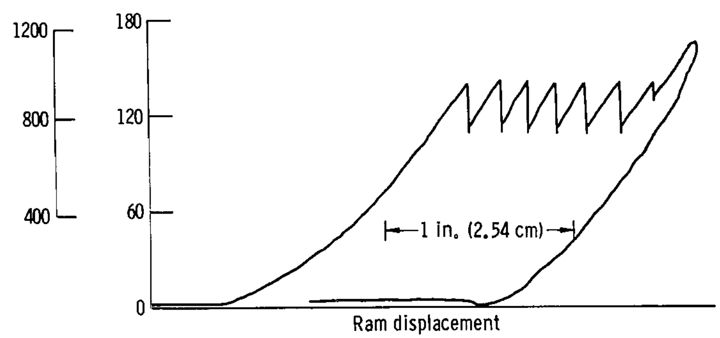


Figure 2. - Hydrostatic extrusion press.



(a) Fairly uniform extrusion; 50-percent reduction in area.



(b) Samples extruded under conditions of stick-slip; 20-percent reduction in area.

Figure 3. - Typical extrusion pressure - ram displacement traces for hydrostatic extrusion of 300-grade maraging steel solution treated and aged 1 hour at 900° F (480° C).

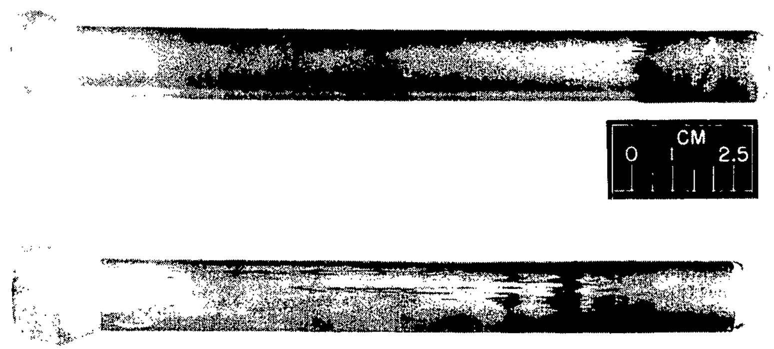


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Figure 4. - 300-Grade maraging steel extrusions. Reduced 50 percent by hydrostatic extrusion.

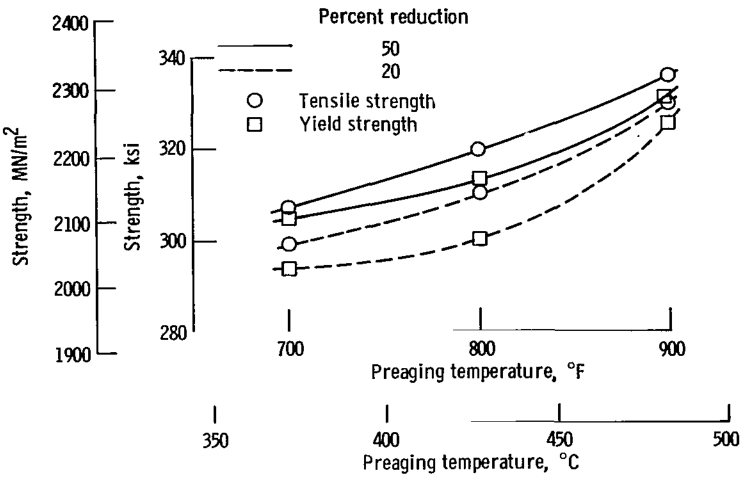


Figure 5. - Effect of preaging temperature on strength of 300-grade maraging steel after cold extrusion. All samples preaged for 1 hour at temperature and aged 3 hours at 900° F (480° C) after cold extrusion. Conventional aging treatment: tensile strength, 291 ksi (2000 MN/m^2); yield strength, 280 ksi (1930 MN/m^2).

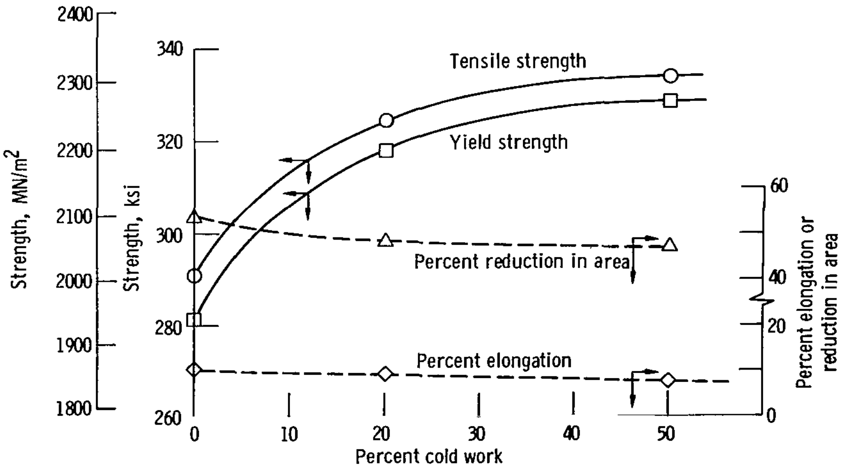
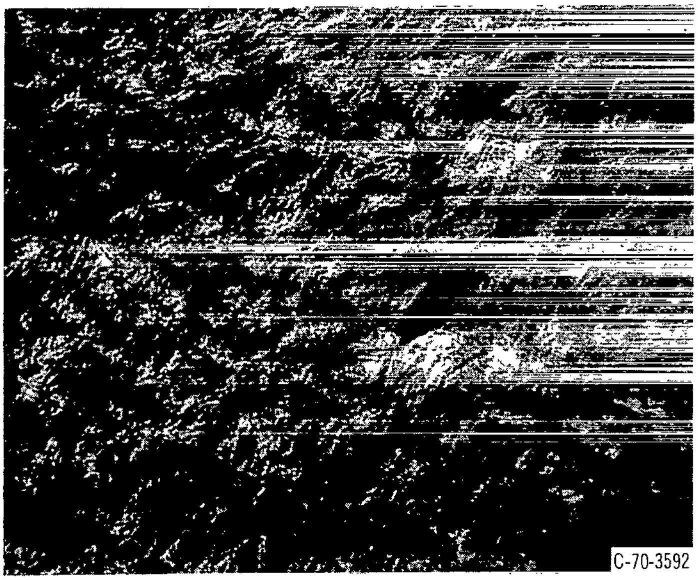


Figure 6. - Effect of cold work on tensile properties of 300-grade maraging steel cold worked in fully aged condition (900° F (480° C), 3 hr) and reaged at 900° F (480° C) for 3 hours.

(a) As-extruded. 0.2μ



(b) Extruded and reaged at 900° F (480° C) for 3 hours.

Figure 7. - Carbon extraction replicas of fully aged, 300-grade maraging steel in as-extruded and extruded and reaged conditions.

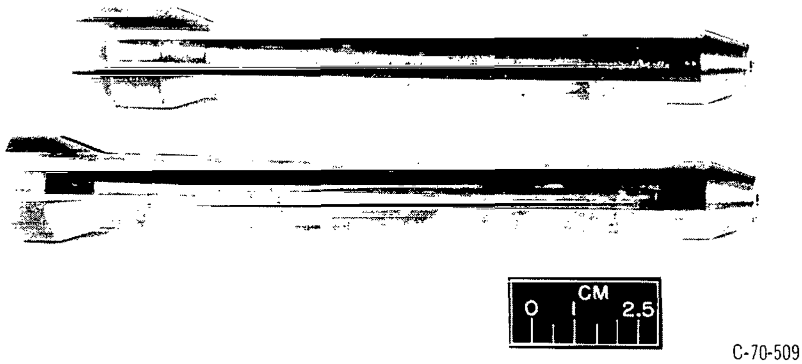


Figure 8. - AISI 4340 steel extrusions. Reduced 50 percent by hydrostatic extrusion.

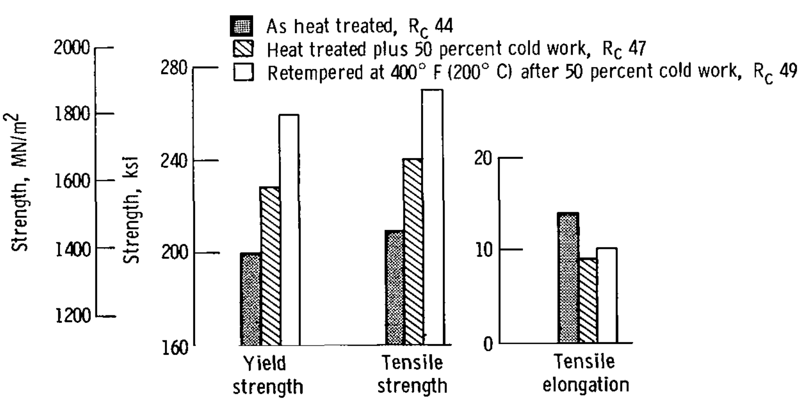


Figure 9. - Effect of cold working and retempering on tensile properties of AISI 4340 steel.

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