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The Cold Reduction of High Strength Materials by Hydrostatic Fluid Extrusion

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ABSTRACT

It is well documented that the ductility of even quite brittle materials can be enhanced if they are deformed under a superposed hydrostatic pressure of sufficient magnitude. The ability to enhance ductility by a superposed hydrostatic pressure is of considerable practical significance and has become the basis for a new family of metal forming processes. One such process is hydrostatic fluid extrusion.

Using a hydrostatic fluid extrusion process, it has been possible to sucessfully cold reduce a variety of high strength materials that, as a result of their strength level and low ductility, could not be deformed by conventional means. The techniques used and the typical results for such materials as T. D. Nickel, Maraging Steel, Nickel-base superalloys and carbon steels in the untempered martensitic condition will be presented.

Of equal importance to the ability of cold reducing such materials is the effect of cold reduction by fluid extrusion upon the subsequent mechanical properties. The significant increases in strength achieved over the conventional properties with little or no change in ductility will be described and discussed.

INTRODUCTION

The effects of high superposed pressure upon the mechanical properties, particularly ductility, of metals has long been of interest. In fact, since the work of VanKarman(1) in 1910, it has been known that the ductility of even the most brittle materials is enhanced if they are deformed while under a superposed pressure of sufficient magnitude. The effects of superposed pressure upon the tensile ductility of a variety of metals have been measured by several investigators.(2)(3)(4)(5) Typical results from these investigations are shown in Figure 1. As can be seen, the type of the ductility-pressure relationship varies considerably between materials ranging from linear for mild steel and cast iron to a brittle-ductile transition behavior in the case of zinc, bismuth, magnesium, tungsten and untempered 4145 steel.

The form of the ductility-pressure curve has been found to be not only affected by the material, but is also structure sensitive and depends upon the condition of heat treatment. Figure 2 shows the form of the ductility-pressure curves for a series of iron-carbon alloys in two conditions of heat treatment.(6) As can be seen, the materials fall into two categories. The 0.004% C and the spheroidized materials, wherein the cementite is in the form of isolated spherical particles in a ferrite matrix, exhibit a linear ductility-pressure relationship with the slope decreasing with increasing carbon content. In the case of the three annealed materials, wherein the cementite is in the form of closely spaced platelets (pearlite) or as a continuous network along prior austenitic grain boundaries, the ductility-pressure relationship is non-linear.

The ability to enhance ductility by pressure is of considerable practical significance and has become the basis for a new family of metal forming processes. One such process is hydrostatic fluid extrusion. Figure 3 compares, in schematic fashion, hydrostatic fluid extrusion and conventional extrusion apparatus. It should be noted that in the hydrostatic fluid extrusion technique the uniaxial ram force of the conventional extrusion technique is replaced by a hydrostatic pressure. The advantages of this technique are to reduce the frictional forces between the billet and the containing vessel and exploit the enhancement in ductility of the deforming billet by the superposed hydrostatic pressure. Accordingly, this technique offers the ability to cold deform a variety of materials previously considered not deformable.

For extremely brittle materials and/or for high reductions, it is possible to further exploit the pressure enhanced ductility of metals by utilizing a fluid to fluid technique. This technique is compared schematically to normal hydrostatic extrusion in Figure 4. With this technique the deforming material leaves the high pressure chamber and enters a pressure chamber of lower hydrostatic pressure; the pressure in this chamber being greater than one atmosphere. Since the pressure differential must remain essentially constant for a given extrusion application, the presence of a high hydrostatic pressure at the die exit necessitates a higher forward pressure. Accordingly, the billet material is inherently more ductile because it deforms at a higher mean pressure.

Using a hydrostatic fluid extrusion process, it has been found possible to successfully cold reduce a variety of high strength materials which, as a result of the strength level and inherently low ductility, could not be deformed by conventional processes. It is the objective of this paper to describe the techniques used and the typical mechanical response for such materials as T.D. Nickel, nickel-base superalloys, maraging steels and low carbon alloy steels in the untempered martensitic condition.

EXPERIMENTAL PROCEDURES AND MATERIALS

Equipment

A schematic of the fluid extrusion system utilized in these investigations is shown in Figure 5 and a photograph of the apparatus in Figure 6. The system, as shown in Figure 5, is composed of three main segments consisting of an extrusion pressure chamber, extrusion die and die support, and an exit pressure chamber. The extrusion pressure chambers are joined by the die support.

The high pressure chamber consists of a one inch internal bore diameter. The tapered cylinder or liner of 250 grade maraging steel mates with the tapered support ring of AISI 4340 steel. Pressure is generated by means of the 188-ton jack which forces a tungsten carbide piston into the chamber. The pressure capacity of the billet chamber is 450 ksi. To prevent plastic flow or fracture of the liner at this pressure level, the tapered liner is forced into the matching tapered jacket by means of the 750-ton jack. In this manner, the stresses in the liner are progressively counteracted by increasing the 750-ton jack pressure as the billet chamber pressure is increased.

The exit chamber consists of a 3/4 inch internal diameter 250 grade maraging liner with an AISI 4340 steel jacket. Back pressures up to 300 ksi can be developed by the 70-ton jack which forces a piston into the chamber.

The extrusion die and die support are fabricated of a 350 grade maraging steel. The extrusion die has a 45° included entrance angle.

Schematic representations of sealing arrangement for the extrusion die is shown in Figure 7.

Materials

The chemical composition of the materials used for this investigation is shown in Table I. All the materials were in the wrought condition except INCO 713LC which was in the cast form and one form of the T.D. Nickel which was in the pressed and sintered condition.

The mechanical properties of the nickel-base superalloys and T.D. Nickel were determined using an 0.125 inch diameter, 0.500 inch gage length tensile specimen utilizing a strain rate of 0.005 in/in/min. Standard 0.252 tensile specimens were used for the 18 Nickel maraging and low carbon martensitic steels utilizing the same strain rate.

Extrusion Procedure

Each of the extrusion billets was machined to the diameter necessary for the desired reduction. The length of each billet was four inches and a 45° included angle was machined on the forward end to match the extrusion die angle. Each billet was then sandblasted and coated with either Emerlon 323 (for use up to pressures of 230 ksi), a resin bonded colloidal teflon or a baked teflon coating (for use at pressures greater than 230 ksi). The pressure medium was either caston oil (less than 230 ksi) or a mixture of 75% glycerine and 25% ethylene glycol (greater than 230 ksi).

RESULTS AND DISCUSSION

T.D. Nickel

No difficulties were encountered in cold extruding commercial T.D. Nickel to reductions of 78% R.A. by hydrostatic fluid techniques. The room temperature tensile mechanical properties of this material at various reductions are shown in Table II. It should be noted that the strength was significantly improved with a corresponding slight improvement of ductility as a result of the cold reduction.

In addition, a comparison of hot tensile mechanical properties of the as-received and cold worked (78% R.A.) materials was made at a test temperature of 1600°F. As can be seen in Table II, the mechanical properties were found to be essentially equivalent since any increase in strength due to strain hardening would be reduced by annealing effects.

It was also attempted to extrude T.D. Nickel in the pressed and sintered condition directly into a usable product. For this purpose, the pressed and sintered compact was fitted into a hollow container which had been machined to the shape of an extrusion billet.

Some difficulties in the form of transverse cracking were encountered by extrusion of the pressed and sintered T.D. Nickel billets. The cracking problem was eliminated when a back pressure of 90 ksi was used in the exit chamber. A comparison of the two techniques is shown in Figure 8. The sound product was extruded using the 90 ksi back pressure. Table II shows the mechanical properties of the pressed and sintered T.D. Nickel compacts. It should be noted that at a reduction of 78% R.A., the properties are essentially identical for both the conventionally processed material and the material extruded directly from the pressed and sintered condition.

Maraging Steels

The reductions investigated and the nominal extrusion pressures required for the maraging steels studied are summarized in Table III.(7) It should be noted that in the case of the 250 and 350 grade maraging steels extruded in the solution-treated and aged condition, reductions of 65% R.A. and 25% R.A. respectively were obtained. Reductions of up to 50% were also accomplished in the 250 grade steel in the solution-treated condition. Much higher reductions are possible, but for this investigation such reductions were not required.

To investigate the necessity to use hydrostatic fluid extrusion to plastically deform high-strength materials such as maraging steels, the hydrostatic extrusion press was modified to do conventional extrusion. Figure 9 compares the extruded product of both conventionally and hydrostatically extruded 250 grade maraging steel in the fully heat treated (solution treated plus aged) condition. It is clearly shown that these materials cannot be plastically deformed to large reductions at room temperature without massive cracking of the extruded product.

The effects of cold reduction by extrusion on the tensile mechanical properties of 250 grade maraging steel extruded in the solution-treated, and solution-treated and aged condition and post-aged condition after extrusion in the solution-treated and aged condition are seen in Figures 10, 11 and 12, respectively. It should be noted that, in general, the strength increases and the ductility remains essentially constant with increasing amounts of cold work. The greatest increase in strength (77 Ksi) was achieved when the material was extruded in the fully heat-treated condition followed by re-aging (Figure 13).

Figure 13 shows the effect of cold deformation by hydrostatic fluid extrusion on the tensile mechanical properties of 350 grade maraging steels in the fully heat-treated condition. Again, the strength increased with no loss in ductility.

Nickel-Base Superalloys

Table IV shows the effect of cold reduction on the mechanical properties of several nickel-base superalloys.(8) It is of importance to note that in all cases the cold reduction had a considerable effect on enhancing the strength of already high strength materials. This strength increase was due to strain hardening in combination with enhanced secondary precipitation during the re-aging treatment.

The effects of cold reduction on ductility tended to vary widely between materials. Rene 41 exhibited no significant ductility change. The Inconel 718 exhibited a ductility decrease, but, considering the strength increase, it is not deemed too serious. The Udimet 630 alloy lost significant ductility whereas the as-cast INCO 713LC actually increased substantially in ductility.

Low-carbon Martensitic Steels

The effect of various amounts of cold reduction by hydrostatic fluid extrusion on AISI 4320 and 4340 steels in the quenched and untempered condition are shown in Figures 14 and 15, respectively. As can be seen, the strength increased with little or no loss of ductility. A post-extrusion tempering treatment at 400°F had a negligible effect upon the mechanical properties.

CONCLUSIONS

In general, it can be concluded that the enhancement in ductility due to superposed pressure can be utilized to cold reduce many materials by hydrostatic fluid extrusion that cannot be cold worked by conventional techniques. The mechanical properties of the extruded products invariably show an increase in strength due to strain hardening and in cases enhanced secondary precipitation. With the exception of Udimet 630 alloy which exhibited a severe degradation in ductility and as-cast INCO 713LC which exhibited a large increase in ductility, the ductility remained essentially constant with increasing amounts of cold reduction and associated increase in strength.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Dr. J. Uy to some of the early work on the extrusion on AISI 4320 and 4340 steels and to Mr. H. Nazarian for his assistance in the performance of the extrusion experiments.

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TABLE I

CHEMICAL COMPOSITIONS OF THE VARIOUS MATERIALS STUDIED (WT.%)

MATERIAL	C	Mn	Si	Ni	Cr	Mo	Co	Ti	Al	Fe	OTHER
Inconel 718	0.05	0.01	0.10	53	18.2	3.1	--	1.1	0.5	18.0	5.4 (Ta + Cb)
René 41	0.09	0.04	0.10	55	18.8	9.8	11.3	3.2	1.6	1.4	--
Udimet 630	0.03	0.15	0.10	57	7.3	2.9	0.10	1.0	0.6	17.5	--
Inco 713LC	0.06	1.0	0.10	72	13.5	4.5	0.11	0.80	6.1	0.2	0.01(B), 0.08(Zr) 2.4 (Ta + Cb)
250 Grade Maraging	0.006	0.01	0.02	18.31	--	4.81	7.33	0.46	0.10	Bal	--
350 Grade Maraging	0.009	0.01	0.02	18.12	--	4.80	12.37	0.66	0.45	Bal	0.50(W), 0.99( )
4320	0.19	0.76	0.29	1.89	0.82	0.30	--	--	--	--	--
4340	0.37	0.78	0.29	1.90	0.85	0.30	--	--	--	--	--
T.D. Nickel	--	--	--	98	--	--	--	--	--	--	2.0 (ThO_2)

TABLE II

MECHANICAL PROPERTIES OF T.D. NICKEL

CONDITION	TEST TEMP.	0.2% YIELD STRENGTH KSI	TENSILE STRENGTH KSI	PERCENT ELONGATION	PERCENT R.A.
As Received*	Room	103	115	23	57
Extruded, 50%	Room	125	132	16	65
Extruded, 78%	Room	135	144	20	68
As Received*	1600°F	31.8	32.2	0.05	9
Extruded, 78%	1600°F	33.8	34.0	2.0	8
As Received** + Extruded, 78%	Room	135	144	21	67

* Pressed, Sintered, Hot Extruded, Cold Swaged and Recrystallized
**Pressed and Sintered

TABLE III

SUMMARY OF EXTRUSION CONDITIONS FOR THE 18 Ni MARAGING STEELS

MATERIAL	CONDITION	COLD EXTRUSION % R.A.	EXTRUSION PRESSURE KSI
250 Grade Maraging	Solution Treated	15	68
		25	104
		35	124
		50	156
	Solution Treated and Aged	15	107
		25	136
		35	181
		50	265
		65	346
350 Grade Maraging	Solution Treated and Aged	15	121
		25	234

TABLE IV

MECHANICAL PROPERTIES OF NICKEL BASE SUPERALLOYS

MATERIAL	CONDITION	EXTRUSION PRESSURE KSI	0.2% YIELD STRENGTH KSI	TENSILE STRENGTH KSI	PERCENT ELONGATION %	REDUCTION OF AREA %
Inco 713LC	As Cast	--	111.6	139.0	14	15
	Extruded 50%	17.1	136.5	149.0	18	71
Inconel 718	As Heat Treated	--	153.4	198.5	20	30
	Extruded 50% + Re-Aged	15.1	300.0	304.8	2	5
René 41	As Heat Treated	--	133.8	193.2	7	12
	Extruded 50%	15.8	243.0	291.0	3	11
Udimet 630	As Heat Treated	--	177.6	204.0	8	10
	Extruded 50% + Re-Aged	15.6	268.8	268.8	0	0

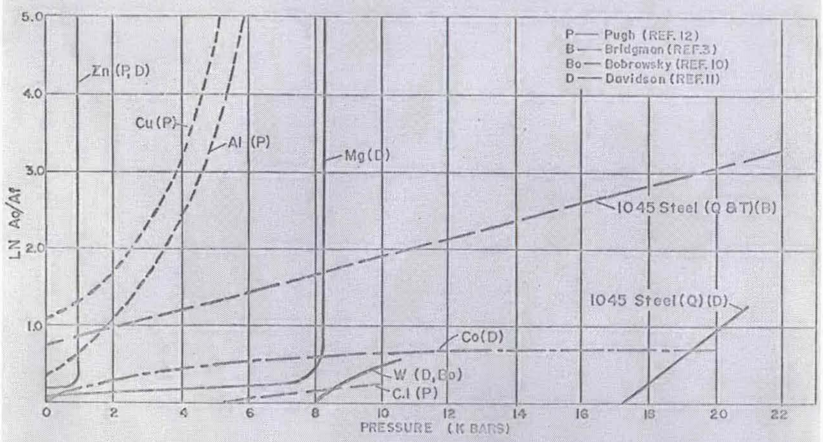


FIGURE 1. DUCTILITY VERSUS PRESSURE FOR VARIOUS TYPICAL MATERIALS

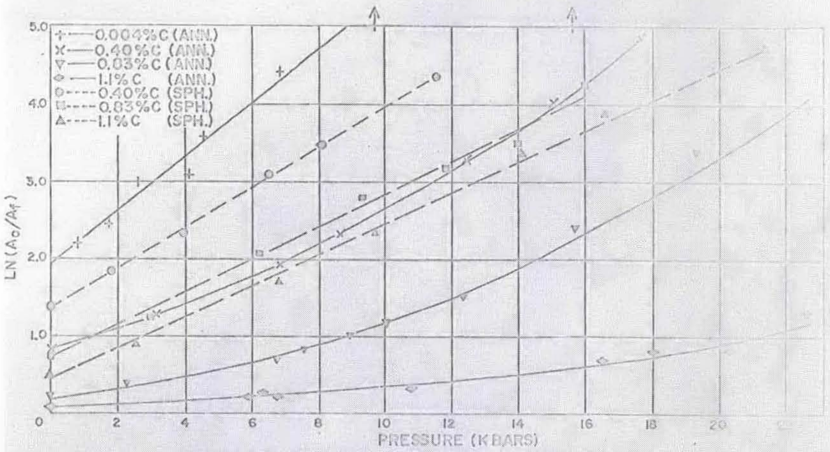
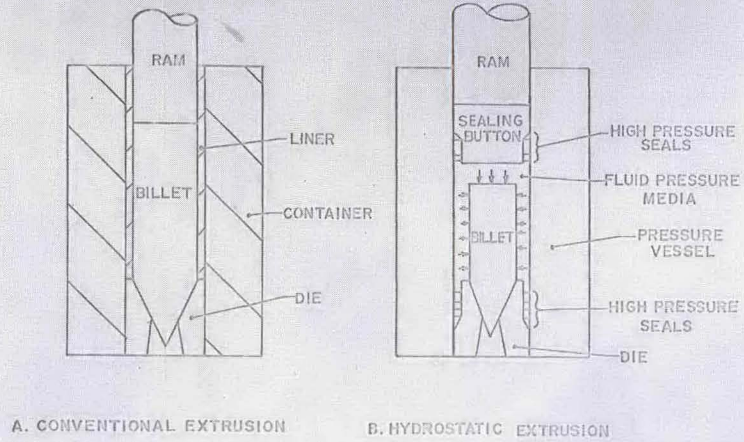


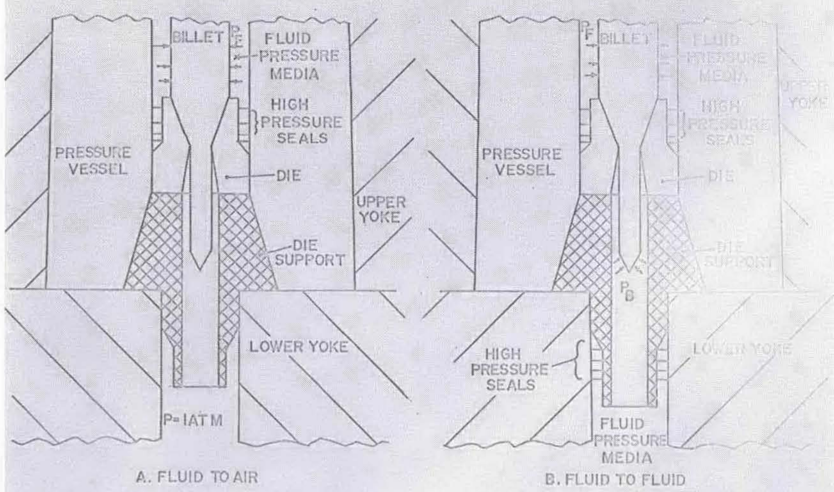
FIGURE 2. DUCTILITY VERSUS PRESSURE FOR Fe-C MATERIALS



A. CONVENTIONAL EXTRUSION

B. HYDROSTATIC EXTRUSION

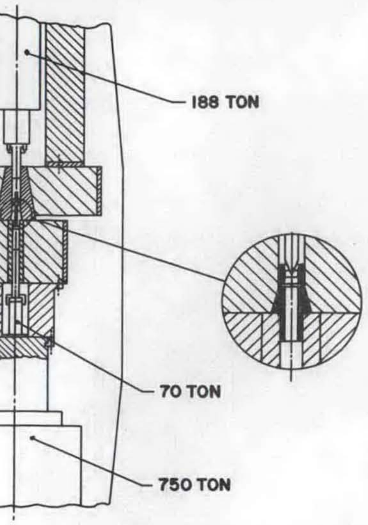
FIGURE 3. SCHEMATIC REPRESENTATION OF VARIOUS EXTRUSION TECHNIQUES



A. FLUID TO AIR

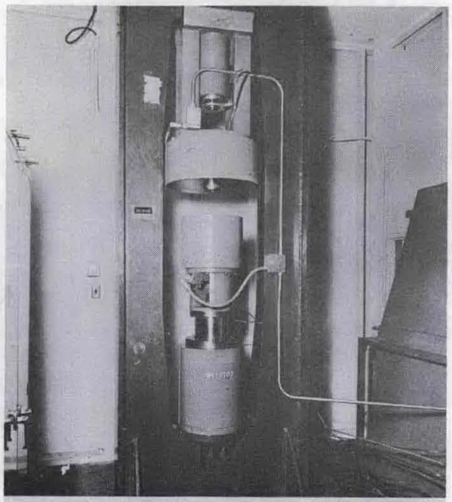
B. FLUID TO FLUID

FIGURE 4. SCHEMATIC OF HYDROSTATIC FLUID TO ATMOSPHERE AND FLUID TO FLUID EXTRUSION TECHNIQUES



ATIC EXTRUSION PRESS

FIGURE 5



HYDROSTATIC FLUID EXTRUSION PRESS

FIGURE 6

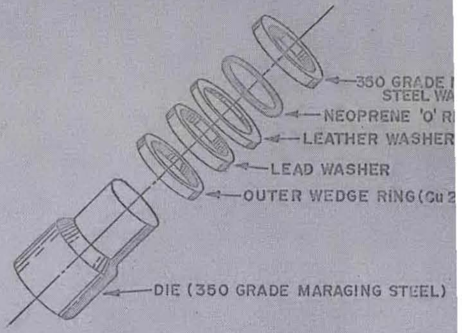
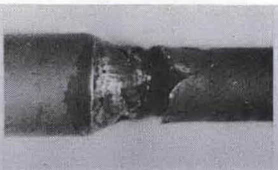
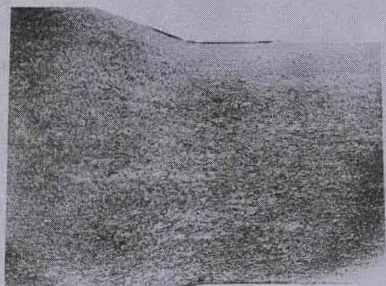


FIGURE 7. HIGH PRESSURE SEALING ARRANGEMENT FOR EXTRUSION DI



A. CONVENTIONAL EXTRUSION



B. HYDROSTATIC EXTRUSION:
EXTRUSION PRESSURE - 258 KSI

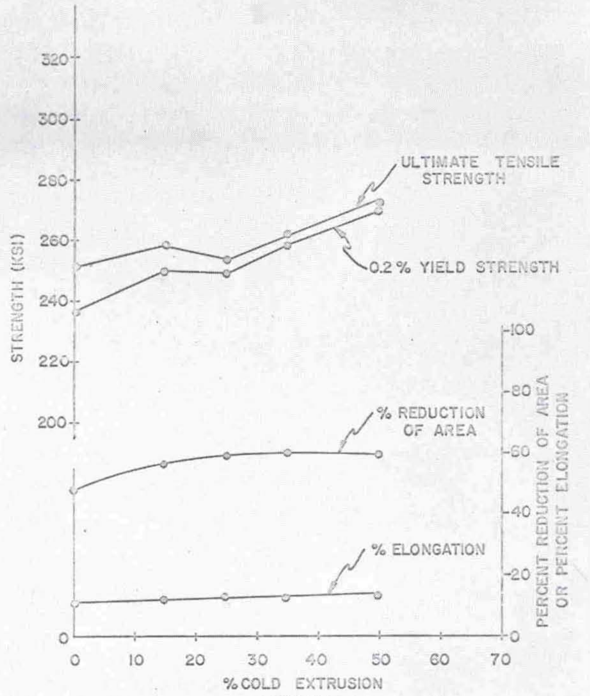
FIGURE 9 250 GRADE 18% NICKEL MARAGING STEEL EXTRUDED 50% IN THE FULLY HEAT-TREATED CONDITION BY TWO TECHNIQUES

75% FLUID EXTRUSION INTO A BACK PRESSURE OF 90KSI FLUID

75% FLUID EXTRUSION INTO ATOMSPHERE

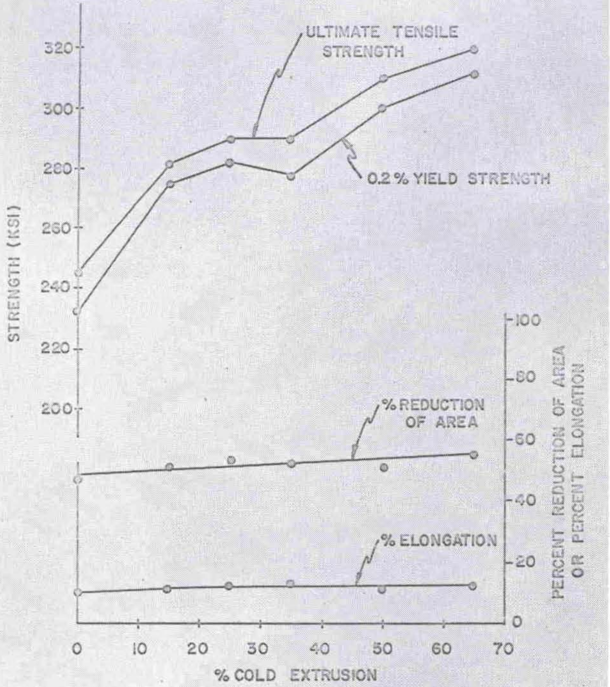
COMPARISON OF T.D. NICKEL EXTRUDED FLUID TO FLUID AND FLUID TO ATMOSPHERE

FIGURE 8



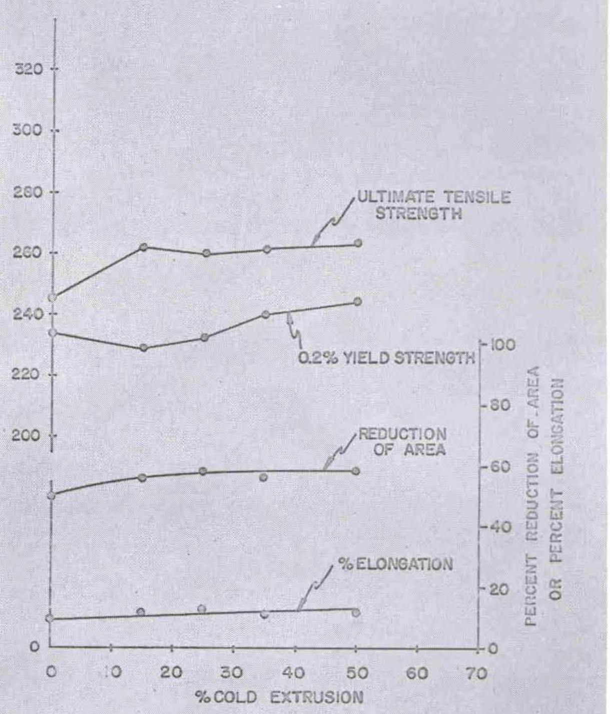
MECHANICAL PROPERTIES VERSUS PERCENT COLD REDUCTION BY FLUID EXTRUSION IN THE SOLUTION TREATED CONDITION — 250 GRADE MAR-AGING STEEL POST AGED AT 900°F - 3 HRS—AC

FIG 10



MECHANICAL PROPERTIES VERSUS PERCENT COLD REDUCTION BY FLUID EXTRUSION IN THE SOLUTION TREATED AND AGED CONDITION —250 GRADE MAR-AGING STEEL POST AGED AT 900°F — 3 HRS — AC.

FIG 12



MECHANICAL PROPERTIES VERSUS PERCENT COLD REDUCTION BY FLUID EXTRUSION IN THE SOLUTION TREATED AND AGED CONDITION — 250 GRADE MAR-AGING STEEL.

FIG 11

MECHANICAL PROPERTIES VERSUS PERCENT COLD REDUCTION BY FLUID EXTRUSION IN THE SOLUTION TREATED AND AGED CONDITION -350 GRADE MAR-AGING STEEL POST AGED AT 950°F -3 HRS-AC.

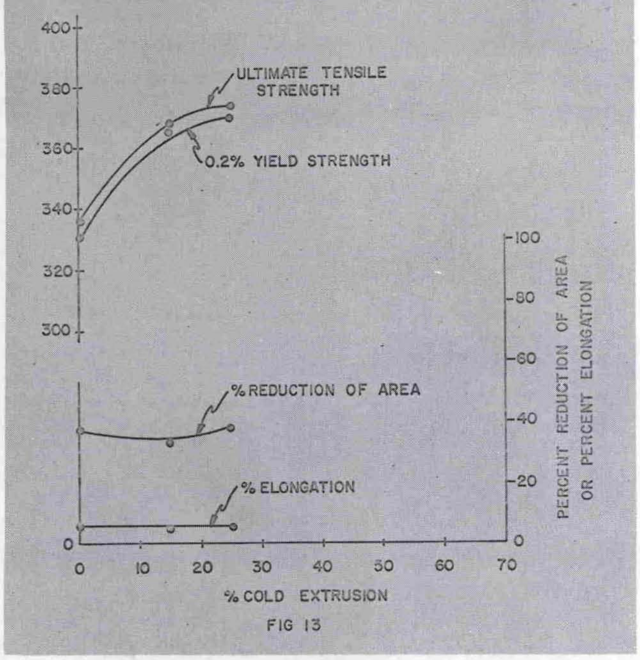


FIG 13

MECHANICAL PROPERTIES VERSUS PERCENT COLD REDUCTION BY FLUID EXTRUSION IN THE UNTEMPERED MARTENSITIC CONDITION - 4320 STEEL.

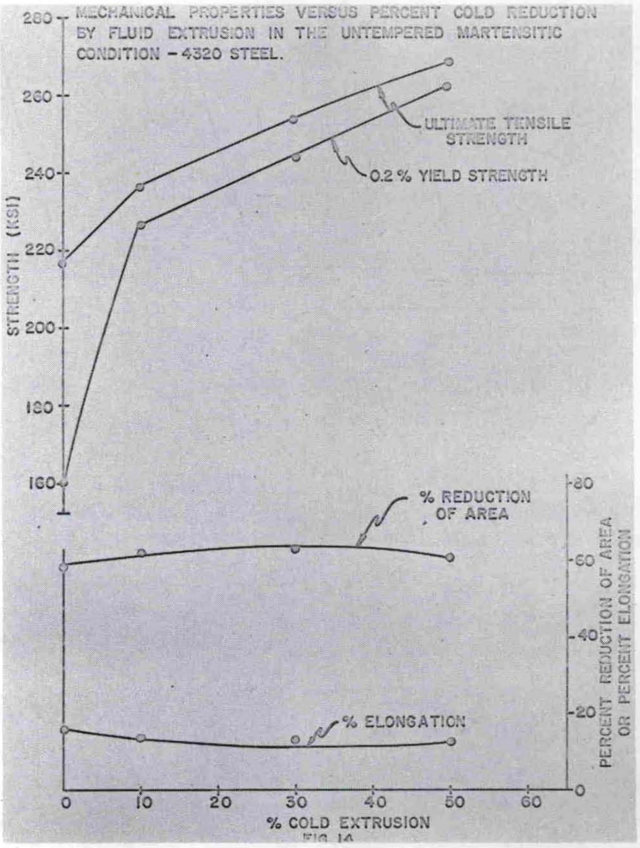


FIG 14

MECHANICAL PROPERTIES VERSUS PERCENT COLD REDUCTION BY FLUID EXTRUSION IN THE UNTEMPERED MARTENSITIC CONDITION - 4340 STEEL.

FIG 15