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Forging and extrusion of powder metallurgy preforms

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FORGING AND EXTRUSION OF POWDER METALLURGY PREFORMS

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ABSTRACT

Investigators have shown that properties of materials made by powder metallurgy techniques may vary considerably for the same level of density depending on the combination of processing variables. In particular, the nature of and amount of plastic flow which takes place has been shown to be significant.

This study treats the forming process for P/M preforms in terms of three major parameters: preform density, amount of deformation, and environmental pressure. Hydrostatic extrusion and restrained disk forging are two processes particularly suited for studies of this nature. The product properties are a function of the energetically favorable flow pattern under the conditions of forming. Those property trends which would be expected for hydrostatic extrusion are discussed. A commercially pure iron powder and an experimental aluminum alloy powder are utilized in experimental studies of actual property trends.

The experimental results indicate that there is a critical amount of deformation for achieving optimum properties. Greater deformations are seen to result in material degradation. The effects of preform density on properties are found to be complex and not amenable to simple explanation.

INTRODUCTION

Typical P/M parts seldom exhibit the properties of chemically similar wrought or cast materials because their normal, residual porosity decreases strength, ductility, and resistance to impact and fatigue failure. Many investigators have since shown that product properties may vary considerably for the same level of density depending on the combination of processing variables. In particular, the nature of and amount of plastic flow which takes place has been shown to be significant. It is therefore desirable to gain an understanding of these parameters and determine whether attempts at optimization would be productive.

This discussion is based on the concept that the forming process for P/M preforms can be treated in terms of three major parameters: preform density, amount of deformation, and environmental pressure. It is obvious that preform density and amount of deformation affect the mode of plastic flow; in addition it can be shown that the environmental pressure (hydrostatic stress component) is an important factor in deformation of porous materials.

It should be pointed out that the concepts presented here are derived from a mechanistic approach to the subject. The goal is description and explanation of general trends. The exact nature of these trends will be influenced by the particular material considered and by characteristics of specific powders. Material and powder characteristics are secondary in effect to the overall trends and can be better understood in light of the general concepts.

Two metal forming processes which lend themselves well to a study of this nature are hydrostatic (fluid to fluid or fluid to air) extrusion and restrained disk forging. These processes have been analyzed by Avitzur and co-workers (1-8) and the parameters are well understood.

A schematic diagram of the process and equipment for hydrostatic extrusion is presented in Figure 1. A cylindrical billet is inserted in a conical converging die. The area above the die is filled with an appropriate fluid which is pressurized by the descending ram. The billet is extruded through the die into the receiving chamber. The receiver chamber can be at ambient pressure or may also contain fluid at a lower pressure than the upper chamber. The entire process takes place at approximately room temperature. The major advantages of hydrostatic extrusion in the study of deformation are the capability for controlling environmental pressure and the fact that the billet makes physical contact with the die only.

The process of disk forging, as illustrated in Figure 2, can be performed with an applied environmental pressure through the use of a restraining ring in the form of a hollow disk. The ring is forged along with the preform. The analysis of hollow disk forging by Avitzur (1-3) allows accurate prediction of the deformation behavior of the ring. The amount of side restraint introduced by the tendency of the hollow disk to flow inwardly is controlled by the ring geometry. This process has the added advantage of being able to control environmental pressure at temperatures above room temperature. It should be pointed out that the concepts developed for metal forming under applied environmental pressure are applicable to many practical metalworking processes and are not limited to the laboratory.

DEFORMATION CONCEPTS

When a material is subjected to a metal forming process, its properties can be improved or be degraded depending on the original properties, the amount of deformation, and the mean pressure accompanying deformation. Figure 3 is a schematic illustration of these effects for the process of hydrostatic extrusion. The abscissa is the percent reduction in area of the billet in a hypothetical case of pressure to pressure extrusion. The ordinate is the density of the product relative to the theoretically dense metal. The parameter is the mean pressure prevailing during the forming process. Three qualities of raw material are presented: perfectly dense material, material of normal porosity, and extensively porous material. For brevity, this discussion excludes factors other than mean pressure, such as cone angle, friction, and porosity distribution.

Perfectly dense material cannot be made more dense by forming, it can only deteriorate. High receiving pressure can minimize the deterioration however.

Normally porous material undergoing gross plastic deformation may increase or decrease in density. Logic demands and experience shows that, with the exception of strain induced transformation materials, an increase in density must be associated with a closure of the pores. Similarly a decrease in density is associated with an increase in the size of existing pores, and/or with the creation of new pores. As pores become larger or as new pores are introduced during the deformation process, they decrease the ductility of the product and may eventually cause fracture by coalescence of the voids. However, if properly applied, the deformation process can also close existing pores and improve the ductility of the product.

P/M preforms fall into the third category, very porous materials. To a degree, the larger the reduction the more dense the product becomes; however, beyond a certain reduction, density may decrease. Introducing a receiving pressure increases the mean pressure of the process, and the improvement in density is then more pronounced and continues to occur at higher reductions. Nevertheless, beyond some critical reduction, the density may start to drop. Theoretically, the mean pressure can always be made large enough so that, for any finite reduction in area, the density will continue to increase. This required pressure may, however, exceed the capacity of available equipment.

When the density of a material decreases at high reductions, it is thought to be due to void initiation, growth of existing voids, or both. If one or both of these phenomena occur, it is assumed that the flow pattern of the material which permits void creation and/or growth is energetically more favorable than sound flow with no void formation. The application of receiver pressure changes the flow pattern of the material by changing the energetics of the process. In pressure-to-pressure extrusion, the extrusion pressure provides the required power, part of which is required to overcome the pressure in the receiver chamber. The power required to overcome the pressure in the receiving chamber (p_b) according to Avitzur (1) is

$$\dot{W} = \dot{V} \cdot p_b$$

where $\dot{V}$ is the volume rate of the emerging product. When pores are closing, the emerging volume rate decreases; when pores open, the volume rate increases.

Higher receiver pressures will require more power to force the product into the pressurized receiving fluid. To minimize the total power, any decrease in $\dot{V}$ associated with decreasing pore size will be very effective when high receiving pressures are considered. Although the receiver power is insignificant at low receiver pressure, it may become a predominant factor at very high receiver pressures. To become effective, receiving pressures of the order of magnitude of the flow stress of the deformed material are usually considered necessary.

It is felt that curves of the same general form as Figure 3c represent the behavior of P/M produced materials with regard to properties other than relative density. Ductility, fatigue life, or impact resistance may reasonably be expected to exhibit the same characteristics although it should not be inferred that the optimum reduction, if one exists, would be the same for all of them.

At the magnitudes attainable by present day equipment, hydrostatic pressure alone, without an accompanying metal forming process, cannot close pores. Although on the macroscale, the pores are still very small compared to the billet. Both pressure and deformation are necessary to cause complete void closure in a material. Bulychev et al (9) presented data which showed that hydrostatic pressure as high as 100,000 atmospheres without simultaneous plastic deformation is not sufficient to eliminate voids and cracks in copper. However, with the shear induced during hydroextrusion, such defects were repaired. By assuming the pressure inside a void to be one atmosphere and that the outer pressure required to cause plastic deformation is related to the inner pressure by an equation of the same form as that for a thick wall sphere, Stassi (10) has shown that the required outer pressure is immense.

Stassi's expression for relative critical pressure required to cause contraction of spherical voids by pressure alone as was also computed through the upper bound approach (7) reads,

$$\frac{p_{cr}}{\sigma_o} = 2\ell n \frac{R_o}{R_i}$$

where σ_o is the flow stress of the material. As R_i decreases, relative critical pressure increases so that the void can never close to $R_i = 0$ by the application of any finite pressure. It can be concluded that without an accompanying deformation process, hydrostatic pressure alone, at least at magnitudes obtainable with current technology, cannot completely close voids.

Kahlow (11) has concluded that the effect of deformation in enhancing material properties is two-fold. First, the deformation flow pattern can alter void geometry and lower the critical pressure necessary to initiate void closure. Second, the shear induced during deformation causes sliding contact of the internal void surfaces, which may become welded in intimate contact.

The importance of plastic flow in P/M forming is undeniable. The nature and amount of flow which occurs for a given reduction in area is highly dependent on initial preform density. Moyer (12) has investigated room temperature plane strain deformation of sintered atomized iron preforms. He concludes that preform density has little influence on impact strength at relatively low forged densities. At high forged densities, flow and hence preform density is shown to result in optimum properties. This is explained by the fact that less strain is required to achieve full density for high preform densities and additional work is required to produce flow necessary to promote strong bonding at interfaces caused by pore closure. For the case of low density preforms, most of the work is spent initially on closing pores, again additional work is required to attain optimum properties.

The experimental work undertaken at Lehigh is directed toward determining the validity of the above concepts. The effects of preform density, effective strain, and environmental pressure are considered. Two distinctly different materials were compared. However, for each single material, variations in powder characteristics were minimized by using powder from a single lot.

EXPERIMENTAL STUDIES

An overall view of the processing sequence is presented in Table I for the two materials included in this study. It should be noted that the first four steps in each case were performed by the material supplier.

Materials

Hoeganaes Corporation has furnished pressed and sintered commercially pure water atomized iron powder preforms. Three preforms densities were provided: 5.5 gm/cc, 6.2 gm/cc, and 7.1 gm/cc. Taking the theoretical density of iron as 7.86 gm/cc, the respective percentages of theoretical density are 70.0%, 78.9%, and 90.3%. After pressing, the material was sintered at 2050°F in an atmosphere of dissociated ammonia for 1/2 hour.

A developmental aluminum alloy preform material has been supplied by Alcoa. Designated MA67, this aluminum base material nominally contains 8% Zn, 2.5% Mg, 1% Cu, and 1.6% Co. The details of powder preparation and the exact melt analysis are provided in Table I. After annealing, the powder was cold pressed to densities of 2.43 gm/cc, 2.54 gm/cc, and 2.66 gm/cc at respective pressing pressures of 23.3, 33.3, and 48.3 ksi. Using a nominal density of 2.879 gm/cc, the respective theoretical densities are 85%, 89%, and 93%.

Hydrostatic Extrusion Procedure

The steps in preparing for hydrostatic extrusion are similar for both materials. Small billets were machined from the stock supplied with the nose prepared to fit the cone angle of the die. Since the materials are porous, they must be protected from infiltration by the pressurized extrusion fluid. This was done by inserting the machined billet into a brass tube with a matching nose configuration. The front of the encased billet is sealed with solder and the rear is sealed with an appropriately sized brass disk soldered into place to insure that no fluid enters. The complete billet-tube assembly is then extruded.

All extrusion dies were prepared with a 15° semi-cone angle from maraging steel (300 ksi nominal yield strength). Each billet had the same initial diameter, various reductions were achieved through the use of dies with different exit diameters. The extrusion fluids used were soybean oil, a mixture of 75% soy oil - 25% kerosene, and gasoline depending on the extrusion pressure expected. Beeswax was used to coat the outside of the tube. This serves as an initial sealant as the pressure is raised and also is a lubricant during extrusion.

Testing

Density meansurements were made by a standard weigh in air - weigh in water technique. The results of these density measurements are presented in Figures 4 and 5 for iron and MA67 respectively.

Both materials were thermally treated following extrusion and density measurements. The iron was resintered at 2050°F for 1/2 hour in an atmosphere of dissociated ammonia. The aluminum alloy was tightly wrapped in aluminum foil; then held at 840°F for 2 hours, cold water quenched, and held at 250°F for 24 hours. This heat treatment was required because the as extruded MA67 proved too brittle to machine successfully.

The thermally treated extrusions were then tested to determine tensile strength and ductility as functions of preform density and percent reduction by hydrostatic extrusion. The results of these tests are presented as Figures 6 - 13.

DISCUSSION

The variation in density as a function of percent reduction by hydrostatic extrusion for sintered iron preforms is shown in Figure 4. Similarly the data for the aluminum alloy MA67 are shown in Figure 5. It can be seen that the hydrostatic extrusion process is very efficient in bringing the density to 98% of theoretical or greater. Both figures indicate that the density will decrease for very high reductions compared to moderate reductions. This indicates that at very high reductions the energetically favorable flow pattern for the material is conducive to pore growth, pore initiation, or both.

Plots of ductility and tensile strength versus deformation for sintered iron with 7.1 gm/cc preform density are shown in Figures 6 and 7. Ductility is represented by total percent reduction in area of a tensile specimen while tensile strength is the engineering stress at maximum load. Note that an optimum amount of deformation is seen for maximum ductility beyond which the ductility decreases sharply. Referring back to Figure 6, it may be seen that this is the same reduction above which density began to fall off. Tensile strengths fall in a fairly narrow range, but there is a definite trend toward increasing strength with increasing deformation. This material was sintered between the steps of extrusion and tensile testing, therefore the increasing strength is not attributable to cold working.

Similar plots of ductility and tensile strength versus deformation are shown in Figures 8 and 9 for the aluminum alloy. In Figure 8 it is seen that for each preform density the ductility starts at zero until some particular amount of deformation has been attained. Ductility then increases to a maximum until at a higher deformation it drops off. These findings are consistent with what has been suggested previously. The data relating tensile strength to deformation for the same specimens is presented in Figure 9. Here one notices generally increasing tensile strength with deformation until a drop-off occurs at high reductions. In two of the cases the strength rises again after the drop. These variations are not considered significant due to limited data and are assumed to be statistical deviations. Such deviations are not surprising in view of the high strength and low ductility nature of this particular aluminum based alloy.

The variation in properties as a result of three different preform densities with a constant amount of deformation for sintered iron is shown in Figures 10 and 11. If the reduction in area of a tensile specimen may at least qualitatively be considered to relate to toughness, the results of Figure 10 agree with those found by Moyer (12) for forging of various preform densities. The maximum strength and maximum ductility for sintered iron are both seen to correspond to the intermediate preform density. Since the unalloyed iron is not responsive to heat treatment, it is assumed that the properties are directly related to pore deformation behavior.

The variations in ductility and tensile strength with preform density are shown for several different levels of deformation of the aluminum alloy in Figures 12 and 13. No measurable ductility was observed for any preform density at the lowest reductions of 52% and 62%. As deformation is increased to 79.5% reduction the ductility increases. The intermediate preform density shows the best ductility at this level of deformation. At a higher reduction (84.5%) the intermediate preform density is at a minimum. The tensile strength data of Figure 13 also show reversals of trends but they occur at different deformations than does that in ductility behavior. Some of this behavior may be attributed to the same statistical variations occurring in previous figures as these are the same data plotted in a different manner. Other possible explanations are the complex nature of the flow patterns which must be considered and those variations which may be due to metallurgical structure changes in such a heavily alloyed material under different processing conditions.

Information of the property variations as a function of processing conditions are very important in design of production processes. It is seen that the trends exhibited are not simple in the case of a material such as the MA67 aluminum alloy. This data can be very important as a predictive tool in determining those product properties which might result from a particular operation. They also alert one to possible dangers and inferior areas in a product. This data should also contain information about the effect of a hydrostatic stress state accompanying deformation. The results obtained thus far have been limited to receiver pressures of about 70 ksi. No significant differences from the results obtained by extrusion into atmospheric pressure have been noted. It is felt that higher environmental pressures will give meaningful property differences. This is based on the concept of a threshold or critical pressure. The uppermost curve of Figure 3c is a schematic presentation of the critical pressure effect for which no density degradation occurs regardless of percent reduction.

SUMMARY

The data presented suggest that for hydrostatic extrusion of P/M preforms with no receiver pressure:

1) There exists a critical amount of deformation above which the properties of the product begin to deteriorate.

2) For a given amount of deformation, preform density plays an important role in determining final properties. This role is complex and not a constant for different amounts of deformation. The energetically favorable flow pattern of the material varies with conditions resulting in the property variation.

3) The concepts discussed earlier have been shown to apply to a commercially pure metal of good ductility (sintered iron) and also to a heavily alloyed metal of relatively high strength and low ductility (MA67).

TABLE I

MATERIAL PROCESSING STEPS

Iron Powder (Hoeganaes Corporation)	Aluminum Alloy MA67 (Alcoa)
Analysis: Fe, 0.016S, < 0.01P, 0.08 Cu, 0.19 Mn.	Analysis: Al, 8.01 Zn, 2.48 Mg, 1.12 Cu, 1.36 Co, 0.07 Fe, 0.06 Si.
Water atomized Anchorsteel 1000.	Air atomized - 14.4 micron average diameter.
Cold die compact using zine stearate as die wall lubricant to densities of 5.5, 6.2, and 7.1 gm/cc.	Powder annealed in flowing argon at 750°F - 1 hour, slow cooled (approx. 50°F/hr) to 450°F, held at 450°F - 4 hours, cool.
Sinter at 2050°F for 1/2 hour in atmosphere of dissociated ammonia.	Cold press to densities of 2.43, 2.54, and 2.66 gm/cc.
Machine to billet configuration.	Machine to billet configuration.
Encapsulate in brass tube, seal with solder, and extrude.	Encapsulate in brass tube, seal with solder, and extrude.
Remove brass capsule.	Remove brass capsule.
Measure density (Figure 4).	Measure density (Figure 5).
Re-sinter at 2050°F for 1/2 hour in atmosphere of dissociated ammonia.	Solution treat at 850°F for 2 hours, cold water quench, age at 250°F for 24 hours.
Machine tensile specimen.	Machine tensile specimen.
Test (Figures 6, 7, 10 and 11).	Test (Figures 8, 9, 12 and 13).

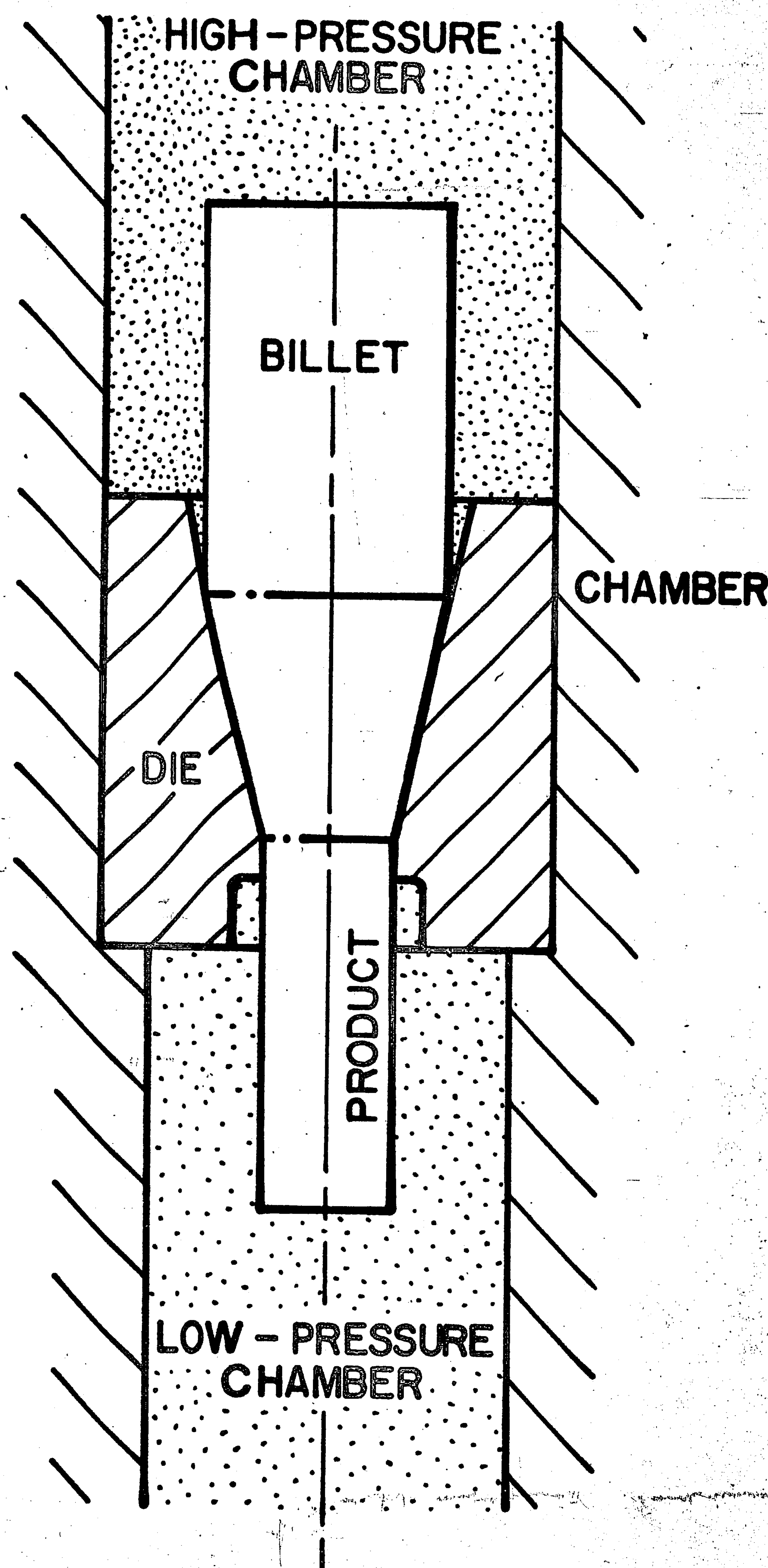


FIG.1 PRESSURE - TO - PRESSURE EXTRUSION.

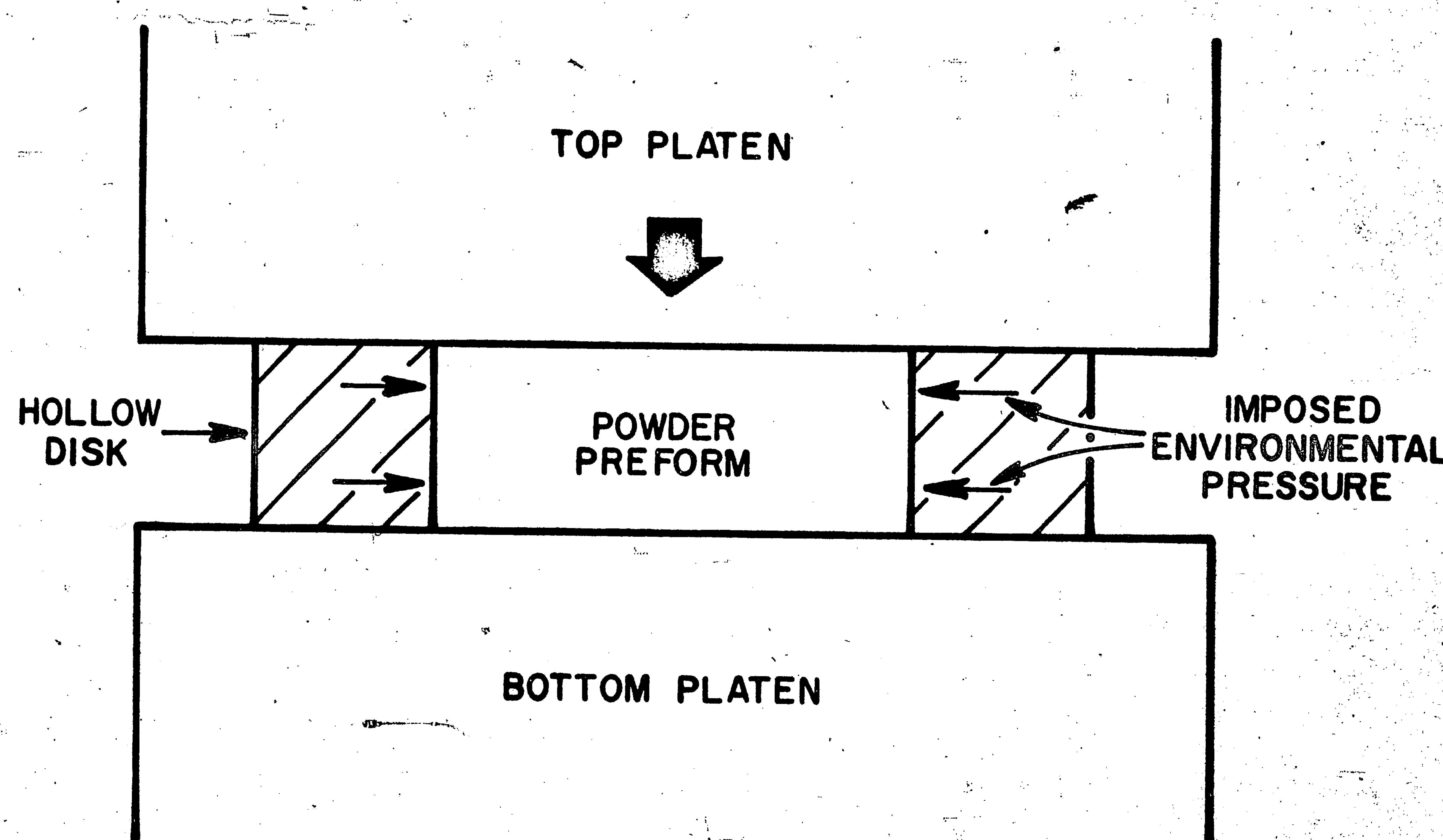


FIG.2 DISK FORGING WITH ENVIRONMENTAL PRESSURE.

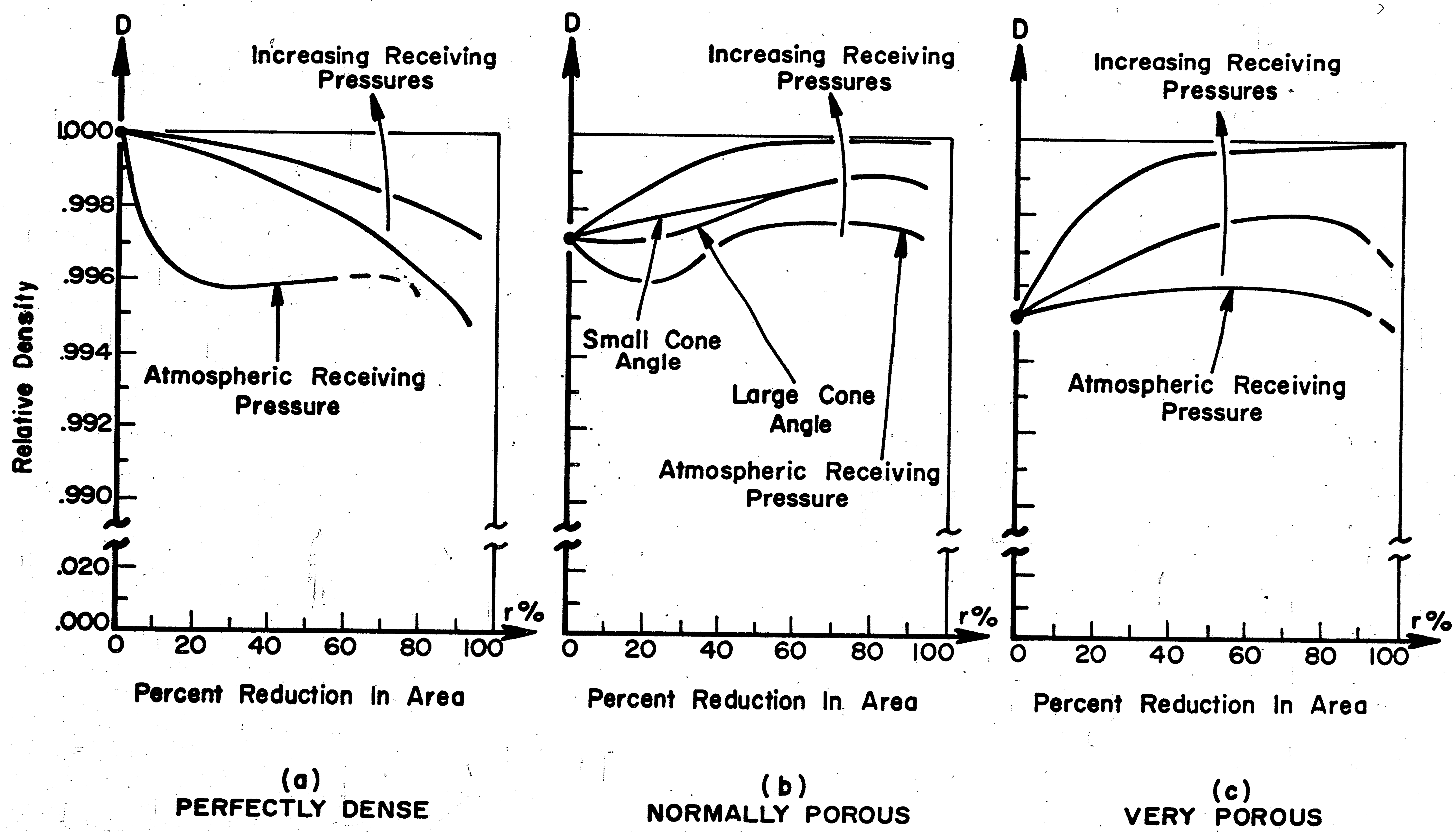


FIG. 3 EFFECT OF MEAN PRESSURE, REDUCTION IN AREA, AND ORIGINAL POROSITY ON THE RELATIVE DENSITY OF THE PRODUCT IN PRESSURE-TO-PRESSURE EXTRUSION.

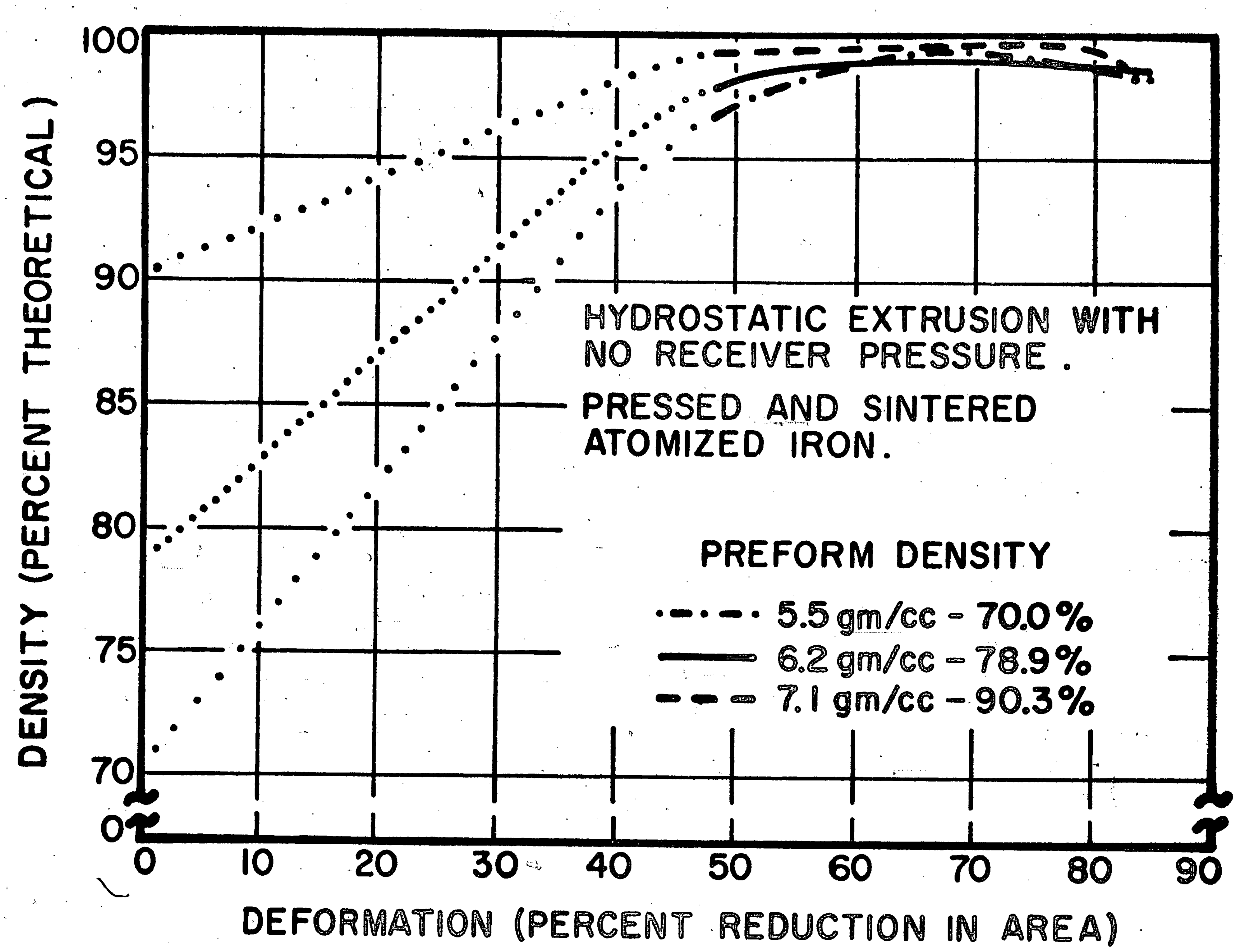


FIG.4 DENSITY CHANGES FOR IRON PREFORMS.

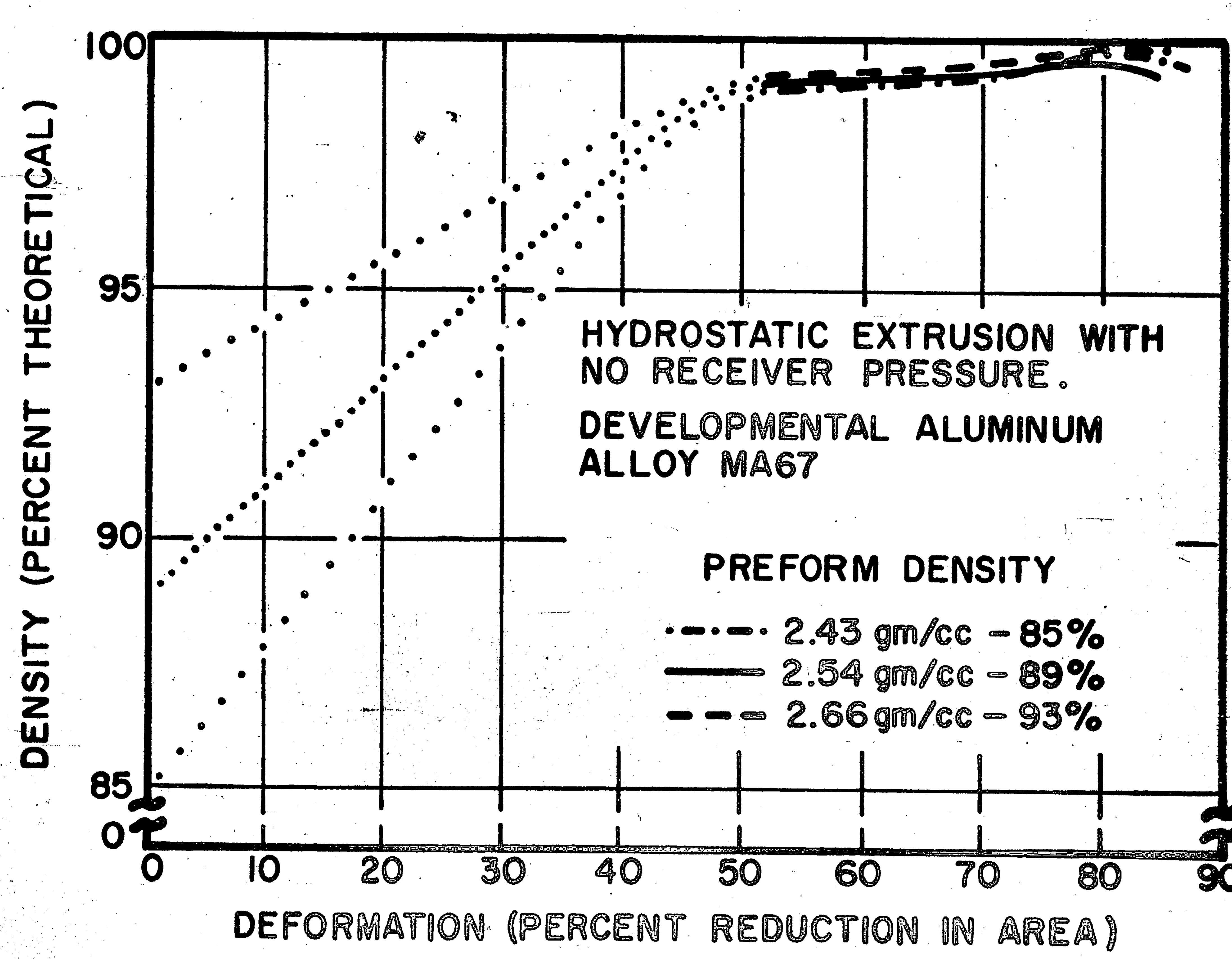


FIG.5 DENSITY CHANGES FOR ALUMINUM MA67 PREFORMS.

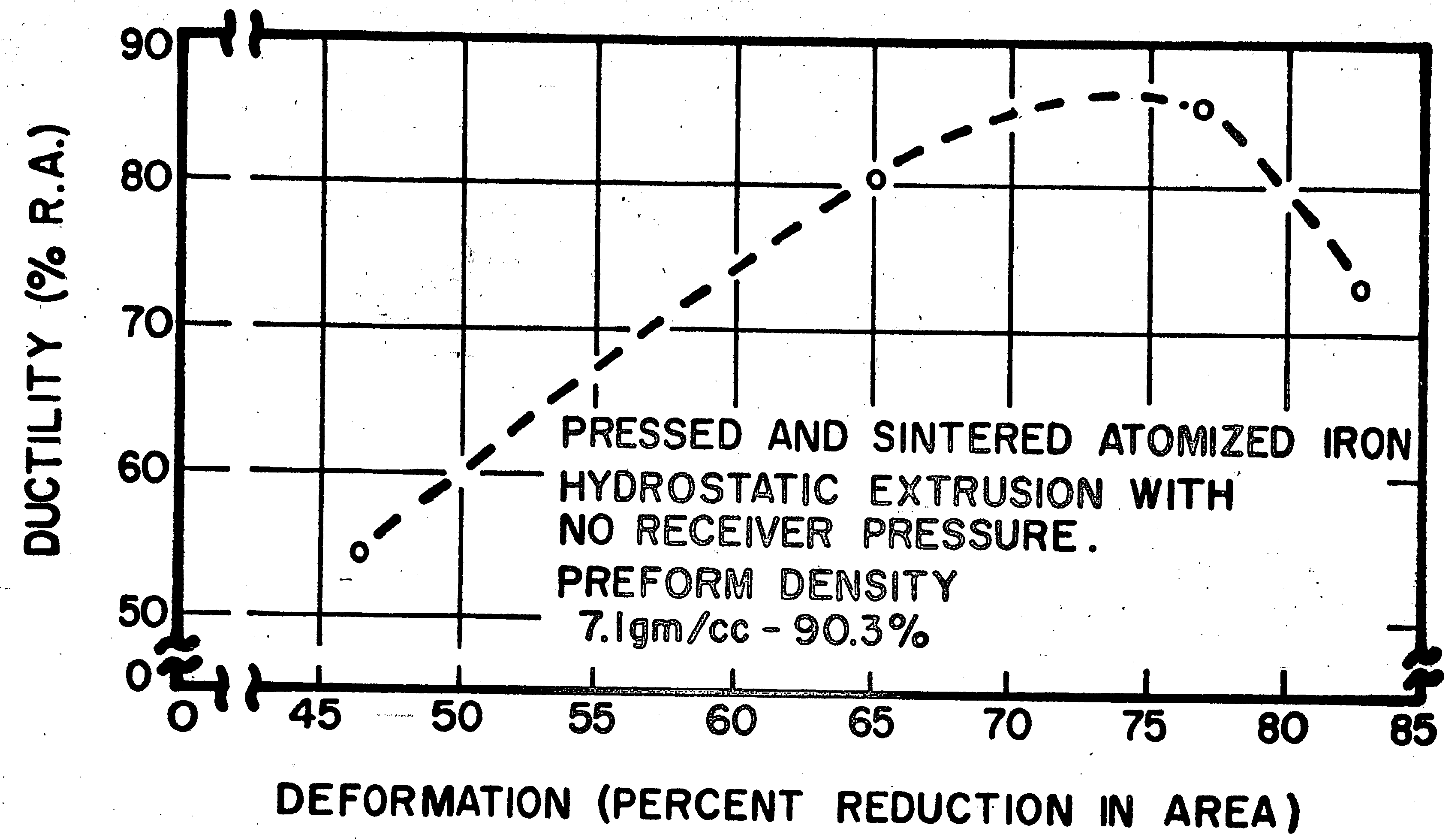


FIG.6 DUCTILITY VERSUS DEFORMATION FOR IRON.

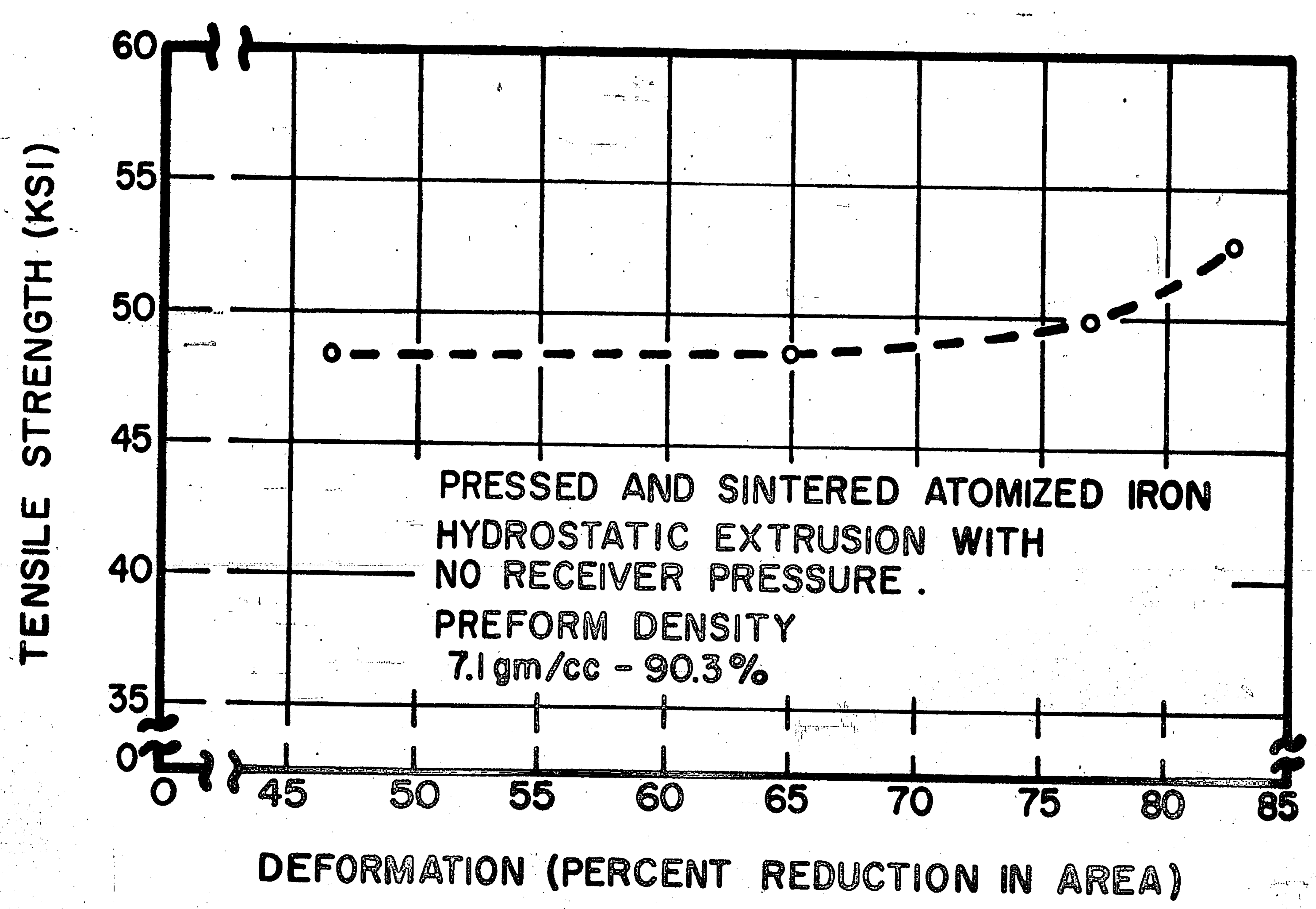


FIG.7 TENSILE STRENGTH VERSUS DEFORMATION FOR IRON.

HYDROSTATIC EXTRUSION WITH NO RECEIVER PRESSURE.
ALUMINUM ALLOY MA67

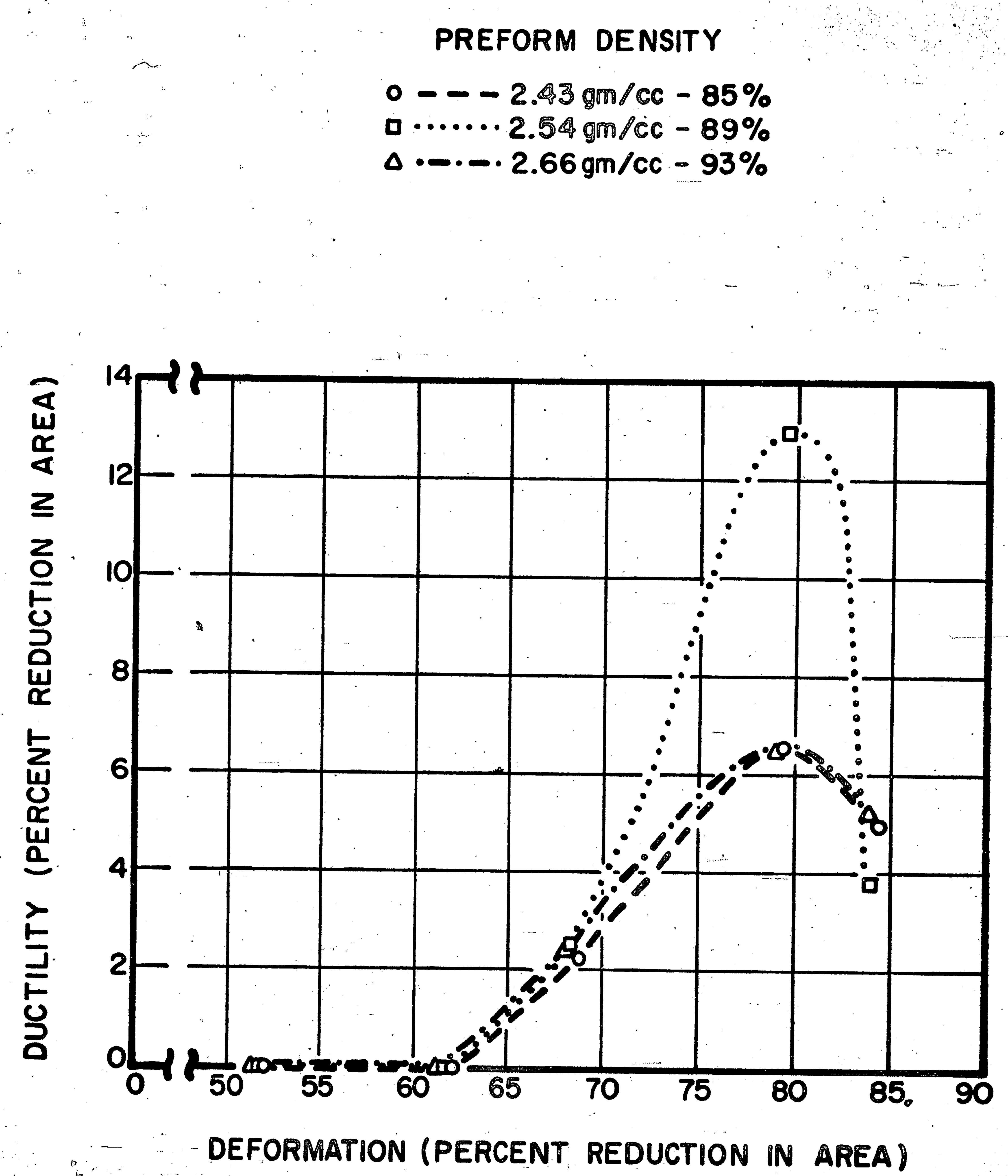


FIG.8 DUCTILITY VERSUS DEFORMATION FOR MA67 ALLOY.

HYDROSTATIC EXTRUSION WITH NO RECEIVER PRESSURE.

ALUMINUM ALLOY MA67

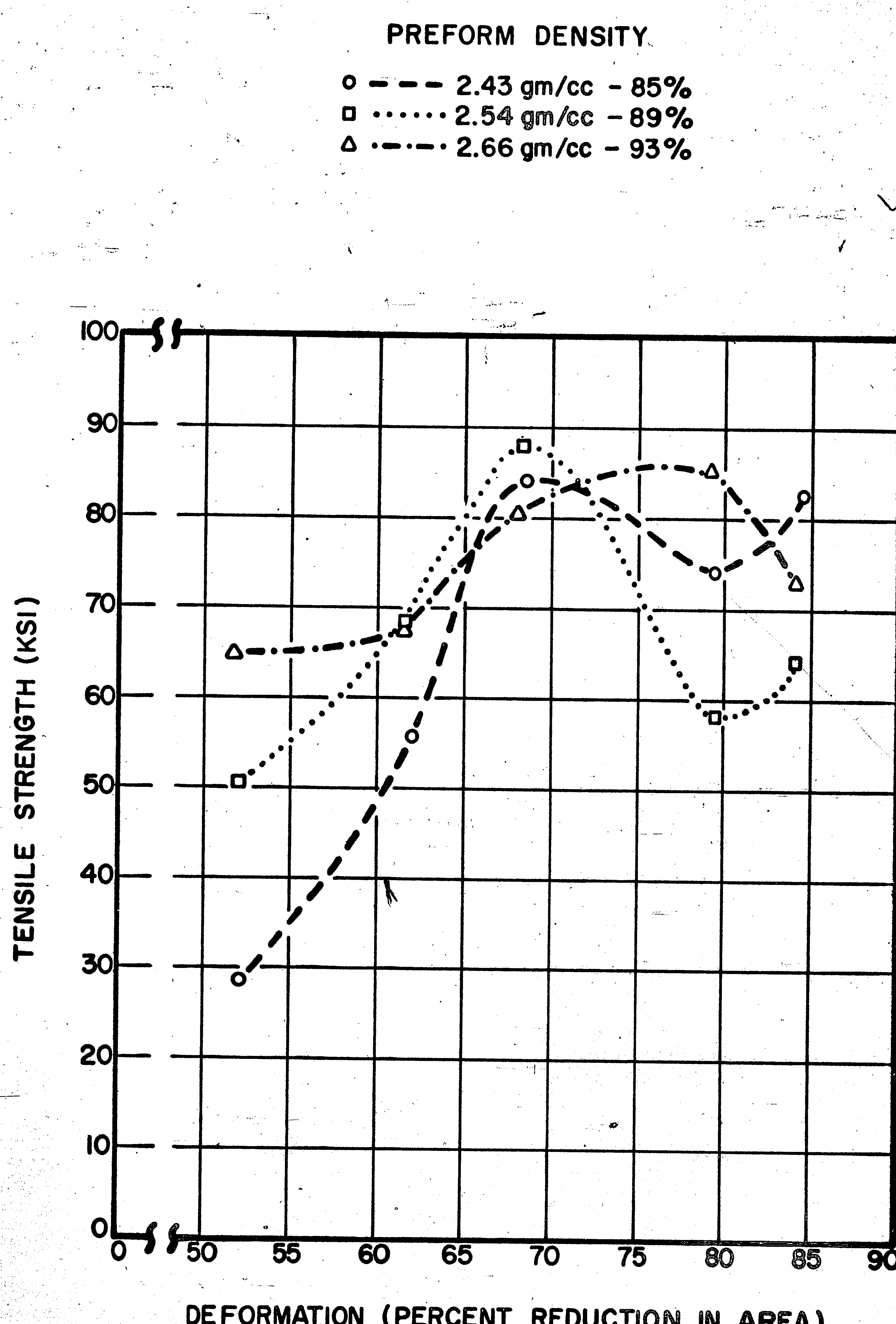
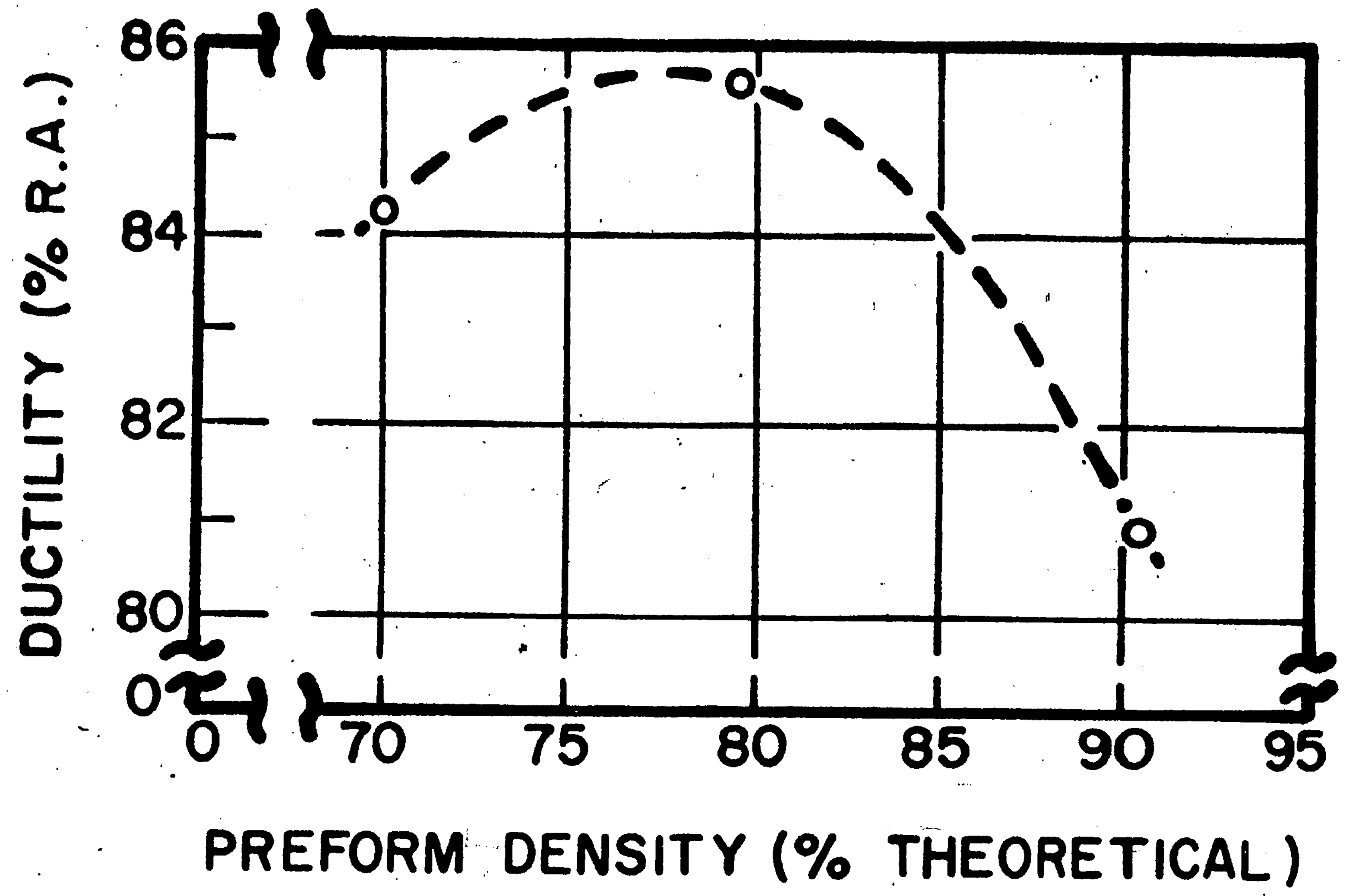
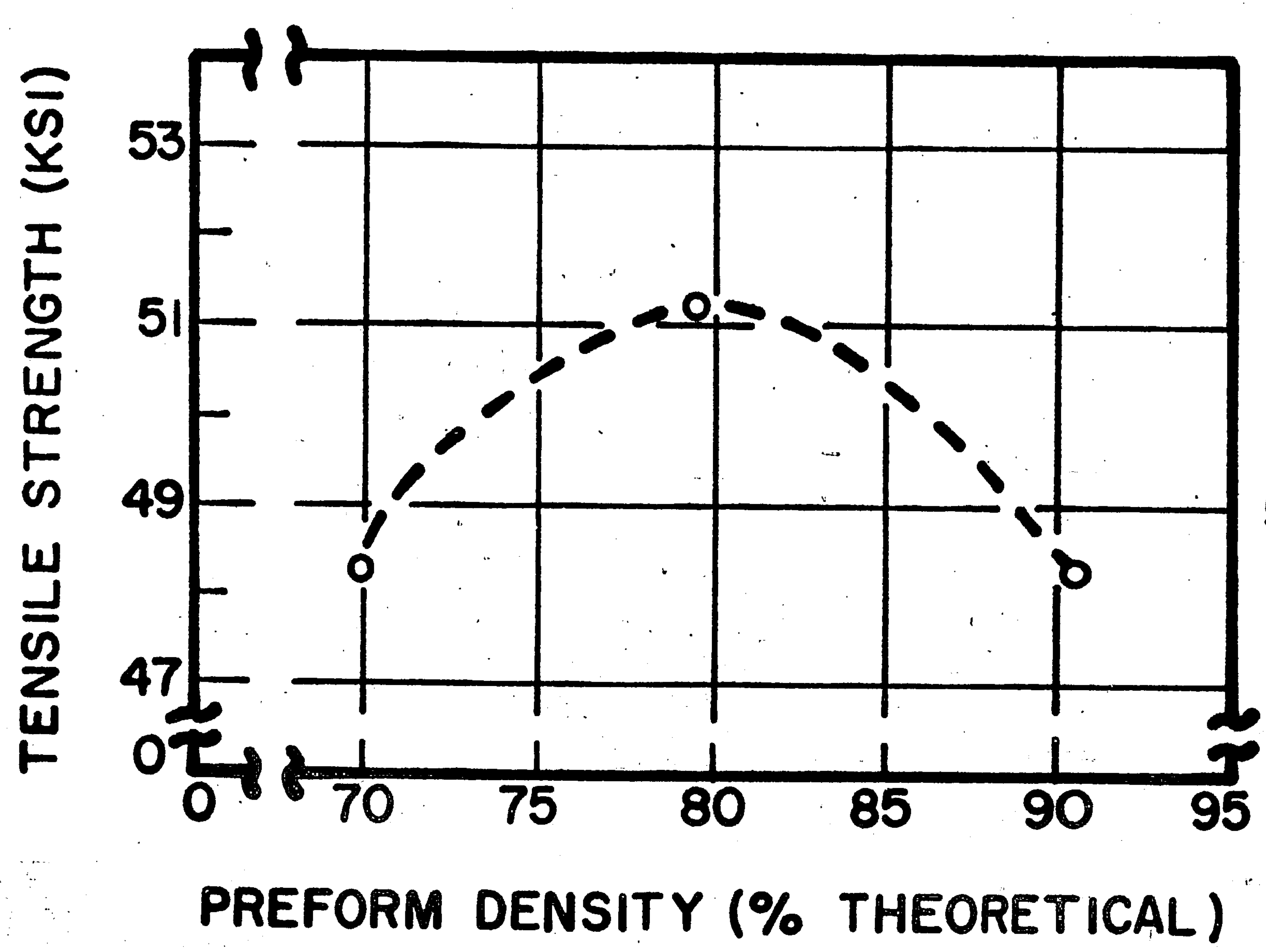


FIG.9 TENSILE STRENGTH VERSUS DEFORMATION FOR MA67 ALLOY.



PRESSED AND SINTERED ATOMIZED IRON.
HYDROSTATIC EXTRUSION WITH NO RECEIVER PRESSURE.
59% REDUCTION BY EXTRUSION.

FIG.10 DUCTILITY VERSUS PREFORM DENSITY FOR IRON.



PRESSED AND SINTERED ATOMIZED IRON.
HYDROSTATIC EXTRUSION WITH NO RECEIVER PRESSURE.
59% REDUCTION BY EXTRUSION.

FIG.11 TENSILE STRENGTH VERSUS PREFORM DENSITY FOR IRON.

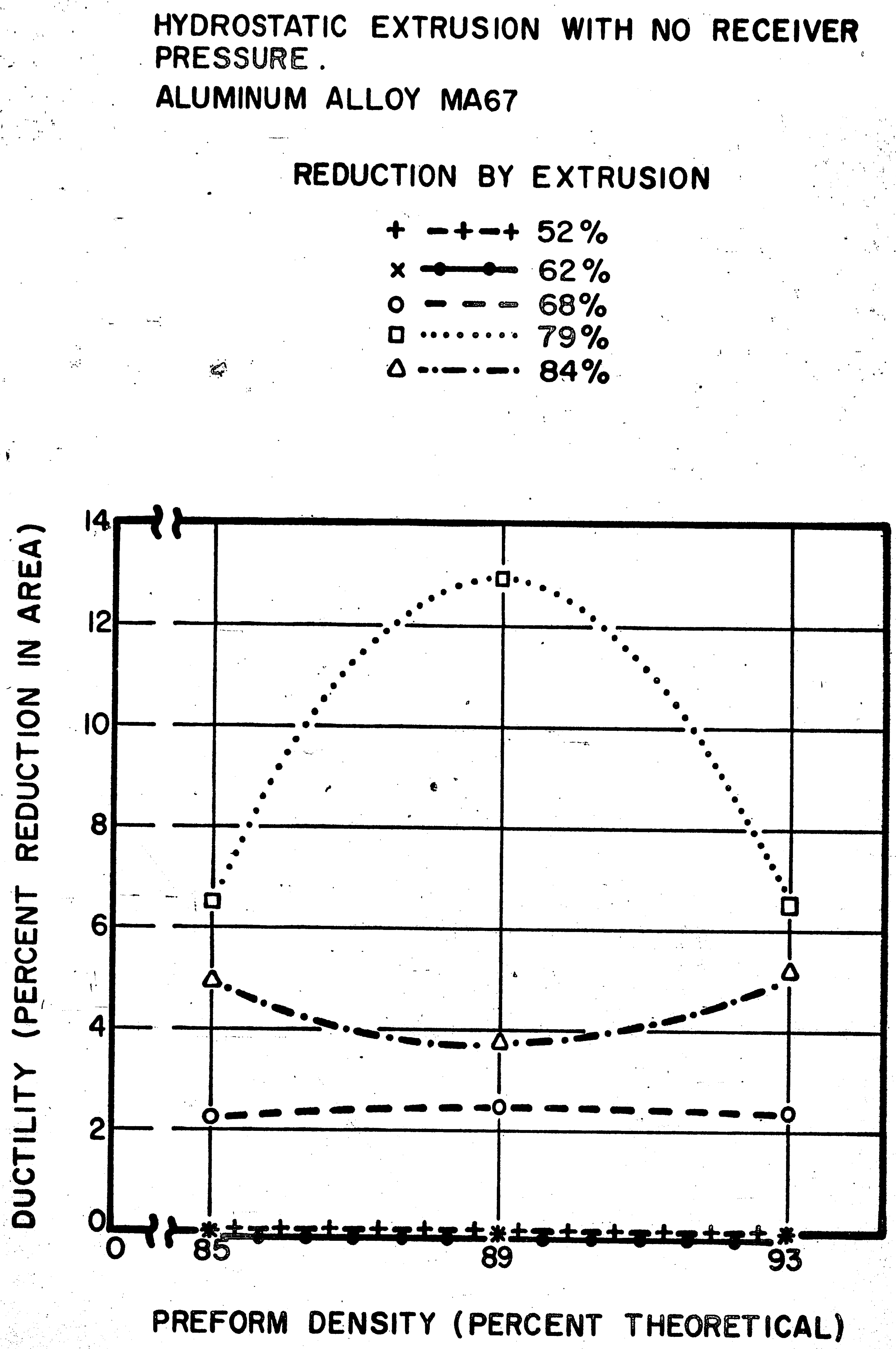


FIG.12 DUCTILITY VERSUS PREFORM DENSITY FOR ALLOY MA67.

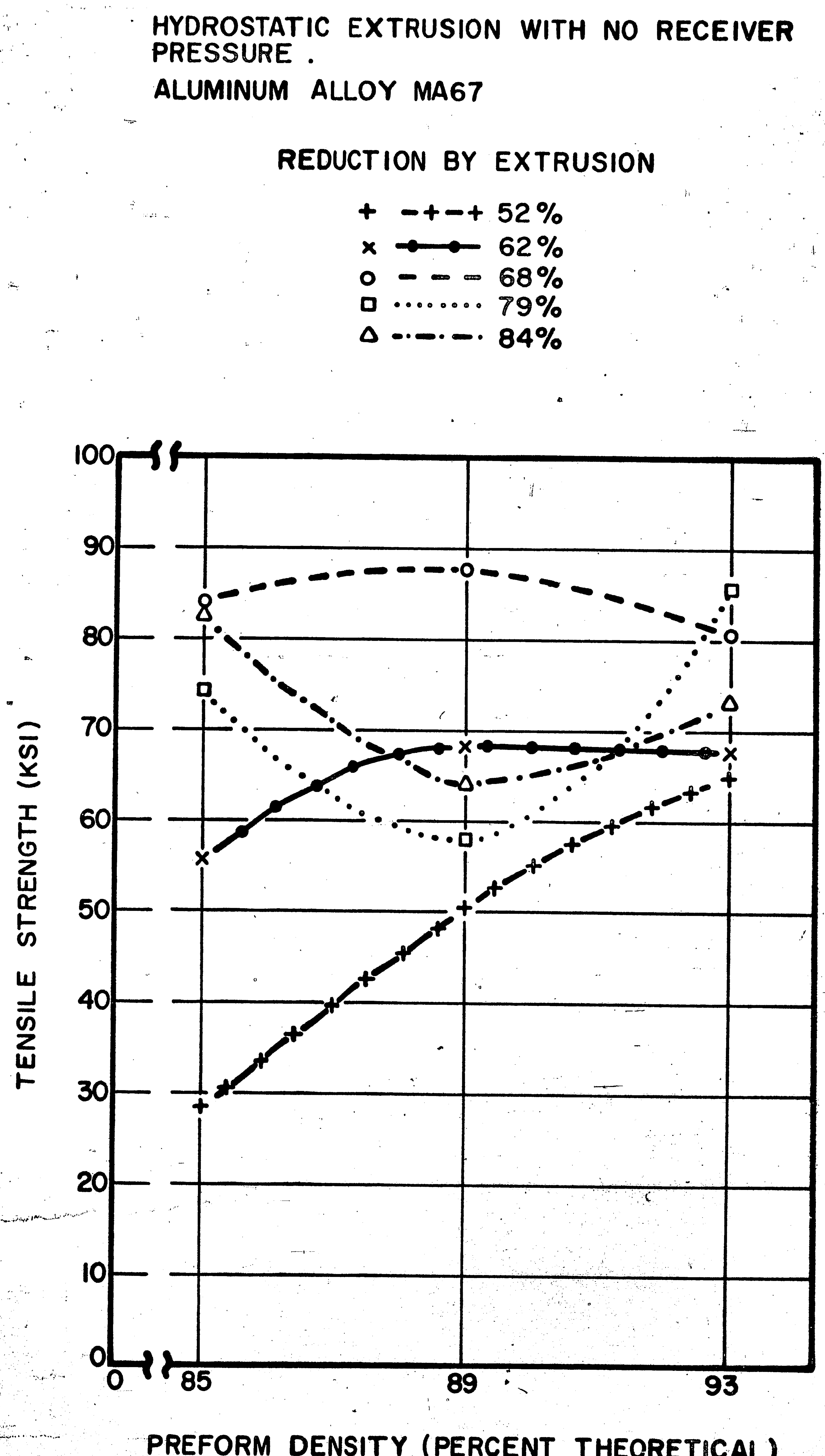


FIG.13 TENSILE STRENGTH VERSUS PREFORM DENSITY FOR ALLOY MA67.

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VITA

The author was born on October 8, 1950 in the town of Ried im Innkreis, Austria to parents Nikolaus and Maria Blum. The family immigrated to the United States in August, 1951, and settled in New Brunswick, New Jersey. In 1962, the author became a naturalized U. S. citizen. Upon graduation from the public school system of New Brunswick in June, 1968, the author entered Lehigh University. He received the Bachelor of Science degree, with honors, in Metallurgy and Materials Science in June 1972. Since that time he has been enrolled in the graduate curriculum under the supervision of Professor Betzalel Avitzur.

The author presented a paper on this research at the 4th International Powder Metallurgy Conference in Toronto, Canada during July, 1973. That paper is to be published in the conference proceedings.