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THE BENDING OF POLYMER MATERIAL UNDER TENSION AS RELATED TO A DEEP DRAWING PROCESS

by

William Bradley Buettner

A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in Metallurgy and Materials Science

Lehigh University

1969

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

12 May 1969
Date

Professor in Charge

Chairman of the Department of Metallurgy and Materials Science

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Appreciation is also expressed to the Marbon Chemical Company and R. R. Kozlowski of the Diamond Shamrock Chemical Company for the materials they provided.

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ABSTRACT

Two engineering plastics, an acrylonitrile-butadiene-styrene resin (ABS resin, Cycolac MS) and a rigid polyvinyl chloride resin (PVC resin, Dacovin 2082) were investigated to determine the effects of cold working. In particular, the "bending under tension" stress system of a deep drawing process was considered. The object was to determine which operating variables were most significant and what effect the stress system had on the material. The processing variables were: the blank holder pressure, the ratio of the punch radius to the material thickness, the speed of deformation, and the temperature of deformation. Their effects were determined by studying the dimensions, the tensile and impact properties, the density and the morphology of the deformed parts.

In general, the properties of the deformed parts were significantly different than those of the undeformed material. Material which had conformed to a radius subsequently yielded under tension in a markedly different manner than undeformed material. An upper yield point no longer existed, and the tensile strength was decreased about 10%. The higher the blank-holder pressure and the smaller the ratio of the punch radius to the material thickness, the more pronounced was the effect. The tensile strength was not further decreased, however. Instead, the material yielded such that a greater strain was required to reach the maximum strength. Also for the more severe deformations, a density decrease and a morphology change was observed. These new material properties are attributed to non-homogeneous yielding in tension and crazing.

I - INTRODUCTION

It has been established recently(1-5) that a feasible method for making a plastic part is by cold working the material by methods developed for the manufacture of metal parts. One of these methods is deep drawing. In this case, a sheet of the material is deformed by a punch and a die which draw the sheet over the die profile as the punch advances, while the flow of the flange of the sheet is controlled by the friction of the material between the die and the blank holder. Figure 1 shows a cutaway view of a sheet being deformed in such a manner.

During the deformation of the material, three basic stress systems must be considered:(6-8)

1. Biaxial stress in the plane of the sheet, causing stretching over the head of the punch.
2. Radial extension accompanied by circumferential shrinkage.
3. A "bending" under tension of the material as it flows over the die radius.

S. Y. Chung and H. W. Swift(9) made a thorough study of the experimental and theoretical aspects of the deep drawing of a cylindrical metal cup, and using these stress systems, obtained accurate predictions of stress and strain in the system.

The term "bending" is used in a somewhat unfortunate sense, since the material actually flows over a radius rather than being bent over it in the classical sense of the word. However, throughout the literature on deep drawing, "bending under tension" is used, and it seems best to conform to that terminology. The distinction between "bending" and "bending under tension" should be kept in mind, however.

The work presented herein is a study of this latter stress system as it applies to the deep drawing of polymer material. The objective was to determine the effects of such a stress system on the material, as well as the variables that are important in deep drawing, as far as this stress system is concerned.

A. Deep Drawing of Metals

Since deep drawing is a relatively new method for forming plastics, a suitable background of the process must be obtained from work in the deep drawing of metals. A brief discussion of the effect of processing variables on the manufacture of a part follows.

1. Effect of Blank Holding Pressure

The purpose of the blank-holder is to prevent the formation of wrinkles within the part, but at the same time cause minimum interference with the draw.[9] According to Swift, the blank-holding pressure, once it has exceeded a necessary minimum to prevent wrinkles, does not have a great effect on the maximum punch load or thickness distribution of the deformed parts.[8] Thus, the amount of force does not have to be precise as far as metals are concerned.

Landberg[10] points out that too high a blank-holder force will cause premature failure of the part. This observation is important when considering a much weaker material than a metal. Thus, a balance must be maintained so that there is enough pressure to prevent wrinkles but not enough to allow failure to occur.

2. Effect of Speed of Deformation

Coupland and Wilson[11] have considered the effect of speed in deep drawing of metals, and Swift[8] mentions it also. The results show that no simple statement can be made concerning the effect of speed, since the effects of die geometry, lubricant, and the speed of draw are all interrelated. For instance, Coupland and Wilson determined that, with mineral oils as lubricants and with a flat-nosed punch, the drawing ratio (the ratio of the initial blank diameter to the punch diameter) improved for annealed mild steel, both with increased speed and increased lubricant viscosity. For a round nosed punch, it was found that the drawing ratio decreased with increased drawing speed. This decrease was reduced with lower viscosity lubricant. The presence of lubrication on just the punch or die side of the blank can also interact with changes in speed and yield different results.

Thus, due to the interaction of speed with other parameters, the individual situation must be known before an accurate explanation of the effects of speed can be obtained.

3. Effects of Die Geometry

There are three important die dimensions which play the most significant role in deep drawing. They are: the die profile radius, R_1 (See Figure 1), the punch profile radius, R_2, and the clearance between the punch and die, C.

The die profile radius is the radius which the material conforms to as it is moving into the die cavity. This is the radius about which the "bending" and "unbending" of the material takes place. Chung and Swift's experimental results indicated that for their case the size of this radius did not provide added punch load if its radius was at least ten times the blank thickness. A smaller die radius caused the punch load to increase faster and reach a higher maximum. However, the larger die radius caused a greater tendency for wrinkling within the drawn cup.(9)

The punch profile radius forms the radius in the base of the part being drawn. In this case Chung and Swift's results indicated that its effect is dependent on the size of the blank. They found that on an 8" diameter blank the punch load did not increase, due to a smaller punch radius, although the maximum punch load was reached earlier in the draw and kept at its peak for a greater amount of punch travel. With a smaller blank, the more generous profile gave lower loads.

The clearance between the punch and the die affects the drawing process, in that it controls the freedom of the material to thicken. The restraint that it puts on the material is called ironing, and its degree of importance depends upon the thickening or wrinkling of the material during the draw.

4. Effect of Material Properties

Many investigations have been made in attempting to correlate the material properties with the deep drawability of the material. Although most of the attempts were not successful, one method is particularly interesting. This is a method developed by

R. L. Whitely.[12] He correlated the average strain ratio R_{avg} as developed by R. Hill[13] and the drawing ratio.

R is defined as:

$$R = \frac{\ln w_o/w}{\ln t_o/t}$$

where w_o and t_o are the initial width and thickness of the specimen.

Whitely determined R_{avg} by obtaining the value of R at different angles to the rolling direction of the sheet and taking their average.

A linear relationship between R_{avg} and the drawing ratio was indicated by the results of his experiments, drawability increasing with R_{avg}. Lloyd[14] later determined that a titanium alloy, having an average strain ratio of 3.8, will allow a cylindrical cup to be drawn nearly twice as deep as a good drawing-quality steel with a strain ratio between 1 and 2. This result demonstrated the validity of using the strain ratio as a reliable criterion for the drawability of metals.

5. Summary

The investigations of the deep drawing of metals have been extensive and have contributed significantly to the understanding of the process. Unfortunately, the complexity of the process has not allowed the development of a general theory that can predict the correct tool design and operating conditions that will produce a particular part. The final conditions for manufacture still remain an art. The studies of the effect of each of the variables, however, have aided in tool design and in specifying the operating conditions.

Also, Chung and Swift's analysis demonstrated that consideration of each of the stress systems independently can be of particular value.

B. Cold Working of Plastics

1. Effects of Cold Working on Polymer Material

Due to the nature of polymer material, the effect of cold working on polymers is not an easy problem to analyze. In contrast to metals polymers respond to applied stresses in a viscoelastic manner. Thus, the strain may not be instantaneous because of a retarded elastic behavior. There also may be an irrecoverable viscous flow due to entire polymer chains being moved relative to their neighbors.[15] Both the temperature and time of deformation play a significant role in determining the response of a polymeric system. A material formed at temperatures well above or below its glass transition temperature, Tg,* will behave in a markedly different manner.

Most of the previous studies of cold working have been on cold rolling or cold drawing of the material. Andrews et al[16] looked into the aspect of yielding in the cold drawing process. Particularly, he concerned himself with the formation of the neck. The difference between the thinning of plastics and that of metals could be significant when considering the design of a deep-drawing tool. For metals the punch and die radii are determined to some extent by the thinning of the material as it conforms to them.

*T_g corresponds approximately to the midpoint of a range in temperature above which response is viscoelastic, and below which, elastic. Below T_g, a polymer is typically glassy, and above T_g, rubbery.

For soft metals, the initial neck grows until finally the material is pulled apart. For polymers, a "strain softening" process allows the yield or neck to initiate. Rather than continuing to grow, however, there is a "strain hardening" process which causes the yield to terminate when the neck has reached a certain reduction. The neck, instead of continually becoming smaller in area, propagates along the length of material, allowing a stable drawing process to occur.

Andrews was not able to successfully give a molecular model for the necking process of plastics. He stated that the "strain hardening" effect was probably due to some type of molecular orientation, but the results of interrupted loading complicated the problem.

A polymer that lends itself well to the study of the effect of cold work is polyethylene. This material has amorphous and crystalline regions. The amount of each and their interactions determine the properties that polyethylene exhibits. Rothchild and Maxwell [17] made a thorough and very clear study of this, and their conclusions are interesting.

They cold worked polyethylene by cold rolling. The result was an anisotropic material exhibiting a higher strength in the rolling direction. The effects of cold working depended upon the amount of crystallinity, the temperature of cold working, and the degree of cold working. The higher the temperature and degree of cold work, and the lower the amount of crystallinity, the greater the degree of anisotropy of the material.

Rothchild and Maxwell determined that in the direction perpendicular to the rolling direction, the ductility was equal to or greater than the unworked material. They also observed a slight decrease in density, which they felt might be attributed to the uncoiling of amorphous chains by the cold working.

Wilchinesky[18] also discovered an effect on ductility by cold work. He cold rolled polypropylene and determined that there was a significant reduction in brittleness temperature in the rolling direction, but only a small effect in the transverse direction. He also noted a decrease in density of the rolled specimens.

These results indicate that molecular orientation may be occurring as a result of cold work. Generally, orientation is accomplished by deforming a polymer at a temperature above its glass transition temperature.[21] In cold working, if the polymer is below T_g, one explanation for orientation is that localized temperatures within the specimen are actually higher than the ambient temperature. The polymer, therfore, is actually being worked above T_g. The material then "cools" so that the molecules become frozen in a nonrandom configuration. This results in a material that has significantly different properties than unoriented material. For instance, the material may have a change in tensile strength such that it is 2 to 5 times greater parallel to the direction of orientation, and only 1/2 to 1/3 the strength of unoriented material perpendicular to the direction of orientation.

2. Deep Drawing of Plastics

Although several publications have pointed out the feasibility of the deep drawing process,[1-3, 19, 20] none has given an understanding of the process beyond general guidelines which were obtained by experience. The understanding of the actual effect on the material during the process, as well as the processing variables' role, has not reached the stage of development that cold rolling or cold-drawing has. The reason, besides the short period of time the process has been studied, is that the complexity of the deep drawing process does not lend itself well to theoretical study. As pointed out previously, the role of speed of deformation of metals, for instance, is interlocked with other variables to the extent that one must consider the actual case before the results of varying speed can be considered. In a polymer material, where the viscoelastic property of the material must also be considered, speed may have an extremely important role.

Despite these conditions, success has been achieved in the development of a plastic which has shown great promise for deep drawing. The plastic is an ABS (acrylonitrile butadiene styrene) material, Cycolac MS, which is manufactured by Marbon Chemical Company. The majority of the experimental work presented here was done using this material.

Royer and Meadors[19, 20] have worked with this material quite extensively. They have made several conclusions which are meant to be guidelines for the manufacture of plastic deep drawn parts, but the authors do not clearly relate how some of their conclusions were drawn and just how generally they can be applied.

For instance, they maintain that lower speeds of deformation, such as those obtained with a conventional hydraulic press, will cause an increase in the springback of the drawn part. Cheesmore and Sanders claim that the speed of drawing plastic sheet, in general, requires precise control and is of the order of half the speed usual in metal forming.[3] Both of these statements do not indicate the possible complexity of the situation which has been established in the deep drawing of metals. Also, the viscoelastic properties of the material must be considered. Viscous response is maximized at low rates. High rates normally give elastic response. However, if at very high rates there is a localized increase in temperature, there may be a significant degree of viscous response.

Royer and Meadors also maintain that the physical properties of the material are not changed significantly by deep drawing. They do not, however, define what they mean by "significant" nor give any idea of how much of a change, if any, that they observed.

From the discussion of the deep drawing of metals the average strain ratio, R_{avg}, would seem to be the desirable property to determine which plastic is the most suitable for deep drawing. Broutman and Kalpakjian[22] considered this, but could not determine any meaningful relationship as was obtained for metals.

The knowledge concerning the deep drawing of plastics, therefore, is very limited. The complexity of the problem indicates a direction to proceed in evaluating a material for deep drawing or in obtaining a possible die design to make a certain part. This direction, as mentioned previously, is a study of the elemental stress systems as defined by Chung and Swift, to determine how the material is affected by these stress systems, and what variables are the most important. This work is such a study of one of these stress systems.

II. EXPERIMENTAL PROCEDURE

A. Material

The material used in the majority of the experiments was Cycolac MS, an acrylonitrile butadiene styrene (ABS) copolymer, provided by the Marbon Chemical Company. It was obtained in extruded sheet form in three thicknesses, .015", .030", and .050". The properties of undeformed material, as stated by Marbon, are given in Table 1.

For comparison, Dacovin 2082, a polyvinyl chloride (PVC) material, provided by the Diamond Shamrock Chemical Company, was also considered. It was also obtained in extruded sheet form, but only in one thickness, .050". Its properties are listed in Table 2. This was the material used by Kozlowski,[23] who determined that it has definite possibilities as a material capable of cold forming.

These materials were chosen because of their favorable balance of engineering properties as well as their demonstrated capacity for being cold formed.

B. Method of Material Deformation

1. Punch Press

A standard Bliss C-22 punch press with a two-inch stroke was used to deform the material. The force on the blankholder was provided by a Wabco MF1-PP air cylinder with a 6" diameter bore, working in conjunction with a 15 gallon tank used to reduce the variability of the air pressure during the stroke.

The speed of deformation was changed by varying the size of the sheave driven by the drive shaft of the press motor. The speed, due to the design of the press, was not constant but varied sinosoidally. Its profile is given in Table 3 for the first quarter of the cycle. The larger sheave yielded a 139% increase in the speed of the stroke and was the maximum speed recommended by Bliss for the safe operation of the punch press. The speed varied in the range of 1000 in/min, which is a normal commercial rate.

The displacement of the punch was measured by a Pacific Scientific Linear Potentiometer Model RP14-0101-1. This allowed accurate determination of the speed. It was also used in conjunction with measuring the blankholder pressure during the stroke, which will be described in the next section.

2. Die Set

The parts were made with a punch and die which is basically shown in Figure 1. The punch and die itself is shown in Figure 2. The die set is a Producto Machine Company Set, Model 88C11B.

This tool, therefore, simulates the deep drawing operation. All the critical variables are present, but only one basic stress system is applied. This is the stress system on the material flowing over the die radius, R_1, and then forming the sides of the deformed piece. A portion of the material also conforms to the punch radius, R_2. The result is a trough about $3\frac{1}{4}$" in length shown in Figure 3. It consists of sides which have been "bent" and "unbent" about the die radius, the top which was in tension during the stroke, and the corner which was bent about the punch radius. The object of the investigation is met, since basically only the "bending under tension" aspect of the deep drawing process is actually being considered.

The portion of the tool which made up the die radius was interchangeable. This allowed the deformation of different thicknesses of material, which effectively changed the ratio of the punch radius to material thickness. The die radius was kept constant at 10 times the material thickness. This is the maximum die radius that Royer and Meadors[19] found practical for the deep drawing of ABS.

The pressure on the blankholder was varied by the amount of pressure applied to the air cylinder. The total force on the blankholder was measured by a set of strain gages mounted on one of the four push rods which transmit the force from the air cylinder to the blankholder. Two gages were mounted on the rod and two dummy gages, which were used to compensate for temperature changes, were mounted on a piece of the same grade steel and placed next to the tool. This strain gage circuit as well as the linear potentiometer were fed into a Sanborn recorder which gave the force as a function of position during each cycle.

Since the force of only one of the rods could be measured, a study was made to determine the degree the four rods varied. The results indicated that there was a slight difference in the force of the rods. However, the four rods were shown to be linearly related, and a regression analysis yielded equations to relate the force in pounds of the left front to the other three rods. The following is a list of the equations along with their correlation coefficients. X is the force on the left front rod. Y_1 is the force on the right front rod, Y_2 is the force on the left rear rod, and Y_3 is the force on the right rear rod; R_1, R_2, R_3 are the respective coefficients of correlation.

$$Y_1 = .85X + 25 \qquad R_1 = .958$$

$$Y_2 = 1.1X - 8 \qquad R_2 = .992$$

$$Y_3 = .85X + 15 \qquad R_3 = .978$$

From this a reasonable knowledge of the pressure on the blankholder during the stroke could be obtained. Further, any strong deviation from these results would not allow the part to be formed properly, since one side would be pulled in sooner during the stroke resulting in a nonsymmetric part.

The friction between the material, blankholder, and die is what ultimately provided the tension in the material during the stroke. The coefficient of friction was measured by placing a piece of material between the blankholder and die, and, with a known force on the blankholder, the plastic was pulled out. The force required to initiate motion and to maintain it was noted. The results indicated that the static coefficient of friction for ABS was .09 with a variance of 4.2×10^{-4} and that the kinetic coefficient of friction was .08 with a variance of 3.8×10^{-4}. For PVC, the static coefficient of friction was .07 with a variance of 4.1×10^{-5}, and the kinetic coefficient of friction was .06 with a variance of 3.6×10^{-5}.

3. Temperature Variation

Besides varying blankholder pressure, speed of deformation, and the ratio of the punch radius to material thickness, the temperature at which the deformation occurred was varied. This was accomplished by heating the plastic and placing it warm into the die. Although the tool acted as a heat sink, and the surface temperature of the plastic dropped a significant amount during deformation, the final temperature was well above room temperature. The results could, therefore, provide some indication of the effect of temperature on the system, at least to the extent of providing a direction for future, more accurate experiments.

C. Methods of Analysis

The effects of blankholder pressure, speed, die geometry, and temperature variation were determined by analyzing the dimensional stability, mechanical properties, and the morphology of the material.

1. Dimensional Stability

The only dimension which showed significant variation during the investigation was the dimension "A" of Figure 3. This dimension indicated the amount of springback which occurred after the part was removed from the die. It was measured by tracing the part immediately upon removal from the die and at various intervals of time later. This method was used, since the continuing change of this dimension immediately after removal from the die made direct measurement impossible.

The variation in the thickness of the undeformed sheet was such that only gross thickness changes, greater than 8.5%, could be confidently observed. Kozlowski[23] found a 3% thinning of a PVC material with a thickness of .059 at the punch radius. Such a small thickness reduction could not be observed in this investigation, although the tensile properties of material in the area of the part that conformed to the punch radius to provide some indication of the strength of this area.

2. Mechanical Properties

a. Tensile Properties

All the tensile properties were determined per ASTM Test D1708-59T. An Instron universal testing machine, Model TTCM1, was used to make the tests. The test specimens were prepared by die-cutting the sample from the deformed part by a tool shown in Figure 2 of ASTM D1708-59T. Five samples were prepared for each of six cases considered. The deformed part had three distinct areas where the type of deformation differed. Each of these areas was tested in two perpendicular directions. The specimen designated Side Transverse (Side T) was taken from the side of the trough perpendicular to the axis of the bend which formed the corner radius of the trough. Side Parallel (Side P) was taken from the side of the trough parallel to the axis of the bend. Bend Transverse (Bend T) was taken from the bend area itself with the tensile axis perpendicular to the axis of the bend. Bend Parallel (Bend P) was taken from the bend parallel to the axis of the bend. Top Transverse (Top T) was taken from the top of the part with its axis perpendicular to the axis of the bend. Finally, Top Parallel (Top P) was taken from the top parallel to the axis of the bend.

The speed of testing was .05" per minute. The temperature ranged from 71° to 74°F, while the humidity ranged from 16% to 30%. Most of the time, however, the humidity remained below 25%.

b. Impact Properties

The impact properties were obtained with an Instrumented Tensile Impact Tester manufactured by Custom Scientific Instruments, Inc., Model CS-137-009. The test specimen was the same as the microtensile specimen used in determining the tensile properties of the material. Although this is not a standard impact test, the results can be considered to be relative.

The samples were taken from the side and top of the part perpendicular to the axis of the bend.

3. Morphology and Physical Properties

a. Density

The density of the material was determined by measuring its weight in air and in butanol. The latter was chosen for its favorable density and vapor pressure characteristics.

The samples were obtained by cutting the material from the desired section of the deformed part. Since the area of the bend was so small, samples measured about $1\frac{1}{4}$" by $\frac{1}{4}$". This small a sample reduces the accuracy of the density measurements. Further, error depends upon the variation of the amount of wire holding the sample that is immersed in the liquid. The temperature variation of the liquid itself is also a source of error, since this causes a change in the density of the liquid. The effects of the deformation on density was large enough, however, to allow adequate measurements of these effects.

The density of the butanol was obtained by comparing the weight of a standard glass pycnometer filled with butanol to the weight of the same pycnometer filled with distilled water. The experiment was done using two different pycnometers yielding densities of 0.807825 g/cc and 0.807943 g/cc, which corresponds to a .0146% difference. The density of butanol was taken as the average of these two, 0.807884 g/cc.

The density of the specimen was then determined from[24]

$$D = \left[\frac{W_2 d_1 - W_1 d_2}{W_2 - W_1}\right]$$

where

W_2 = the weight of the specimen in air

W_1 = the weight of the specimen in liquid

d_1 = the density of the liquid

d_2 = the density of the air

b. Optical Views

The material was viewed with a Reichert Interference Contrast Microscope. This provided sufficient contrast to show surface defects at 190X. An increase in magnification, however, reduced the depth of focus such that no further insight into the defects seen at the lower magnification could be obtained.

c. Electron Microscope Investigation

Replicas of the surface were made at the three areas where the type of deformation differed. The replicas were made by evaporating normal to the surface a very thin layer of Victawet, which is a water-soluble material manufactured by Stauffer Chemical Company. A carbon-platinum shadow at an angle of less than 25^{o} was then applied, followed by a heavy carbon layer, which was evaporated normal to the surface. The replica was removed after soaking in water, allowing the victawet to dissolve.

Replicas were also made of fracture surfaces, which were fractured at the temperature of boiling liquid nitrogen. A fracture was made at the area of the bend and compared with material which was fractured from an unworked specimen.

III. RESULTS AND DISCUSSIONS

A. Description of the Deforming Conditions

Table 4 is a summary of the conditions under which the parts were deformed. These conditions will be referred to by number throughout the following discussion.

Parts made under conditions 1, 2 and 3 were formed at increasing tension at the lower rate of deformation. An analysis of variance indicated that the tension was not the same at the 99% confidence level. Parts made under conditions 4, 5 and 6 were formed at the higher rate of deformation. Conditions 7 and 8 increased the ratio of the punch nose radius to material thickness. Condition 9 was formed at elevated temperatures. Finally, conditions 10, 11 and 12 were made using PVC material.

Parts formed under conditions 1, 4 and 10 were intended to be deformed at the same blankholder pressure. There was a standard deviation of 65 psi, since the pressure could not be calculated until the experiment was completed.

Similarly, conditions 2, 5, 9 and 11 were intended to have the same pressure. In these cases the standard deviation was 75 psi. For conditions 3, 6, 7, 8 and 12 the standard deviation was 152 psi. Thus, any conclusions relating to these similar conditions must be made somewhat cautiously.

B. Dimensional Stability

Springback indicates how well the material can plastically conform to the punch nose radius. For the purpose of this study springback is defined as sin α (See Figure 3). The results may or may not be an indication of the dimensional stability of a deep drawn part, such as a cup, since such a part has geometric constraints which inhibit springback. Figures 4, 5 and 6 show the variation of springback with time. These figures present the data in the form of 90% confidence intervals about the mean of an average of five samples. The numbers refer to the condition of deformation.

Data taken in several cases after 2 days indicated no further change in springback. As Figures 4, 5 and 6 show, the rate of change after 30 minutes was small.

1. Effect of Blankholder Pressure

Figures 7 and 8 show the effect of tension on the springback of the sides of the trough. The points are the average springback of a sample of 5. For any set of conditions the result is linear, with a higher tension yielding less springback. This was confirmed by deforming ABS material at a low rate of deformation and with a minimum amount of blankholder pressure. The tool was also lubricated so that the tension was essentially zero. The result was a springback of .9075. The value obtained by extrapolating the line of Figure 8 corresponding to the above conditions to zero tension was .898, a difference of 1%.

Figures 4, 5 and 6 show that the parts made at higher tension show greater variation than those made at lower tension. Also, the rate of change of dimension A was the greatest immediately after deformation, as would be expected, and a higher tension magnified this effect.

As the part conforms to the punch radius, crazing in this area is evidenced by a stress whitening of the material. As will be shown in the discussion of the effects on density, higher tension may increase this amount of crazing. Such an increase could result in the ability of the material to expand at the outer radius of the bend. Later development will give further strength to this argument.

2. Effect of Speed of Deformation

The effect of an increase in speed on dimension A is shown in Figures 7 and 8. They indicate that for the 139% increase in the speed of deformation there was less springback.

The variation in the springback, however, reduces the significance of this statement. All the points in Figure 8 for conditions 1 through 6 fall well within the 90% confidence limits, so that it is possible that there is actually no significant difference in springback due to an increased rate of deformation. The strong linearity of the results, however, indicate that a trend is probable, and future experiments at higher deformation rates may be worthwhile.

3. Effect of Temperature

An increase in temperature reduced the amount of springback significantly. Figures 4, 7 and 8 show that at condition 9, the amount of immediate springback was 16% less than a part formed under the same tension at the same speed. Even more significant is that there is essentially no increase in springback with time. Thus, after 2 days the decrease was 25%.

4. Effect of Die Geometry

The ratio of the punch nose radius to the thickness of the material had a significant effect on the amount of springback. For condition 7, which had a ratio of 5, the springback after 2 days was .951. For condition 8, with a ratio of 10, it was .987. If the sheet would have completely straightened out, the springback would have been 1.0. Thus, for condition 8 the springback was almost complete.

Figure 9 is a plot of springback versus the ratio of the punch radius to the material thickness, for conditions 3, 7 and 8 after 2 days. The larger ratios seem to cause dimension A to asymtotically approach a value corresponding to complete springback. The change in springback may be due to more crazing in the thicker material. If this is true, then the reason used to explain the effect of an increase in tension would be consistent with these results.

5. Results for PVC

Polyvinyl chloride had greater tendency to springback, in general, than ABS. Figure 8 shows that after 2 days the springback was 7.1% to 7.6% larger. An increase in tension had slightly less an effect than for ABS and the results were not as linear.

C. Mechanical Properties

1. Tensile Properties

The tensile properties of the ABS for each condition are shown in Figures 10 through 27. These are plots of 90% confidence limits for the mean of a sample of five. Each figure is for a property of one of the six cases previously defined.* The tensile strength, the % elongation at yield and the % elongation at break are reported. Table 8 gives similar information for PVC.

Tables 5 through 7 present the % difference of each of these properties within a part by comparing the average of each case with the average of Top T or Top P, depending upon the direction considered.

a. Tensile Strength for ABS

The tensile strength of Side T, Bend P and T was reduced. This was true both in comparison with the undeformed material and in comparison with the top area, which seemed to undergo the least amount of change. The change that did occur in the top area was probably due to the variation of the strength of the different sheets of material used and experimental error.

Figures 28 and 29 indicate that the punch radius and the blankholder pressure influenced Bend P. However, Side T and Bend T do not appear to change in any consistent manner with the operating variables. Initially, this was quite disturbing since it is hard to imagine what variables, other than those considered, could be controlling the magnitude of this decrease. Much of the investigation and the analysis of the tensile properties will be related to this problem.

b. % Elongation at Yield for ABS

Side T and Bend T also showed an increase in the % elongation at

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*See Page (18)

yield. The pattern of the data is shown in Figures 30, 31, and 32.

Speed, blankholder pressure, and the ratio of the punch radius to the material thickness affected the results. The punch radius only affected Bend T, which would follow since this is the only material that must conform to the punch radius. For both Side T and Bend T, an increase in speed and pressure tended to give a higher increase in the % elongation at yield. The effect of the highest tension at the low speed is hard to determine from the amount of data presented.

A notable aspect of these results is that the variables (blankholder pressure and punch radius), which had no effect on the decrease in tensile strength, do have an effect on the elongation at yield. This is interesting since it means that if the material is forced to conform to a radius, its strength will decrease by the same amount whether the radius is three times its thickness or ten times its thickness. But when a material undergoes such a deformation, the amount of strain that is needed for subsequent yielding in tension increases for the more severe deformation.

c. <u>% Elongation at Break for ABS</u>

The large variance for the % elongation at break data reduces the possibility of making any firm conclusions. In general, Side T and Bend P had a greater % elongation at break. For Side T, a greater blankholder pressure seemed to increase this parameter as shown in Figure 33. For Bend P, Figure 34 indicates that as the ratio of the punch radius to the material thickness increased, the % elongation at break decreased. The specimens of Bend P have a curved surface since they are taken from the bend of the part. This geometry is probably the main reason for the result.

d. Stress-Strain Curves for ABS

Figures 35 through 38 are typical stress-strain curves for the complete system under consideration. The most significant information they contain is that there is no upper yield point for Side T and Bend T. These are the same cases that showed a decrease in the tensile strength, seemingly independent of the operating variables, and an increase in the % elongation at yield.

e. Results for PVC

Table 8 gives the changes in tensile properties found for conditions 10 and 12. Table 5 indicates that the tensile strength did not show a decrease for Side T as ABS did. Bend P showed less of a decrease than occurred with ABS.

Side T and Bend T gave a greater % elongation at yield, as was the case for ABS, although the effect was somewhat reduced for Side T. No significant change in % elongation at break was observed.

The stress-strain curves for PVC continued to have an upper yield point for Side T but not for Bend T.

The PVC was a considerably tougher material with a % elongation at break of approximately 120%, as opposed to the 25% elongation at break for ABS.

f. Discussion

Side T and Bend T represent the most interesting, and unexpected, results of this investigation. This discussion will attempt to give an explanation of the results for these two cases as well as for Bend P.

Side T gives the properties of material that has flowed over the die radius and was "bent" and "unbent" under tension. The decrease in strength, as well as the absence of an upper yield point in the stress-strain curve, suggest that a significant change has developed within the material.

To explain the results in terms of molecular orientation, which is frequently done in discussing the effects of cold working, is not at all satisfying. Doane and Matsuoka[25] have determined that for oriented ABS material, the strength and ductility were increased in the direction of orientation and were decreased perpendicular to it. Such an effect was not observed when comparing Side T and Side P. The variation of the results does not make it obvious that Side P exhibited equivalent properties to undeformed material. But it is evident that the tensile strength did not increase nor did the ductility decrease. Also, for oriented material the change in tensile strength and ductility is in the same direction, not in the opposite sense as the results for Side T indicate.

Another explanation could be that the absence of the upper yield point is similar to a tensile test when a specimen has been strained beyond the yield point. The load is released and then reapplied. In this instance the upper yield point no longer appears. Such a tensile specimen contains a neck after it has yielded, and this neck remains when the load is released. Reloading only causes growth of this neck. If the load is not completely released, a smaller upper yield point appears.(26)

Cycolac MS was tested in a manner described above. The reloading did cause only the growth of the neck, and no upper yield point existed. If the load was not completely released, a smaller upper yield point was obtained as was indicated.

The explanation of the formation of the neck and its role in the stress-strain characteristics of a material is debatable. Explanations have been given indicating that a localized heating caused softening of the material, and this in turn caused the drop in strength.(27) Another explanation is that for purely geometrical reasons the decrease in cross sectional area during the formation of the neck is not compensated by an adequate degree of strain hardening.(27) Recently, Brown and Ward(27) determined that for poly(ethylene terephthalate), the upper yield point was due to an intrinsic yielding. However, no molecular model was given to explain how this intrinsic yielding occurs.

Since no evidence of necking appeared in the specimens, the above discussion does not directly apply to the findings of Side T. However, it does indicate that yielded material will exhibit no upper yield point, a fact which is pertinent to the proposed analysis.

The sides of the deformed part contain a slight curvature, indicating that they have not been completely "unbent". This means that one side of the tensile specimen is slightly under compression, while the other side is under tension. Upon the application of a tensile force, the material under compression may yield differently than the portion under tension. This would not allow the material to yield homogeneously. Thus, it would take more strain to arrive at the yield stress, which would be below the upper yield point of normal material.

If the above is true, and if this yielding continues, since the complete cross section does not yield together, the amount of elongation before the material breaks is larger. That is, it takes more strain to establish the stress throughout the material which will finally allow the material to break.

An increase in tension causes more material to be in tension after flowing over the die radius and gives a slightly greater curvature in the sides after withdrawing from the tool. Rather than reducing the tensile strength, as might be expected, the specimen merely yields in a more non-homogeneous manner. That is, more strain is now needed to arrive at the yield point. The strength of the material remains the same.

On the basis of the above evidence such a conclusion seems to be more speculative than proven. There is, however, one other subtlety that gives strength to this argument. After the tensile test is made, a slight curvature still exists in the now broken specimen. The curvature, however, is in the opposite direction, indicating that the material which was previously under compression is now under tension. This only occurs for Side T.

The type of yielding that occurs in the material which had undergone a compressive stress may be similar to a Bauschinger effect,[28] which is a property of some metals. This effect occurs when a metal is strained in compression and then in tension or vice versa. The yield strength of the second test will be reduced. That is, a material that has been compressed will have a lower yield strength in tension.

Side T is a material that has been compressed on one side and placed in tension on the other. If the "unbending" which occurs does not completely remove the effects of the compressive strain, and if the material is subsequently tested in tension, then by the above explanation the material in compression would yield sooner, i.e. with less strain. Further, this intrinsic yielding would not be homogeneous, because only part of the material has undergone compressive loading. Thus, the upper yield point no longer appears, the tensile strength is reduced, and the % elongation at yield is increased.

Bend T exhibits properties that are extremely similar to Side T. Since the material tested has also conformed to a radius, the punch nose radius, this would be expected. However, since the specimens are made directly from the deformed part, they contain a fairly significant curvature. A comparison of such a specimen with a normal tensile specimen presents some uncertainties.

The similarity with the results for Side T suggests that the yielding is in a similar manner. The results are not exactly the same, however. There is no change in curvature such as the tensile specimens for Side T exhibit, and the % elongation at break is not increased as greatly as for Side T, although the large variation of the results make conclusions for this parameter more difficult. Since this area of the deformed part also contained crazing in most of the experimental conditions, the problem is further complicated.

The mechanism of yielding at the bend, therefore, is not very well understood. It depends upon the effect of the geometry of the specimen and the interaction of the crazing with the stressed material.

The results for Bend P are more easily explained since the ratio of the punch radius to the material thickness seemed to have such a strong effect.

At the lower ratios the amount of springback was much smaller. This decrease in springback shown in Figure 9 was interpreted to mean more crazing in that area.

Figure 28 indicated that the reduction in tensile strength also depended upon the radius of the punch nose in a similar manner. A smaller ratio of radius to material thickness gave more reduction in tensile strength. The strength reduction is further evidence of crazing in that portion of the part. More crazing would have the effect of reducing the amount of material in a cross section of a tensile specimen and thereby reducing its tensile strength.

Although the effect is not as great, Figure 29 indicates that an increase in blankholder pressure generally results in a greater decrease in tensile strength. If, as seems reasonable, this also produces more crazing, it would give further strength to the above argument.

Increasing the temperature of deformation did not seem to change any of the above results. The decrease in tensile strength and increase in % elongation at yield followed basically the same pattern.

Finally, these results must be compared with PVC. For PVC, Side T still exhibited an upper yield point, but there was a slight indication that it was reduced. This reduction was not larger with an increase in tension, however.

Since PVC was, in general, tougher than ABS, deforming it under the same conditions did not affect the material as severely as it affected ABS. The amount of compression that the material had to undergo in order to conform to a radius 10 times its thickness apparently was either not sufficient or PVC reacts to such a stress system in a completely different manner.

This latter explanation is unlikely, however, after considering the results for Bend T. At the bend, the tensile strength was reduced considerably, there was no upper yield point and the % elongation at yield increased following the same pattern as ABS. In this instance the material had to conform to a radius of only 3 times the material thickness. Apparently, this more severe deformation produced the same type of effect on the material as it did on ABS. The result was not quite as severe, however, as will be shown when the effects on density are considered.

2. Impact Properties

The results of the tensile properties at low speed indicated that an investigation of the side of the material under impact conditions may be worthwhile. The non-homogeneous yielding could give some interesting results at a high strain rate.

Initially, 5 samples of Side T were compared with 5 samples of undeformed material. The undeformed samples were from a different sheet of material than the deformed samples. The results are given in columns A and D of Figure 39. In this instance, as well as the others, the result is plotted as a confidence interval for a sample of 4. The lowest reading was not used since slippage required more than one impact. These readings were encouraging enough to proceed.

The remaining samples were prepared as indicated in Figure 39. Columns B and F, which show the greatest variation, each contain a result of a sample that had to withstand two impacts. The impact strength used, however, in these instances was of the same magnitude as the others.

Although there was a large variation in these later results, there may be a trend, since in every instance the average of the impact strength was greater for Side T than for Top T and undeformed material.

D. Physical and Morphology Properties

1. Density

Figures 40 and 41 present the data for the results of the density measurements made on undeformed and deformed material. Again, these are 90% confidence intervals for the mean of a sample of 5.

Some of the ranges obtained are quite large considering these are all taken from parts made under similar conditions. Much of this is due to experimental error that was previously identified. The results, however, are such that these errors do not inhibit the analysis to any extent.

The results for PVC indicated that Dacovin 2082 has a density of 1.406 g/cc prior to deformation. The Diamond Shamrock Chemical Company gives a density for the material as 1.42 ± .02 g/cc, a range which includes the value obtained. Marbon Chemical Company gives the density of Cycolac MS as 1.08 g/cc with no range indicated. This investigation found a density of 1.099 g/cc. Both Marbon and Diamond Shamrock give ASTM D-792 as the testing method.

The results for the density of ABS become very interesting when comparing them to the springback of the parts. Figure 42 and Figure 8 are markedly similar. The effects of low speed, high speed, and elevated temperature are identical. Figures 43 and 9 also are simular. Figure 44 is even more striking. Not only does it show a linear relationship between the springback and density, but when the line is extended to 1.0 springback, where springback is complete, it predicts the value of the density of undeformed material to within .001 g/cc, or a .091% difference.

The discussion of the effects of tension and the ratio of the punch radius to material thickness on springback indicated that crazing was the suspected reason for the results. The effect of these two variables on density confirm that suspicion.

The effect of temperature on springback was very significant. The results of Figure 42 indicate that crazing is the determining factor for these results also. That is, increasing the temperature reduces springback only because the material can craze easier.

Kambour[29] defines a craze as a thin region of polymeric material that is abruptly bounded and has more or less different optical properties from the surrounding bulk polymer. He determined that a craze in polycarbonate contains a void content of between 40% and 50% and, thus, a decrease in density of the same amount.

In a recent article Kambour[30] characterizes the voids as spheres approximately 200 Å in diameter. The holes are interconnected since liquids apparently can move through a craze with ease.

The ABS material, therefore, when conforming to a radius will do so plastically only if the material in tension is able to expand. This expansion is accomplished by a crazing of this material in tension.

The results for PVC indicate a slight decrease in density, but the effect of tension is not as clear as it was for ABS. The results for conditions 10 and 11 establish a similar pattern as ABS, but condition 12 apparently did not involve a severe enough increase in tension to give a significant change. The reason for this was that the toughness of PVC did not allow the material to respond to tension increases as readily as ABS.

The tensile properties of PVC for Bend T followed the same pattern as ABS. Since the density change was not as great but the drop in tensile strength was (See Bend T of Table 5), the results indicate that the smaller radius was the cause of the yielding properties.

Thus, although a radius of 10 times the material thickness had no substantial effect on the tensile properties, the reason was not necessarily that the material reacts differently under the stress system, but that the die radius was not small enough to show such a change. This conclusion must be made with qualification, however, since the material at the bend was not "unbent" under tension as it was along the side.

2. Results of Optical Microscopy

Figure 45 shows a comparison of the surface of the top of the trough and the bend of the ABS. The texture clearly shows the crazed area. The direction of the axis of the craze is parallel to the bend (i.e. perpendicular to the applied tension), which is what would be expected.

3. Results of Electron Microscopy

Figures 46 and 47 show electron micrographs of the ABS at the surface and at the interior, as represented by a fractured surface.

The smooth areas of Figure 46 are difficult to understand. No references were found which gave similar results. Since surface effects can be complicated, and the application of the results to this investigation questionable, no further efforts were made at interpretation.

Figure 47 generally agrees with previous fractured surface studies such as those by Kato,[32] Matsuo,[33] and Mann et al.[34] The particles are the polybutadiene rubber components. According to Matsuo the crazes could be visible in these micrographs since they have an initial width of about the same dimension as the diameter of the rubber particles. If the crazes are just at the portion of the bend that is in tension, they may not be able to be seen in a fracture surface which includes only a portion of the cross section.

Matsuo used the surface of a compression molded specimen to observe the crazes. This surface, like Figure 46, did not give the same morphology as a fracture surface, but did show the crazing clearly.

Figure 46 does not show the crazing to the extent that was observed by Matsuo. There are markings which may be an indication of crazing, but this could not be confirmed. The fact that this was extruded rather than compression molded may be part of the explanation for the difference in the results. Another reason may be the magnitude and the duration of the stress, which was not specified by Matsuo. A third possibility may be the limitation of the depth of field which, for this material, may not have allowed the crazing to be observed.

In order to increase the depth of field several attempts were made at looking at the material with a scanning electron microscope. Gold chromium, and carbon were tried as the conductive layer on the surface of the plastics. The conductive layer was evaporated onto the surface at a thickness of 100 Å to 200 Å. None of these attempts provided a satisfactory image.

IV. THEORETICAL CONSIDERATIONS

The material that must conform to the punch and die radii during the deformation is subjected to a bending stress, as well as a tensile stress, due to friction. The result is a complicated system that can only be thoroughly understood with a full knowledge of the material characteristics in tension, as well as compression. Further, any analysis will contain some assumptions which allow computation of the stresses during deformation. These assumptions also must be based on the material characteristics. Since current information does not give all of these characteristics, a complete stress analysis is not possible. However, an attempt will be made at an analsis with the objective of providing at least an insight into the system.

This analysis will consider the effects of pure frictional tension on a material being formed over a radius. It will also consider the effects of pure bending, neglecting the frictional forces. The results will be superimposed, assuming that these stresses are linearly additive.

This last assumption, of course, is quite strong and open to serious question. However, Swift[31] analyzed the problem in exactly this manner. He was able to justify his assumption by considering the degree of flexture sufficient to make elastic strain negligible, yet insufficient to require different stress-strain relationships in tension and compression. Further, he considered the Bauschinger effect negligible by comparison with the total plastic strain involved. And, finally, the strain-hardening factor is unaffected by a stress reversal. These conditions, of course, were applied only to metals.

First, consider the effects of friction on the process. Figure 48a shows a small section of a material conforming to a radius, R. If $\delta\theta$ is taken to be very small, its cosine approximately equals 1, and its sine is approximately $\delta\theta$. If all higher order terms involving $\delta\theta$ are neglected, the following equations can be written:[31]

A summation of the forces in the X direction yields:

$$\frac{dT}{d\theta} = \mu PR - F \qquad (1)$$

T: Applied tension

θ: Angle about radius being considered

μ: Coefficient of friction

P: Intensity of the interfacial pressure between the tool and material

R: Radius about which the material is conforming

F: Normal force applied between the material and the tool

The sum of the forces in the y direction yields:

$$\frac{dF}{d\theta} = T - PR \qquad (2)$$

The sum of the moments about 0 yields:

$$R_1 \frac{dT}{d\theta} = \mu PR^2 \qquad (3)$$

R_1: Location within the thickness being considered

from (3) $$P = \frac{R_1 \frac{dT}{d\theta}}{\mu R^2} \qquad (4)$$

substituting (4) into (1):

$$F = \left(\frac{R_1}{R} - 1\right) \frac{dT}{d\theta} \quad \text{or} \quad \frac{dF}{d\theta} = \left(\frac{R_1}{R} - 1\right) \frac{d^2T}{d\theta^2} \qquad (5)$$

Substituting (4) and (5) into (2):

$$\left(\frac{R_1}{R} - 1\right)\frac{d^2T}{d\theta^2} + \frac{R_1}{\mu R}\frac{dT}{d\theta} - T = 0$$

or

$$\mu\left(\frac{R_1}{R} - 1\right)\frac{d^2T}{d\theta^2} + \frac{R_1}{R}\frac{dT}{d\theta} - \mu T = 0 \qquad (6)$$

Since both μ and $\left(\frac{R_1}{R} - 1\right)$ in this investigation were at most on the order of 0.1, their product is small enough to neglect the $\frac{d^2T}{d\theta^2}$ term.

$$\text{Thus,}\quad \frac{dT}{T} = \mu \frac{R}{R_1}\, d\theta$$

$$\text{or}\quad T = T_1 \exp\left[\mu \frac{R}{R_1}\Delta\theta\right] \qquad (7)$$

where T_1 is the applied tension and $\Delta\theta$ is the angle about the radius being considered.

This gives a tension within the thickness of the material as shown in Fig. 48b. That is, the tension within the strip varies from $A = T_1 \exp[\mu\Delta\theta]$ to $B = T_1 \exp\left[\mu \frac{R}{R+t}\Delta\theta\right]$

Now consider Fig. 49a, which is material being bent about a radius but no tension is being applied.

The strain on the outermost material is:

$$\epsilon = \frac{R_2\Delta\theta - R\Delta\theta}{R_2\Delta\theta} = \frac{R_2 - R}{R_2}$$

R_2: Location of the neutral axis

The stress associated with this strain can be obtained from a stress-strain curve and a plot of the stress within the thickness of the material is shown in Fig. 49b.

If the neutral axis for pure bending is assumed to be midway within the thickness of the material, the quantities A, B and C for condition 1 through 9 (ABS material) are listed in Table 9. This is the stress within the material as it conforms to the radius where $\Delta\theta$ is $\frac{\pi}{4}$.

Fig. 50 shows the resultant stress for the general case. Bending is seen to be the predominant stress system at this point of the deformation.

The subsequent straightening that occurs after deformation about the die radius further complicates the problem. This straightening reverses the stress pattern shown in Fig. 50. The final result is a material that has a cross section of some material in compression and some in tension. This is considered to be the cause of non-homogeneous yielding.

V. CONCLUSIONS

The stated objective of this investigation was to (1) determine the effect of the "bending under tension" stress system on polymer material, and (2) to determine the variables that are important in deep drawing as far as this stress system is concerned.

All the variables within the range considered had an effect on the final result, although the role of speed of deformation could not be fully understood due to the limitation of the range. Increased tension, higher temperature or a smaller ratio of punch radius to material thickness increased the severity of the deformation. An increase in temperature had, in general, the greatest effect, which would be expected with a polymer material. However, its effect was basically the same as that observed by changing the other variables. That is, no variable produced a unique effect on the part. The optimum combination of the variables, therefore, depends upon the particular situation in making a specific part.

Two conclusions may be reached concerning the effects of the stress system on polymer material. The fact that only one stress system in the deep drawing process was considered must be remembered.

In general, both the Cycolac MS (ABS) and the Dacovin 2082 (PVC), were affected by the stress system and exhibited new material properties. The specific conclusions are:

1. Cycolac MS (ABS), which has conformed under tension to a radius of 10 times its material thickness and has then been "unbent" under tension, will subsequently have a new tensile

stress-strain relationship due to non-homogeneous yielding of the deformed material.

Dacovin 2082 (PVC), subjected to a similar deformation, will not be affected similarly, but will exhibit substantially the same stress-strain behavior as the undeformed extruded material.

2. Cycolac MS which has conformed to a radius under tension will be permanently deformed only to the extent that the material which is in tension at the radius becomes crazed. Such a specimen will also exhibit new tensile stress-strain properties. Dacovin 2082 which has conformed under tension to a radius of 3 times its material thickness, but not subsequently "unbent" under tension, will exhibit a change in tensile stress-strain properties similar to the Cycolac MS.

The new stress-strain behavior to which the above refers consists of: (1) a decrease in tensile strength, (2) an absence of an upper yield point, (3) an increase in the % elongation at yield, and (4) an increase in the % elongation at break. Crazing may cause the fourth effect not to be observed at the bend, since the sample could break prematurely due to the crazed material.

The significance of these conclusions is that the subsequent behavior of the ABS and PVC conforming under tension to a radius will be substantially different, depending upon the size of the radius and the amount of tension. This new behavior may not necessarily be detrimental. If the material yields non-homogeneously, as the ABS did when conforming to a radius of 10 times its thickness, non-homogeneous yielding may be used to an advantage through the use of draw beads and other tool design considerations. In general, non-homogeneous yielding could improve the formability of the material.

Crazing also could be an advantage. Material that has not crazed but is restrained due to the geometry of the part may contain internal stresses that would be harmful to a particular application. In this case a crazed material may be more desirable since, as the results of spring-back indicated, this material could retain the shape of the punch nose without the aid of a restraining geometry.

However, crazing can be considered harmful, since there is a loss in strength and the material is more susceptible to contamination such as staining. Non-homogeneous yielding may reduce the amount of this unwanted crazing. If the material that will subsequently be in tension when conforming to the punch radius is previously placed in compression, the material may yield in such a manner that it will no longer craze. Subsequent experiments in this area may be fruitful.

TABLE I

Properties of Cycolac MS as Stated by the Marbon Chemical Company

Property	Conditions	Units	.125" Thickness
Falling Dart Impact	73° F	ft-lbs	18
	-10° F		8
Tensile Strength (at yield)	73° F	psi	6,000
Elongation (at yield)	73° F	%	5
Tensile Modulus	73° F	psi	300,000
Flexulal Strength	73° F	psi	10,000
Flexulal Modulus	73° F	psi	340,000
Density	73° F	g/cc	1.08

TABLE 2

Properties of Dacovin 2082
as Stated by the Diamond Shamrock Chemical Company

Property	Units	Value
Izod Impact	ft. lbs/in. of notch	4 - 5
Tensile Strength	psi	6900
Durometer, hardness		84 ± 3
Density	g/cc	1.42 ± .02

TABLE 3

Speed Profile for $\frac{1}{4}$ Cycle of Punch Press

Distance of Travel (inches)	Low Speed in/min.	High Speed in/min.
0	0	0
1/16	210	502
1/8	292	699
3/16	352	842
1/4	399	955
5/16	438	1049
3/8	471	1127
7/16	499	1194
1/2	522	1251
9/16	542	1298
5/8	559	1339
11/16	573	1372
3/4	584	1398
13/16	592	1418
7/8	598	1433
15/16	602	1441
1	603	1444

TABLE 4

Deforming Conditions

Condition	Material	Thickness (inches)	Temperature, °C, before Deformation	Speed of Deformation	Approximate Tension (psi) in Blank-Holder prior to Deforming over Die Radius
0	ABS	.050	Undeformed		
1	ABS	.050	Room	Low	250
2	ABS	.050	Room	Low	680
3	ABS	.050	Room	Low	1050
4	ABS	.050	Room	High	310
5	ABS	.050	Room	High	800
6	ABS	.050	Room	High	1290
7	ABS	.030	Room	Low	1030
8	ABS	.015	Room	Low	1230
9	ABS	.050	95	Low	680
10	PVC	.050	Room	Low	180
11	PVC	.050	Room	Low	620
12	PVC	.050	Room	Low	920

TABLE 5

Percent Decrease in Tensile Strength*

	Conditions										
	1	2	3	4	5	6	7	8	9	10	12
Side T	13	10	11	14	10	13	14	11	13	5.7	4.4
Side P	7.9	2.2	3.0	3.4	-.54	1.4	1.2	-2.8	5.8	4.5	.2
Bend T	30	16	14	18	17	16	16	14	13	17.	17.
Bend P	11	15	15	12	17	17	6.6	2.5	13	8.2	9.5

*Samples are compared to the tensile strength of the top along the same direction.

TABLE 6

Percent Increase in Percent Elongation at Yield*

Conditions

	1	2	3	4	5	6	7	8	9	10	12
Side T	1.47	45	14	16	89	140	52	40	140	14	4.2
Side P	8.3	.64	.66	8.9	0	0	-10	.74	2.8	-4.2	14.
Bend T	43	150	110	120	160	220	96	4	240	36.	47.
Bend P	2.8	2.6	1.3	3.4	0	4.2	4.3	4.2	3.5	13	18

*Samples are compared to the percent elongation at yield of the top along same direction.

TABLE 7

Percent Increase in Percent Elongation at Break*

	Conditions										
	1	2	3	4	5	6	7	8	9	10	12
Side T	100	92	175	-110	52	190	100	93	120	-1.5	33.
Side P	-44	25	90	67	88	16	82	67	86	-23	+29.
Bend T	-41	-3.8	84	-30	17	52	34	80	100	-17.	-15.
Bend P	82	110	110	310	110	100	91	77	170	-2.8	27

*Samples are compared to the percent elongation at break of the top along the same direction.

TABLE 8

Percent Change in Tensile Properties of PVC from Undeformed Material

	% Decrease in Tensile Strength Condition		% Increase in % Elongation at Yield Condition		% Increase in % Elongation at Break Condition	
	10	12	10	12	10	12
Side T	6.7	7.9	9.7	6.9	0	35.
Side P	7.0	5.2	2.7	4.0	-19.	3.6
Bend T	17.	20.	31	47	-8.3	-6.7
Bend P	11.	14.	5.3	5.7	2.2	2.2
Top T	-.65	3.6	-4.2	0	10.	1.7
Top P	2.6	5.4	-6.7	-9.3	5.1	-20

TABLE 9

Stresses in ABS during Deformation

Condition	A (side)	B (side)	C (side)	A (bend)	B (bend)	C (bend)
1	266	264	5400	266	262	5400
2	722	719	5400	722	712	5400
3	1120	1110	5400	1120	1100	5400
4	329	328	5400	329	325	5400
5	850	846	5400	850	838	5400
6	1370	1360	5400	1370	1350	5400
7	1090	1088	5400	1090	1084	4600
8	1310	1300	5400	1310	1300	4400
9	722	718	5400	722	712	5400

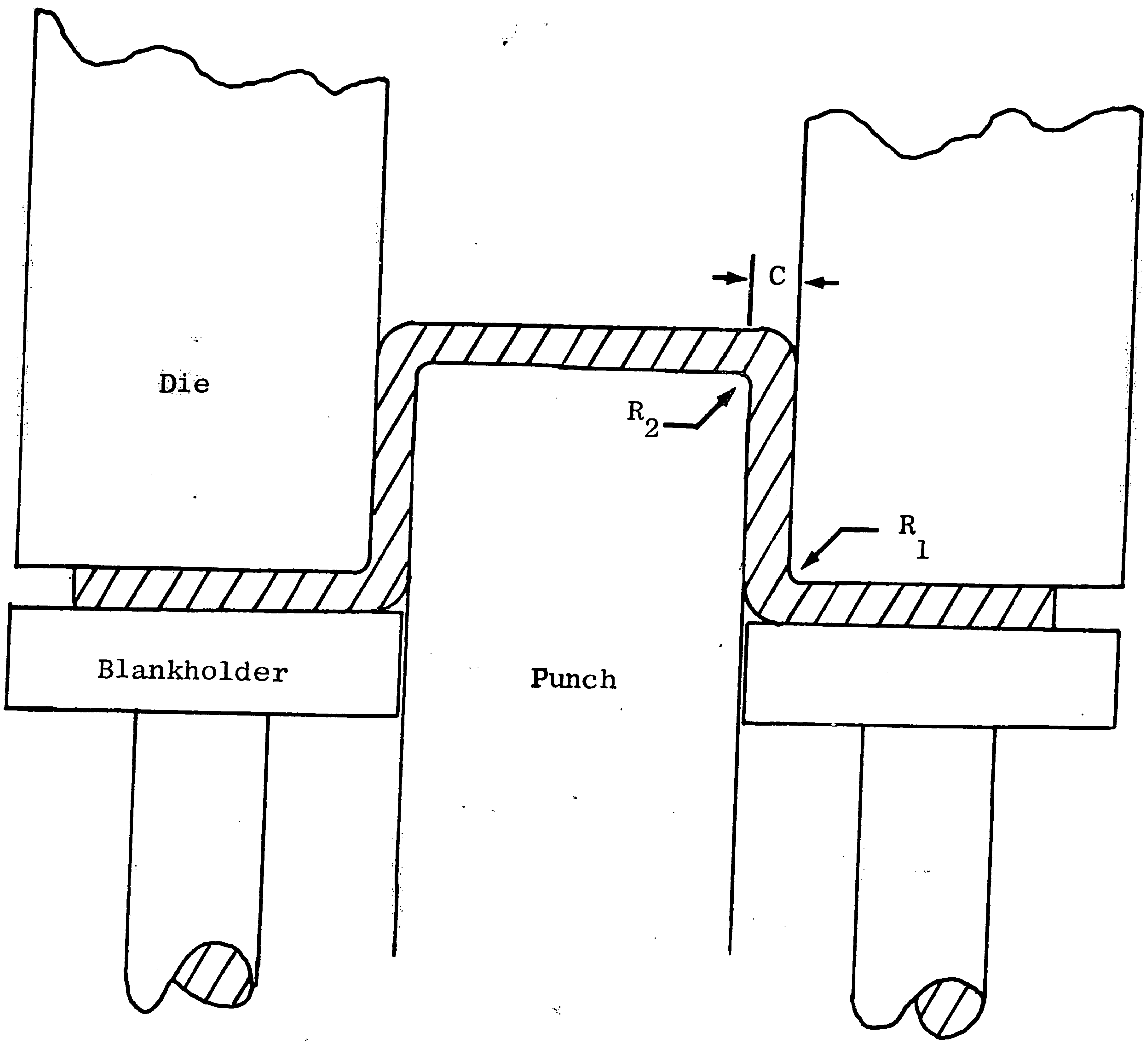


Figure 1. Cutaway View of the Deep Drawing Process

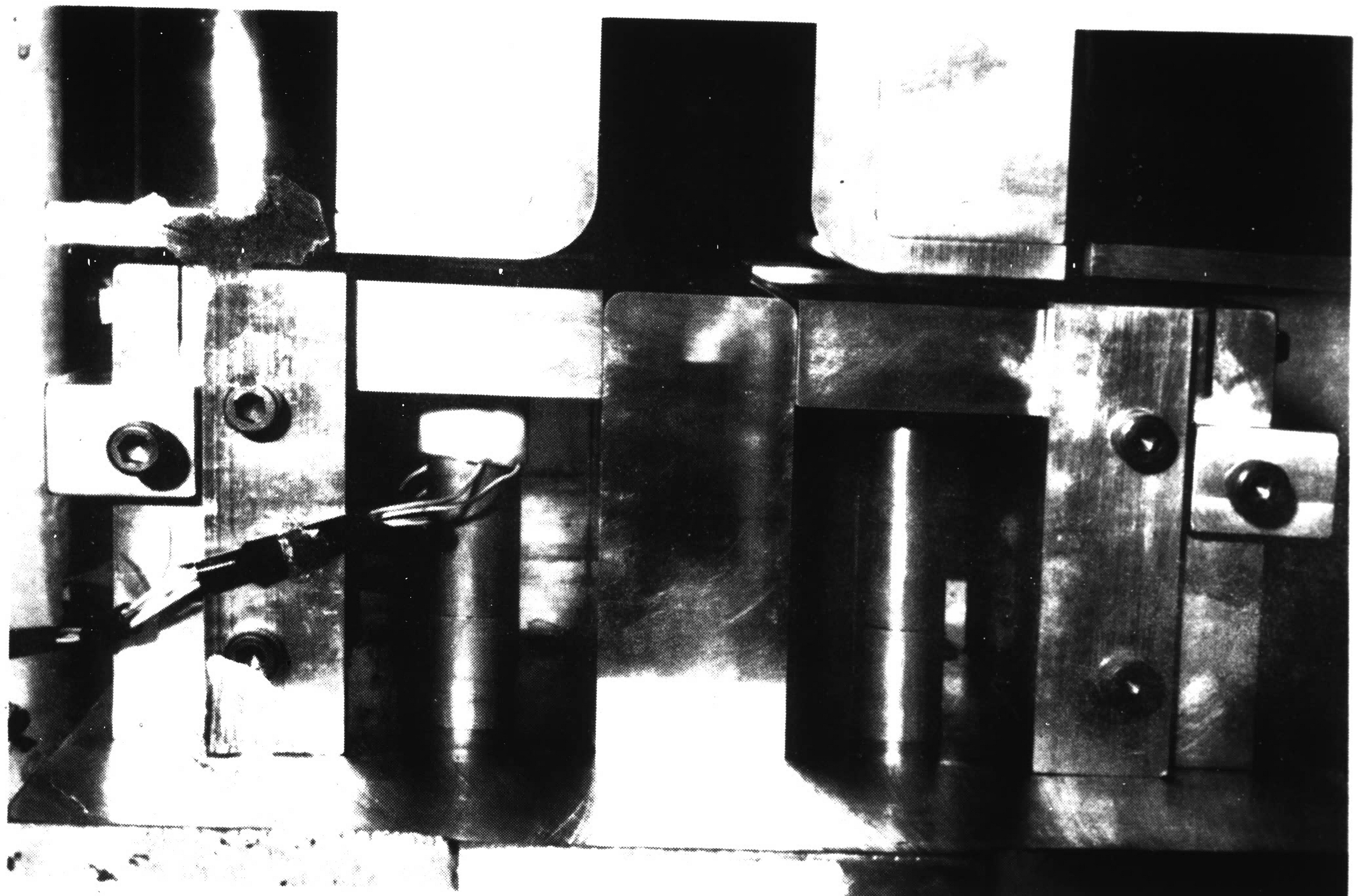


Figure 2. Cold Forming Tool

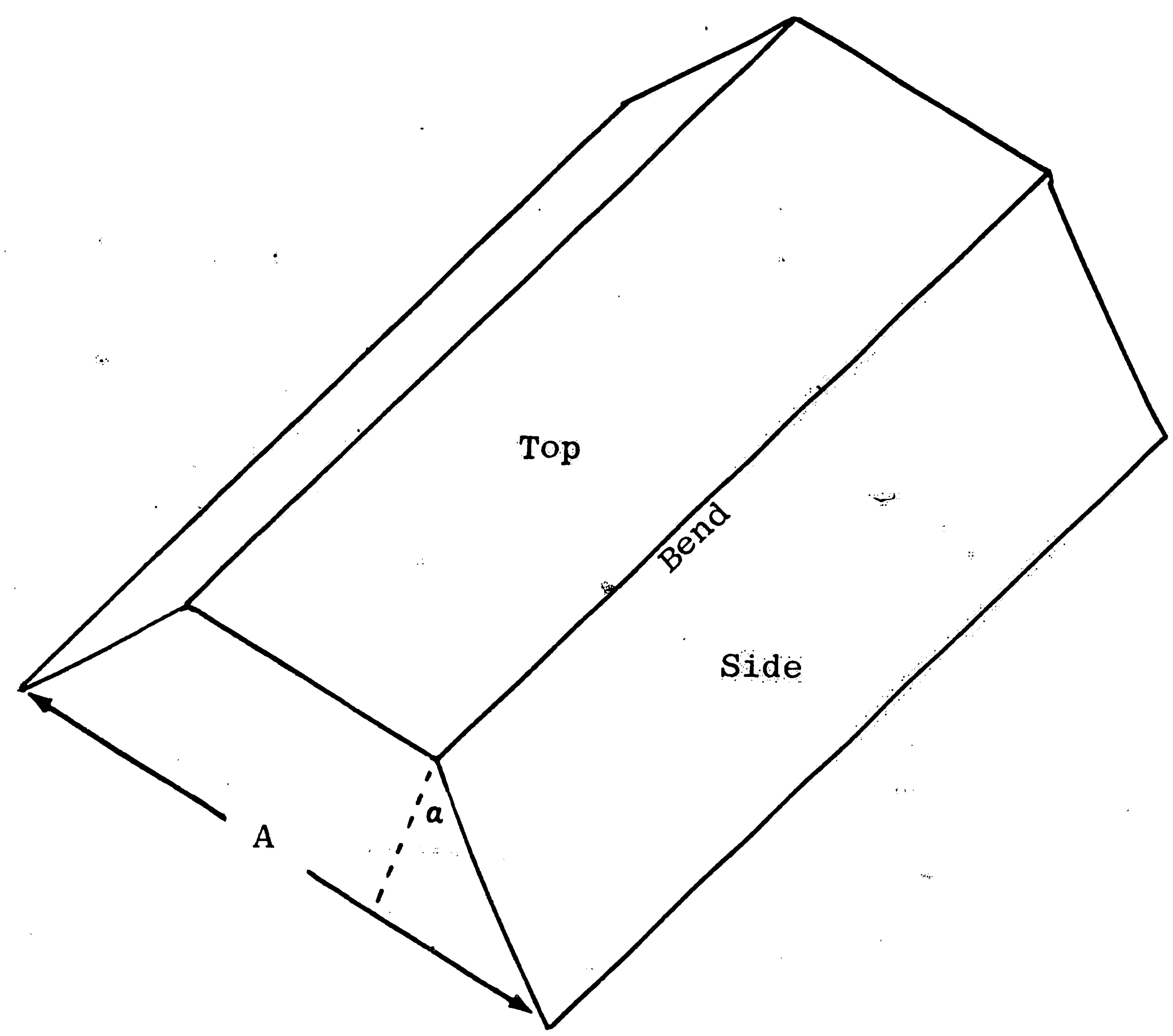


Figure 3. Deformed Part

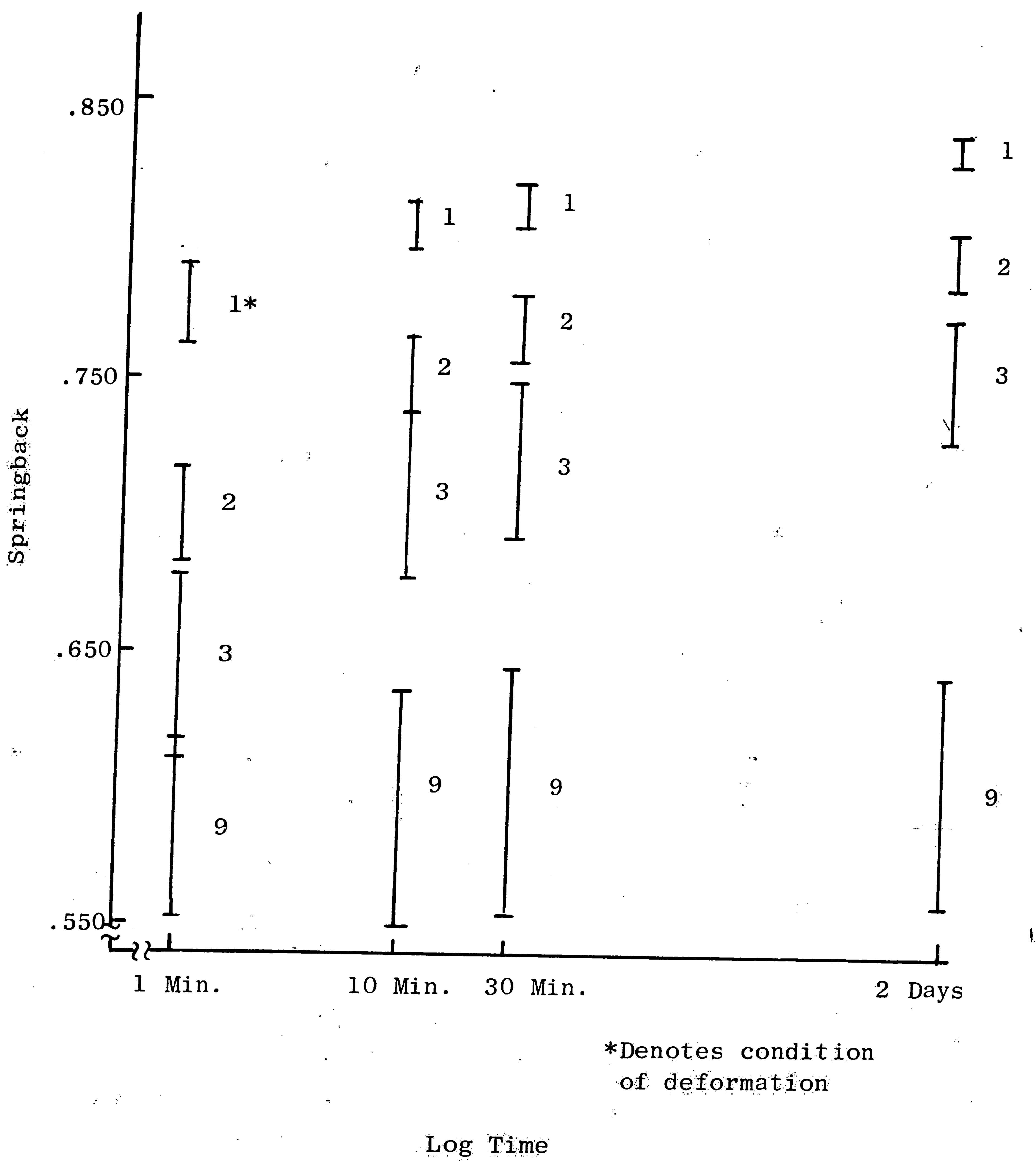


FIG. 4 Springback as a Function of Time for ABS Deformed at Low Speed

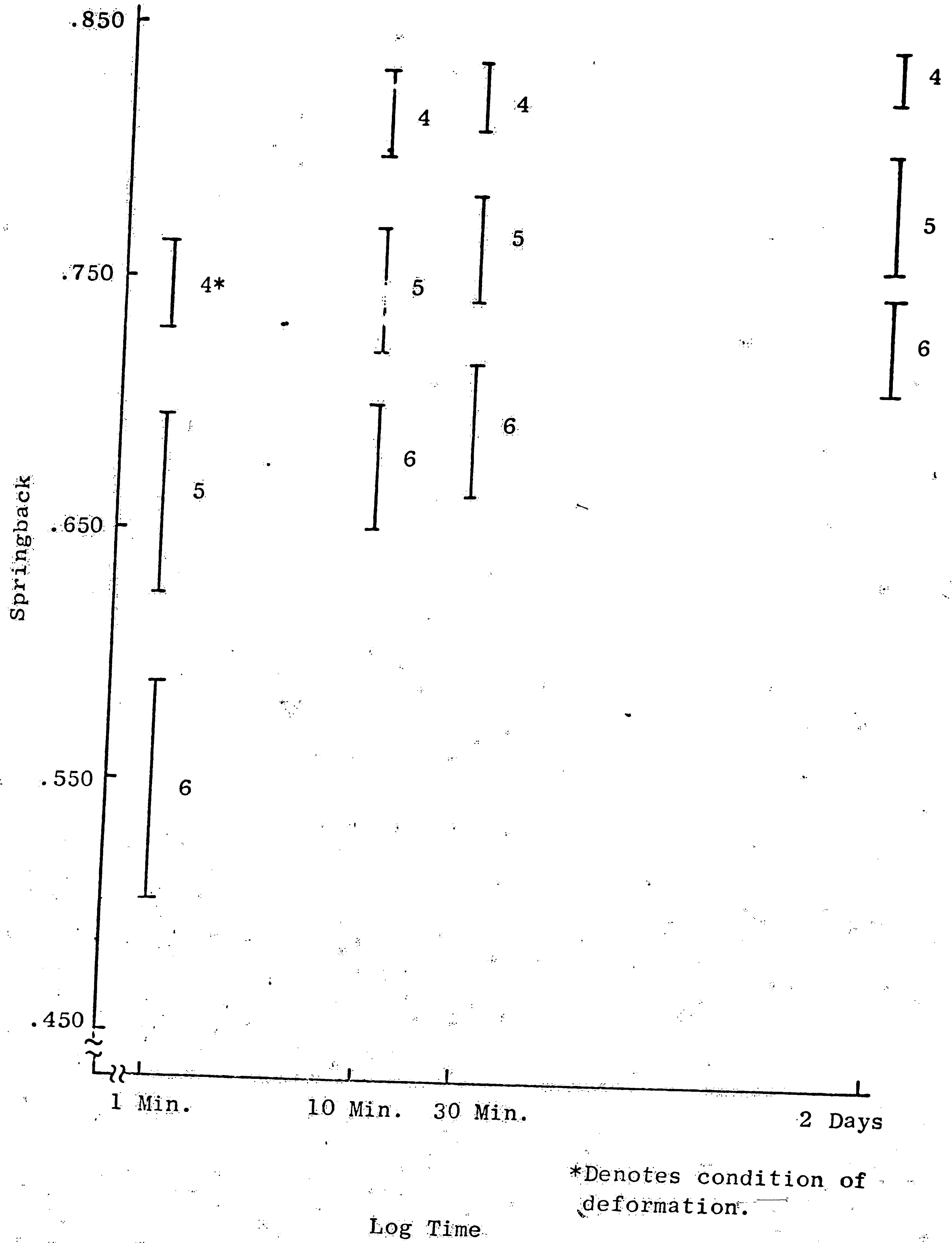


FIG. 5 Springback as a Function of Time for ABS Deformed at High Speed

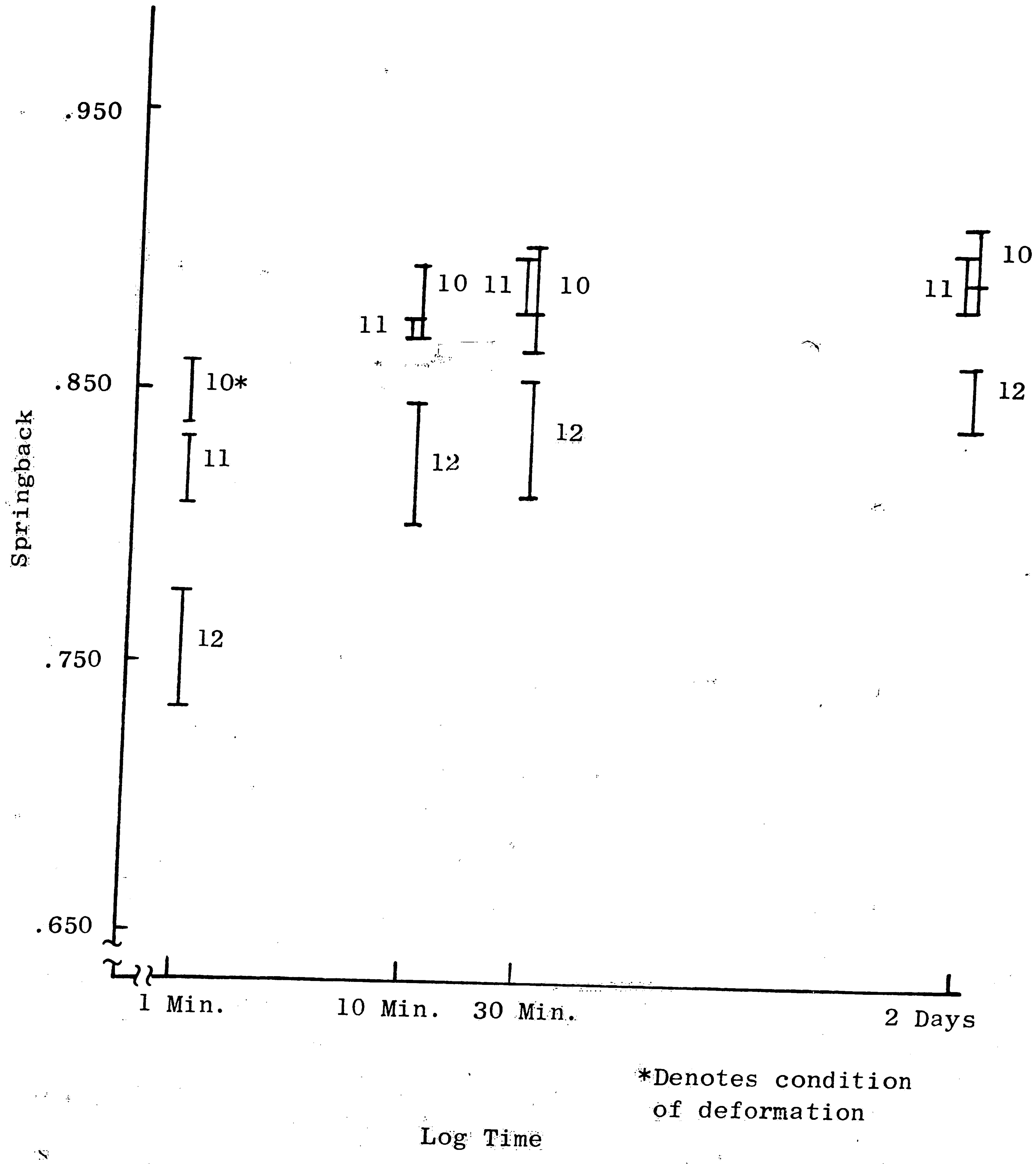
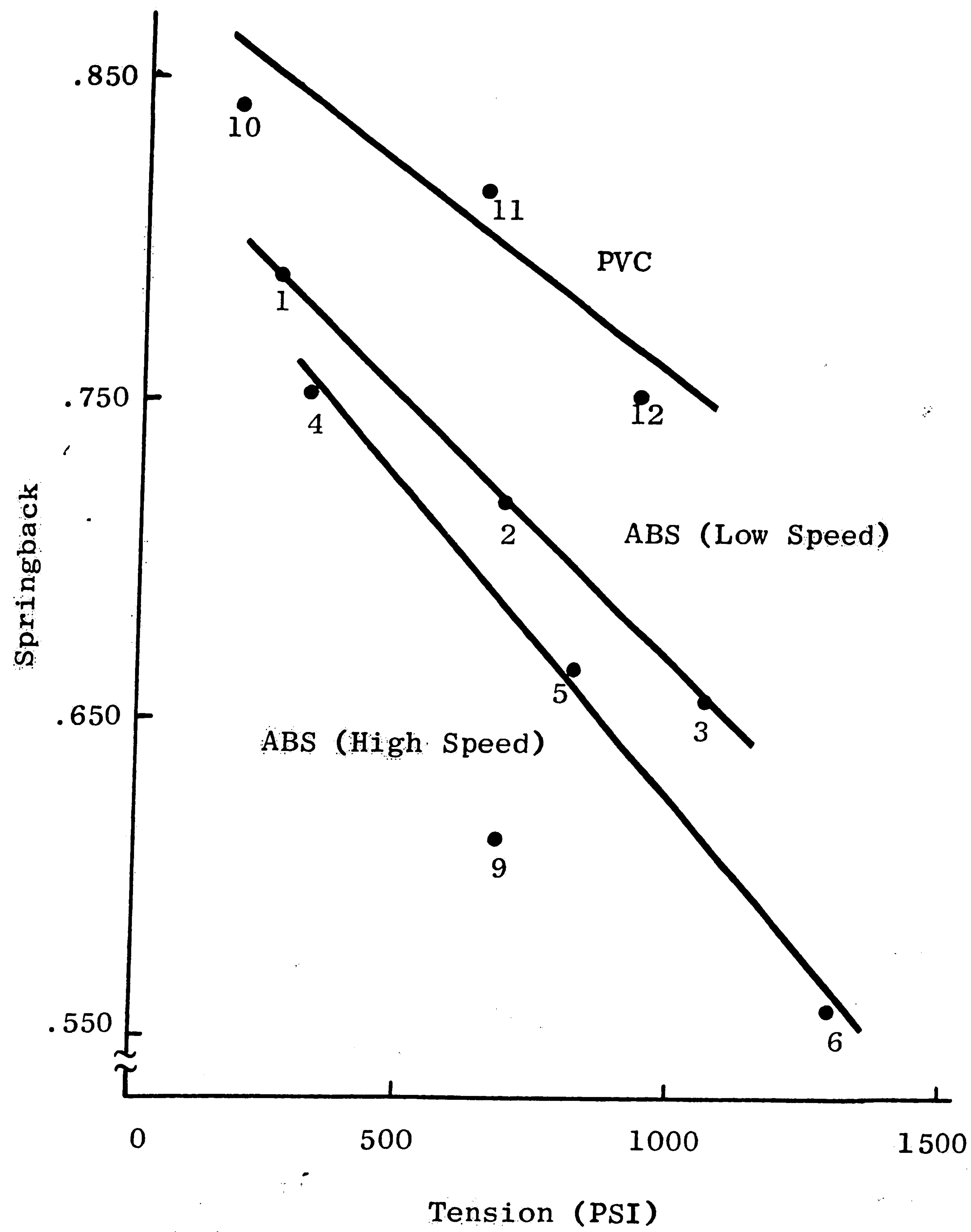


FIG. 6 Springback as a Function of Time for PVC



Numbers denote condition of deformation

FIGURE 7 Springback at 1 Minute as a Function of Tension

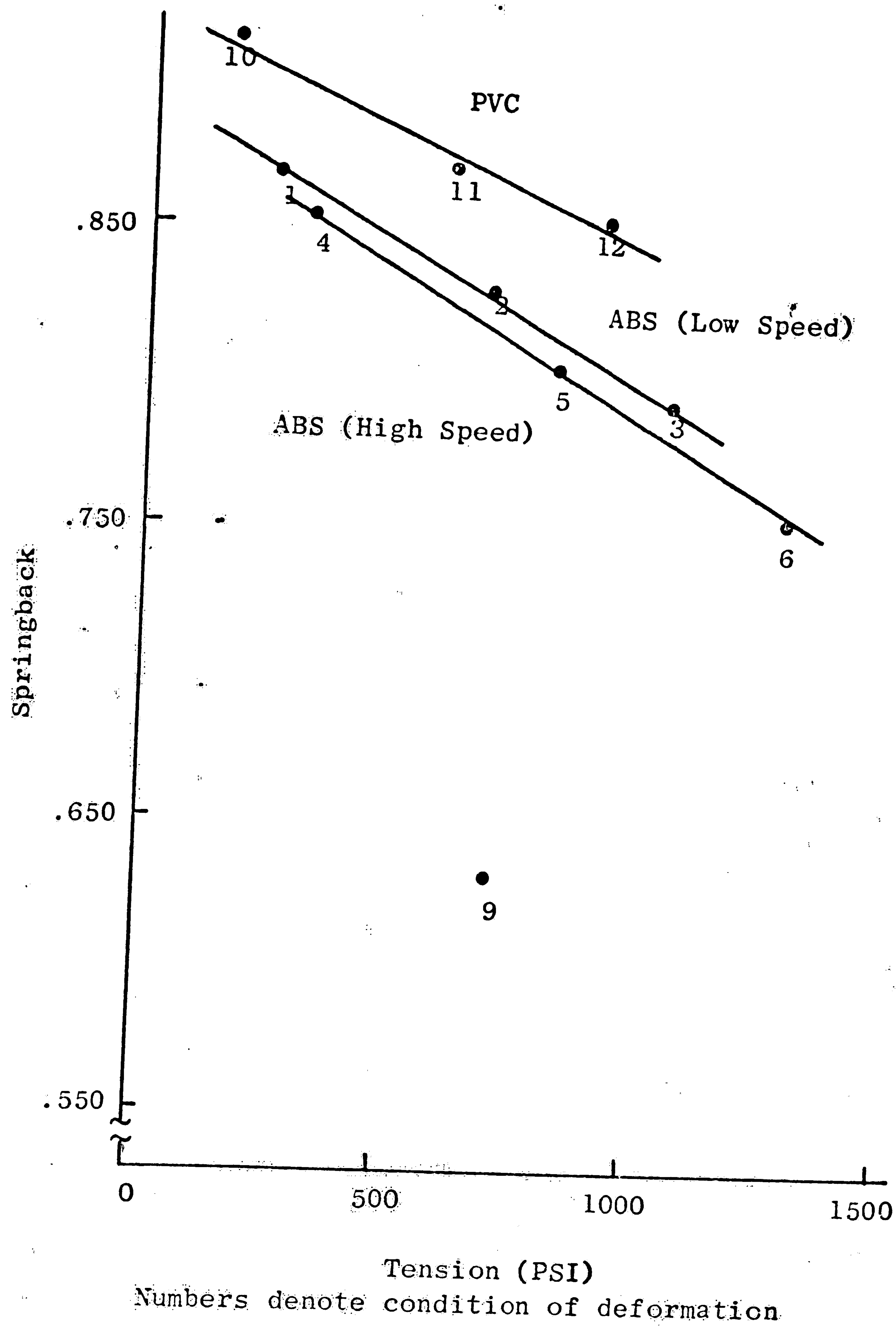


FIGURE 8 Springback at 2 Days as a Function of Tension

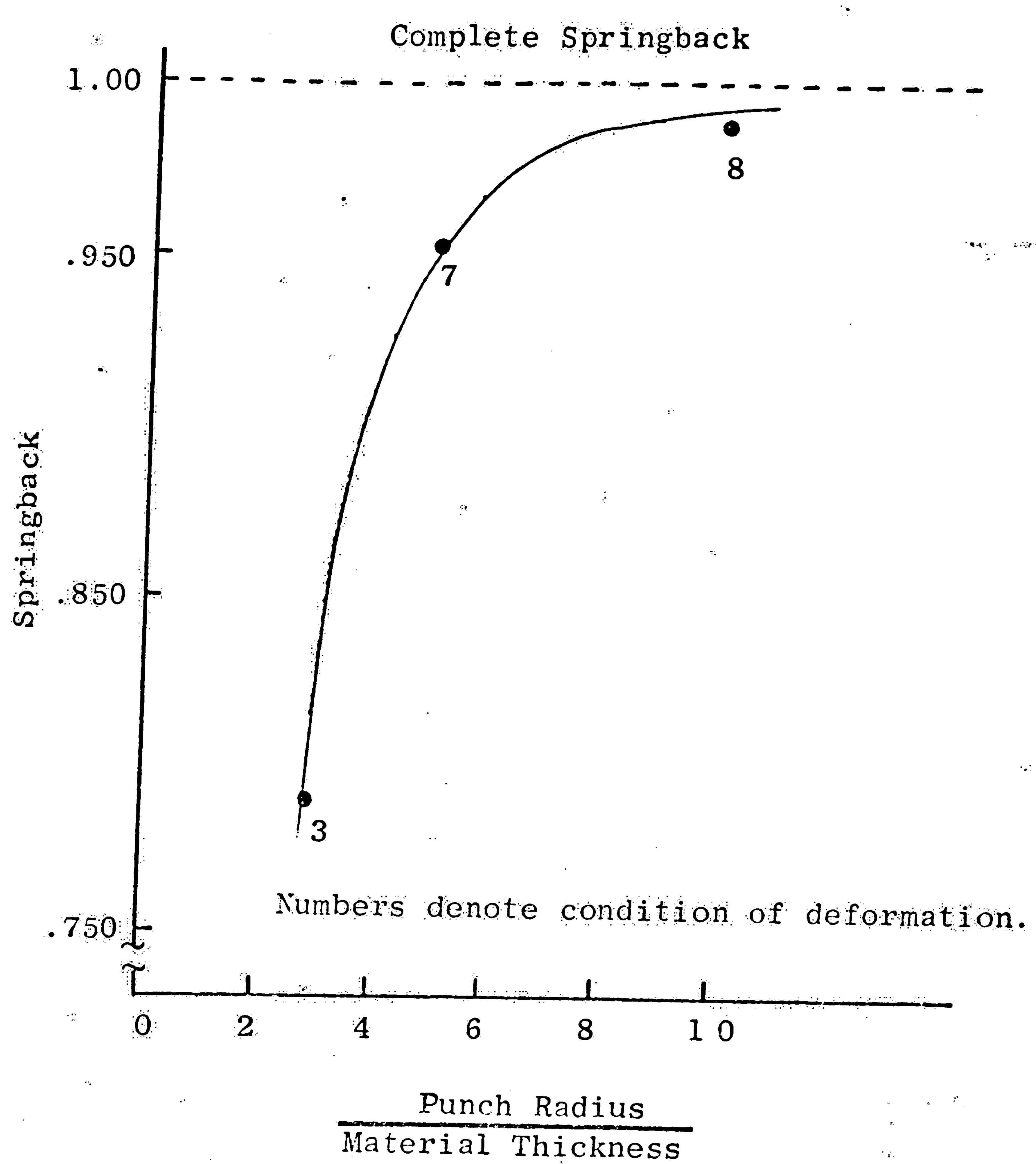


FIG. 9 Springback as a Function of Punch Radius to Material Thickness Ratio for ABS.

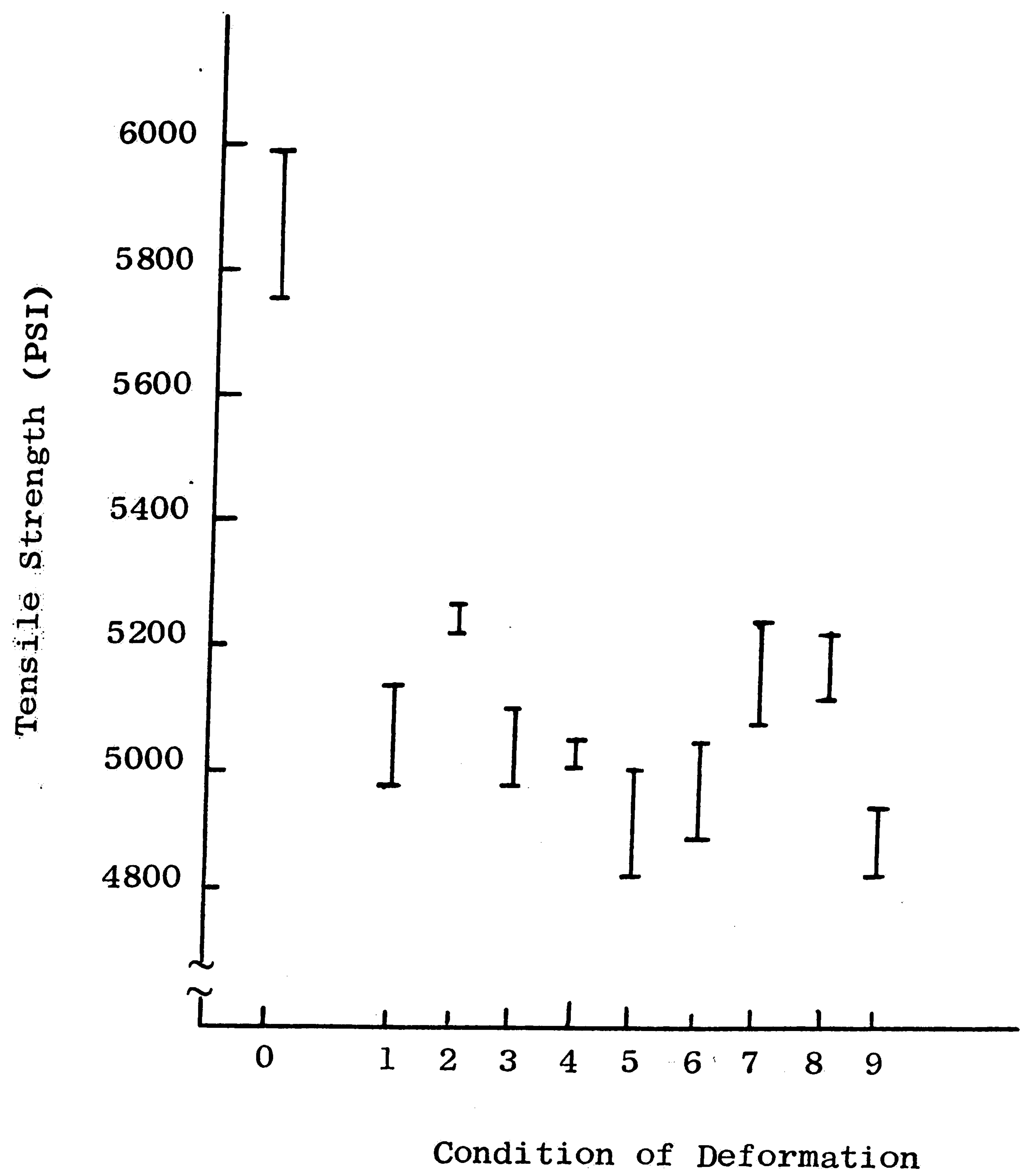


Figure 10. Tensile Strength of ABS Specimens from Side T for the Different Conditions of Deformation

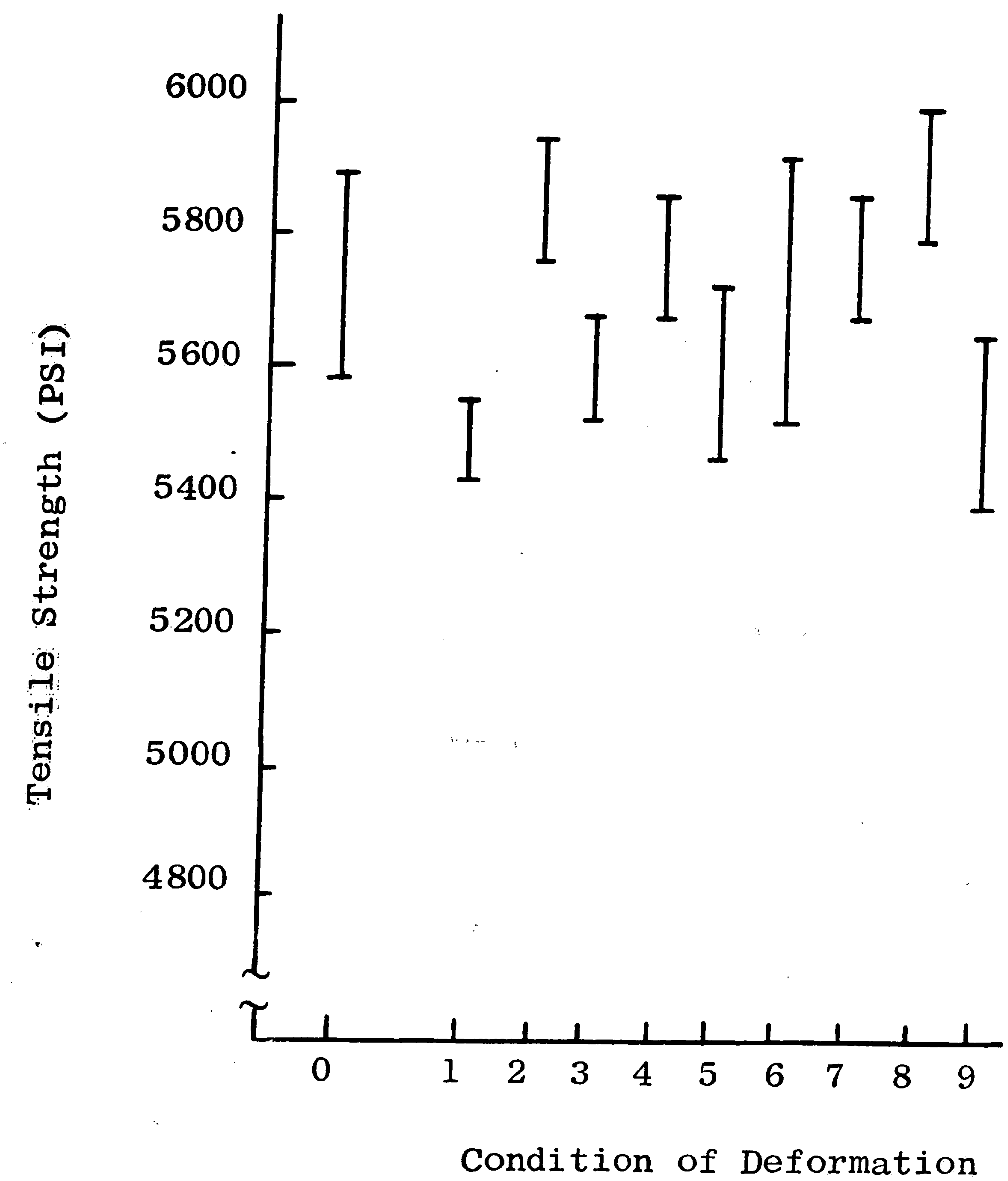


Figure 11. Tensile Strength of ABS Specimens from Side P for the Different Conditions of Deformation

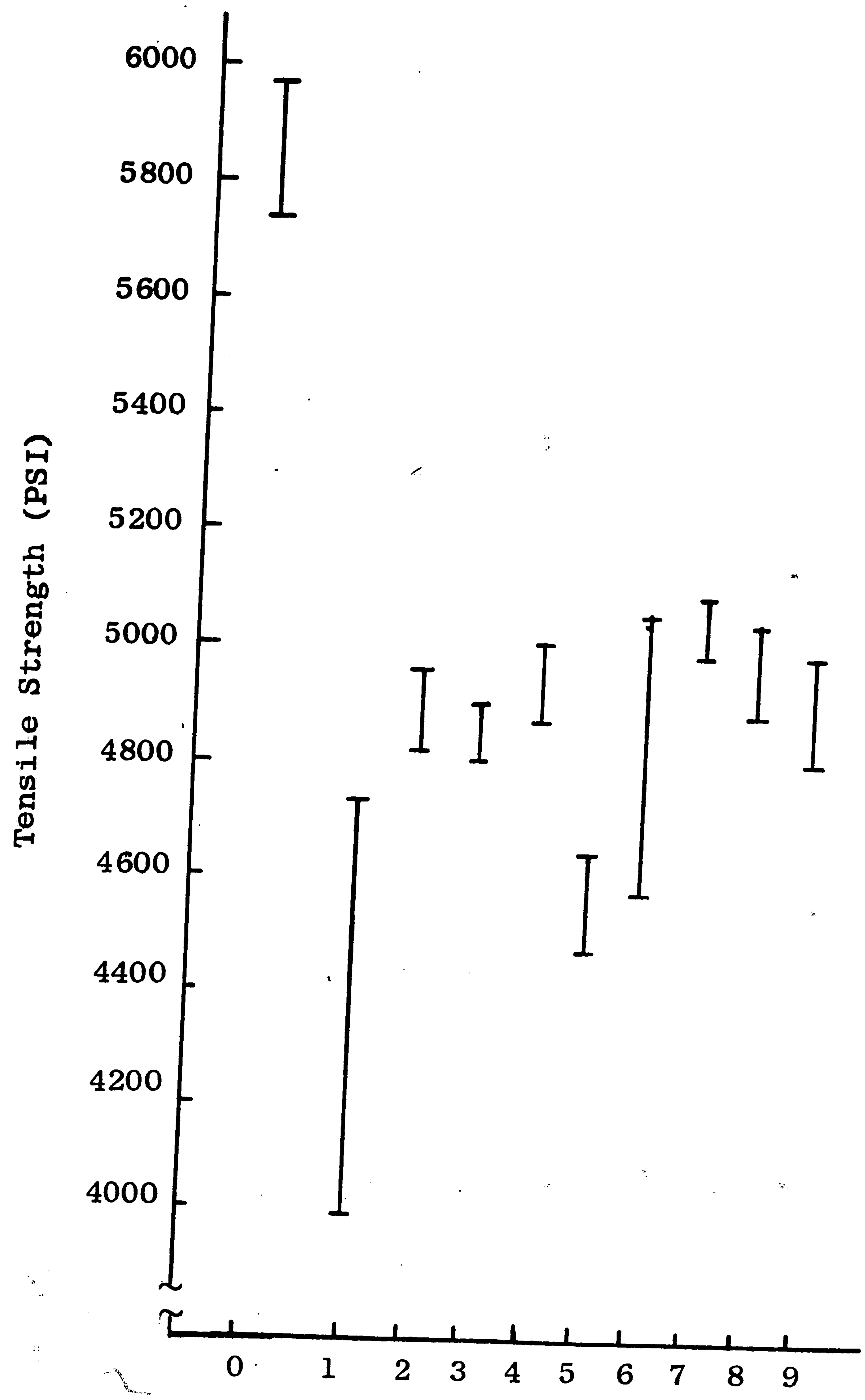


Figure 12. Tensile Strength of ABS Specimens from Bend T for the Different Conditions of Deformation

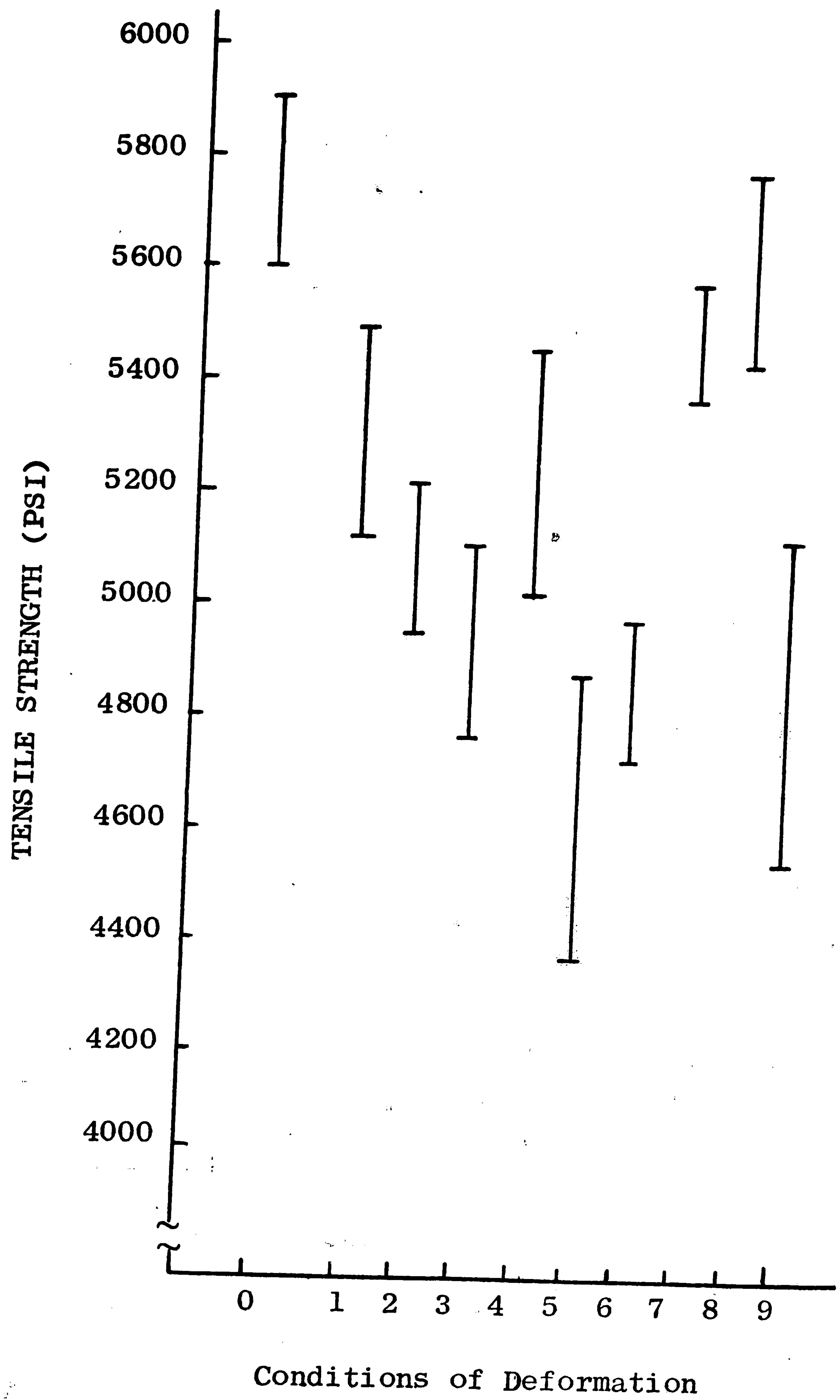


Figure 13. Tensile Strength of ABS Specimens from Bend P for the Different Conditions of Deformation

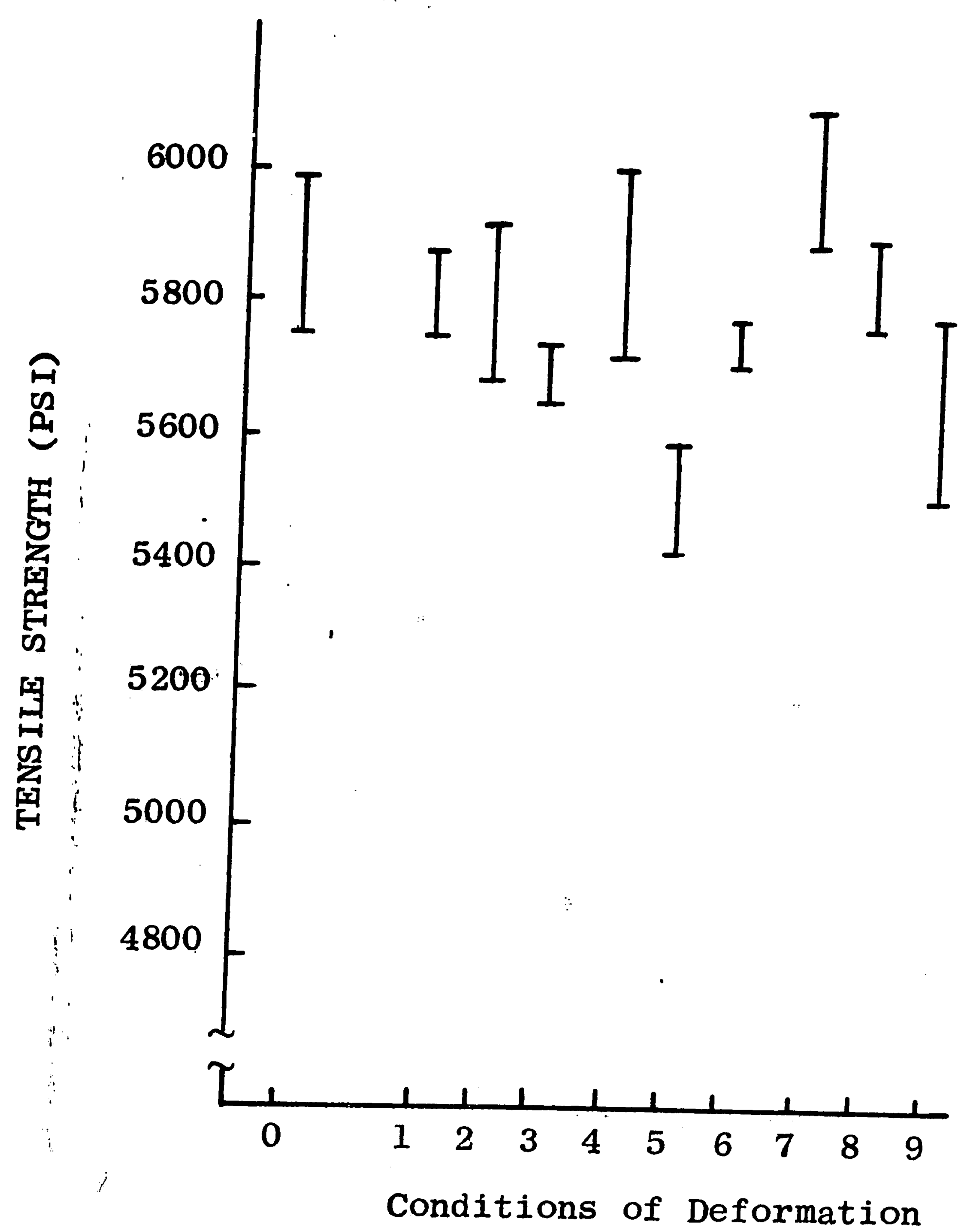


Figure 14. Tensile Strength of ABS Specimens from Top T for the Different Conditions of Deformation

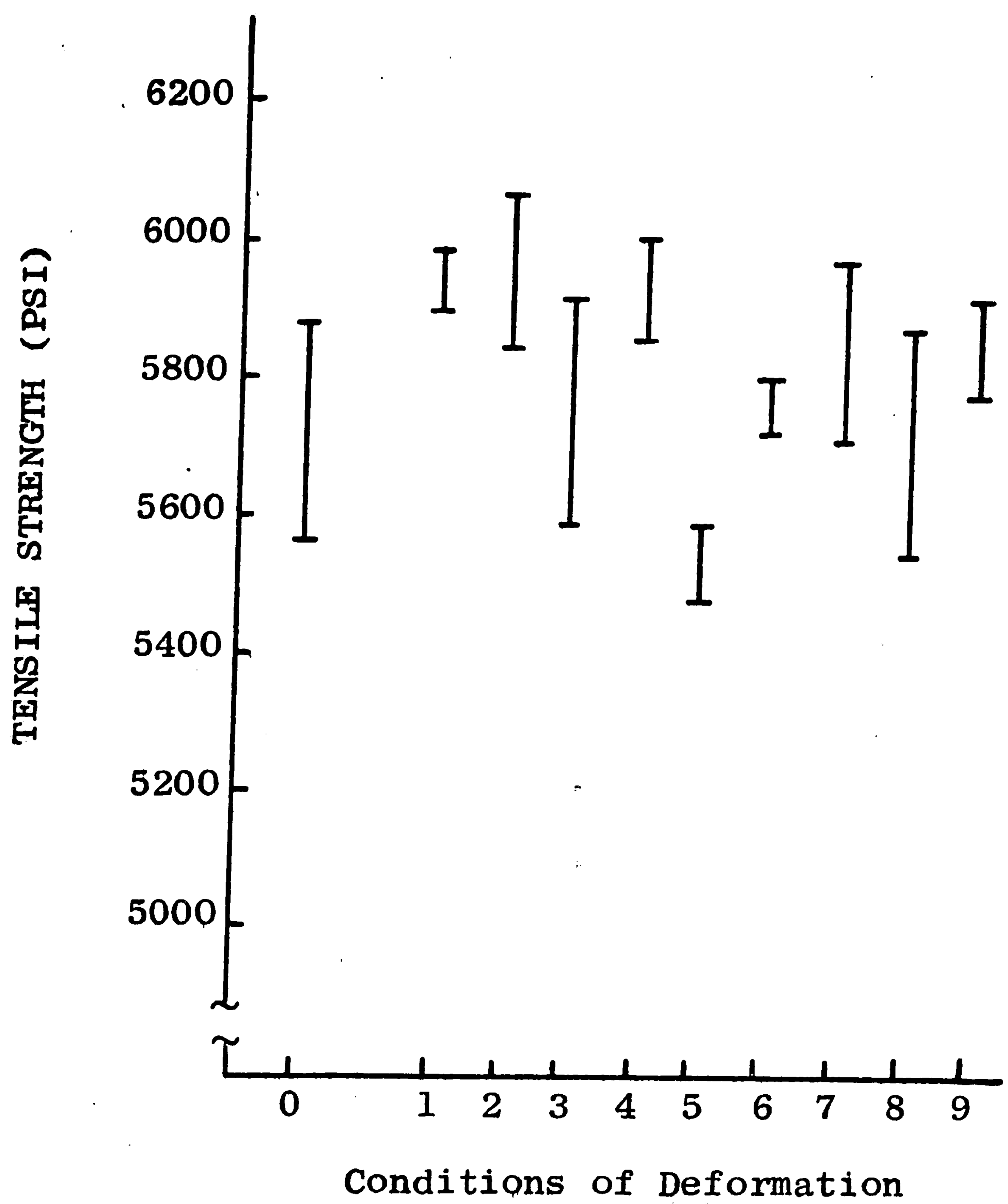


Figure 15. Tensile Strength of ABS Specimens from Top P for the Different Conditions of Deformation

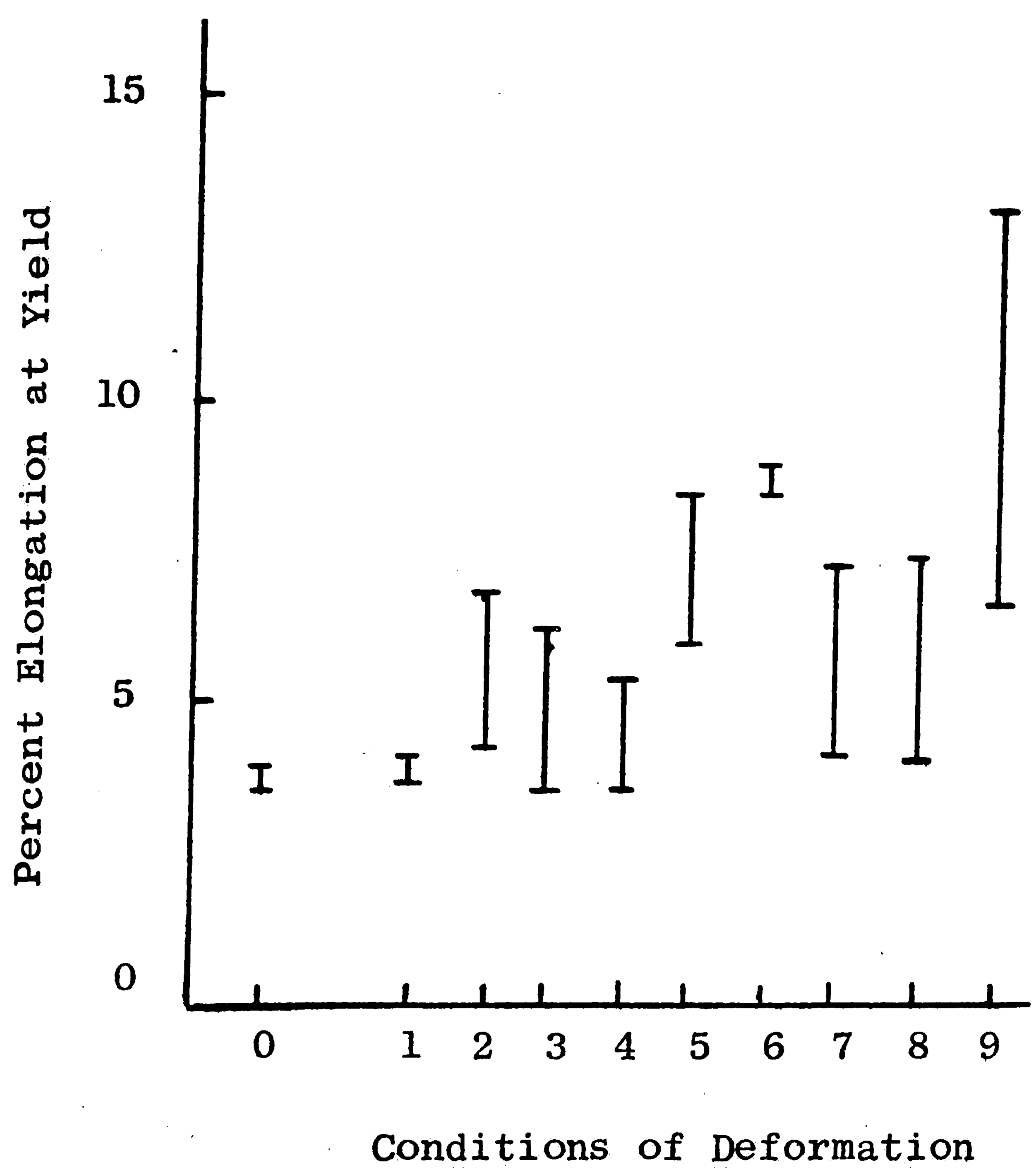


Figure 16. Percent Elongation at Yield of ABS Specimens from Side T for the Different Conditions of Deformation

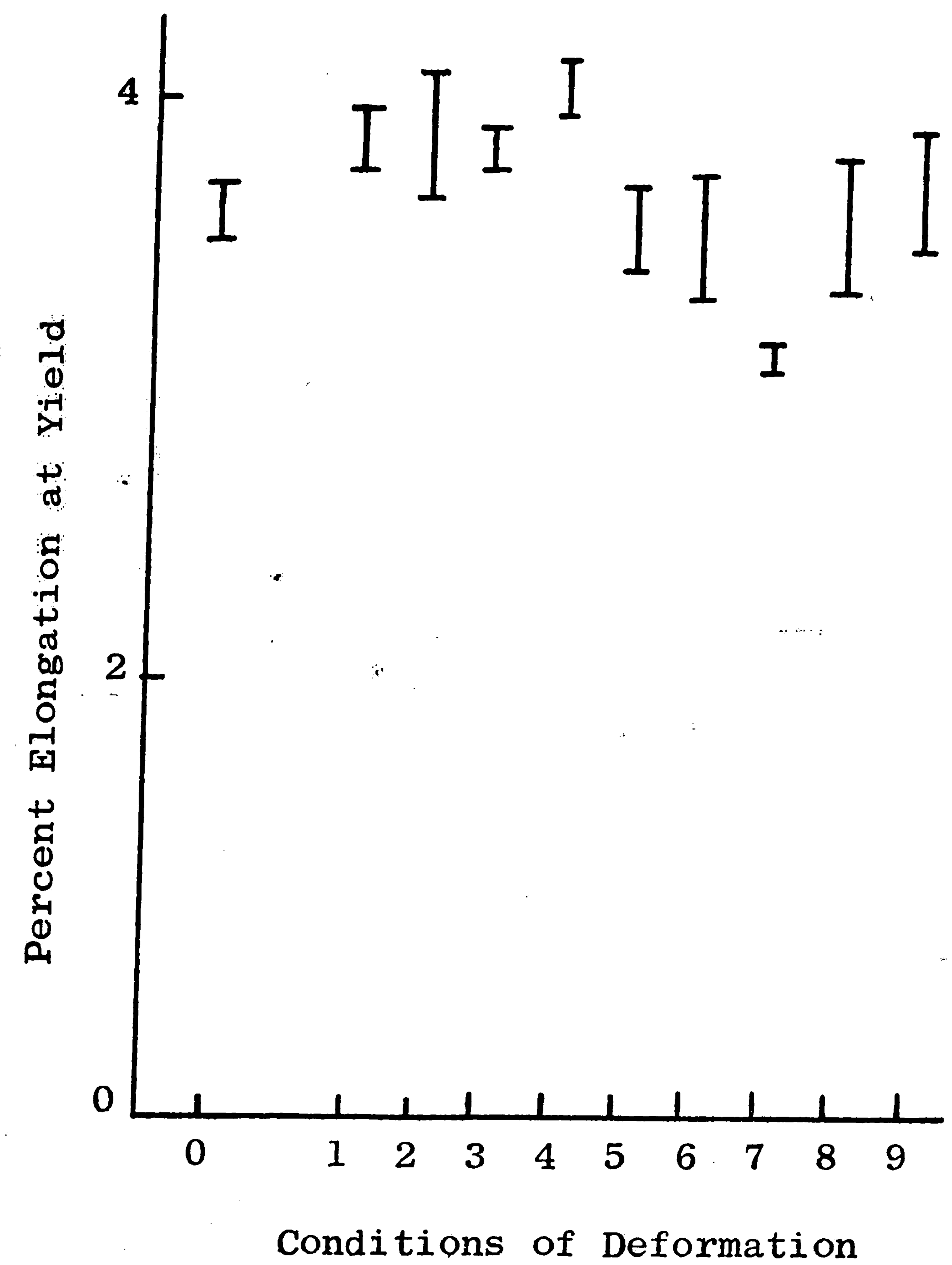


Figure 17. Percent Elongation at Yield of ABS Specimens from Side P for the Different Conditions of Deformation

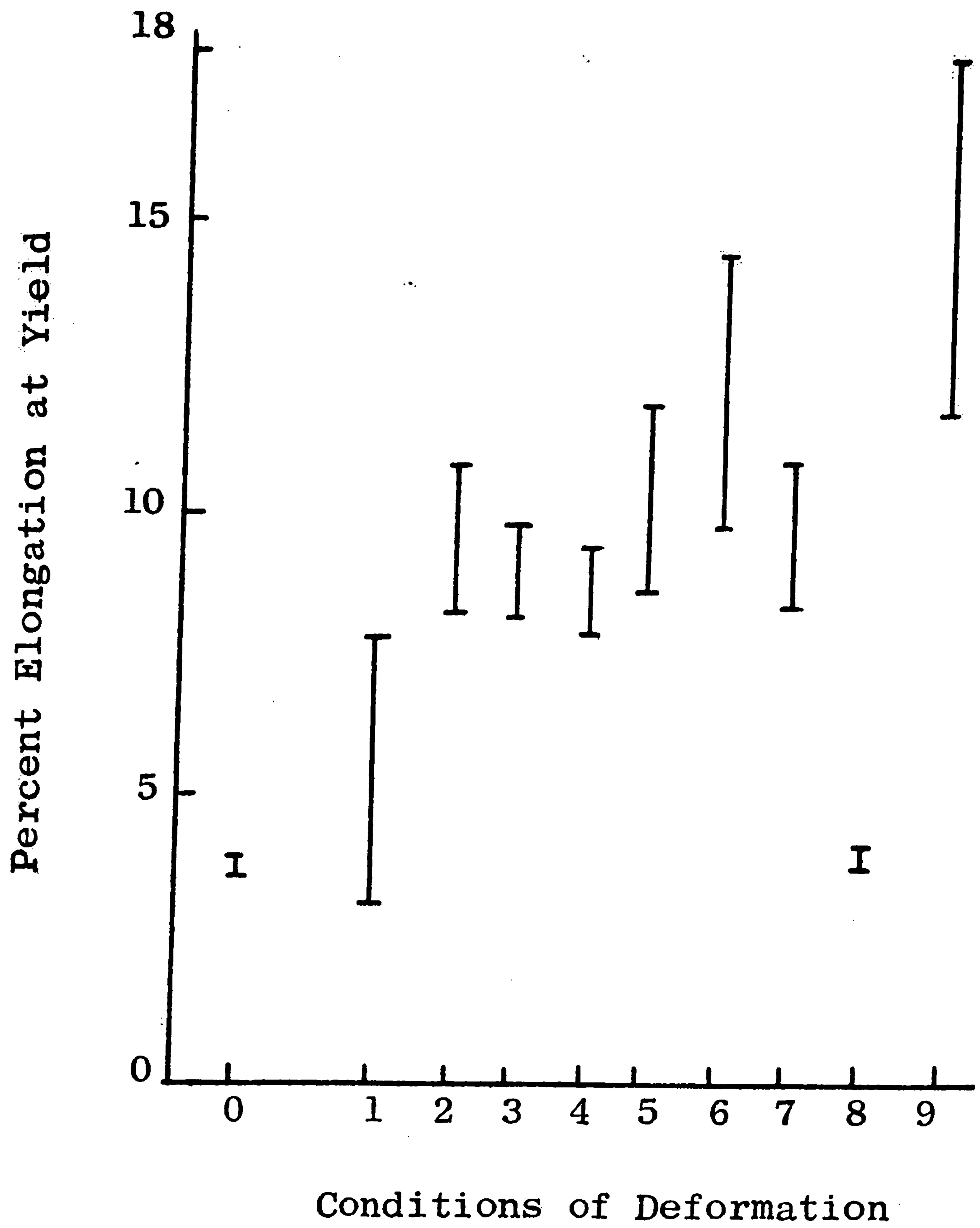


Figure 18. Percent Elongation at Yield of ABS Specimens from Bend T for the Different Conditions of Deformation

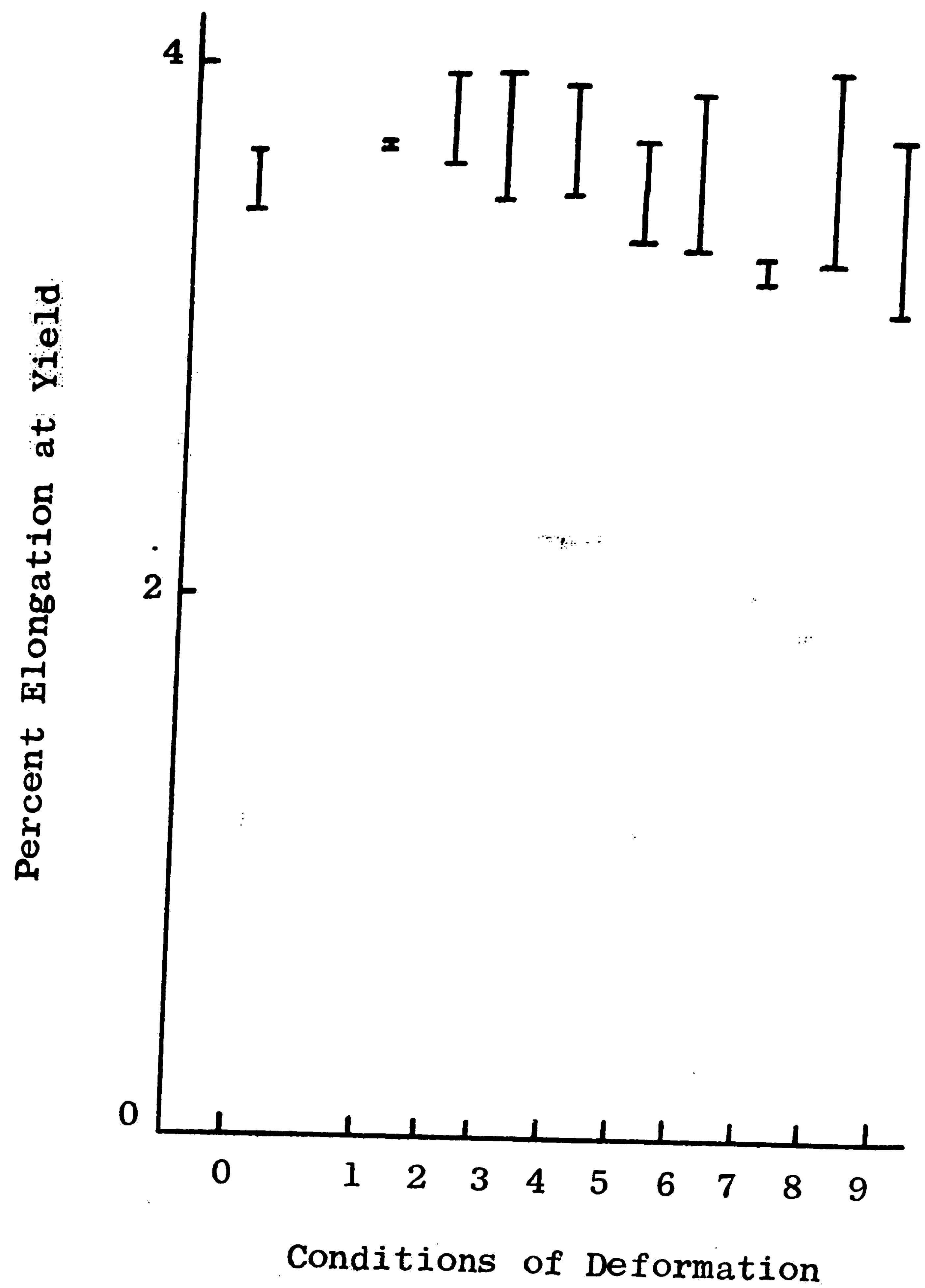


Figure 19. Percent Elongation at Yield of ABS Specimens from Bend P for the Different Conditions of Deformation

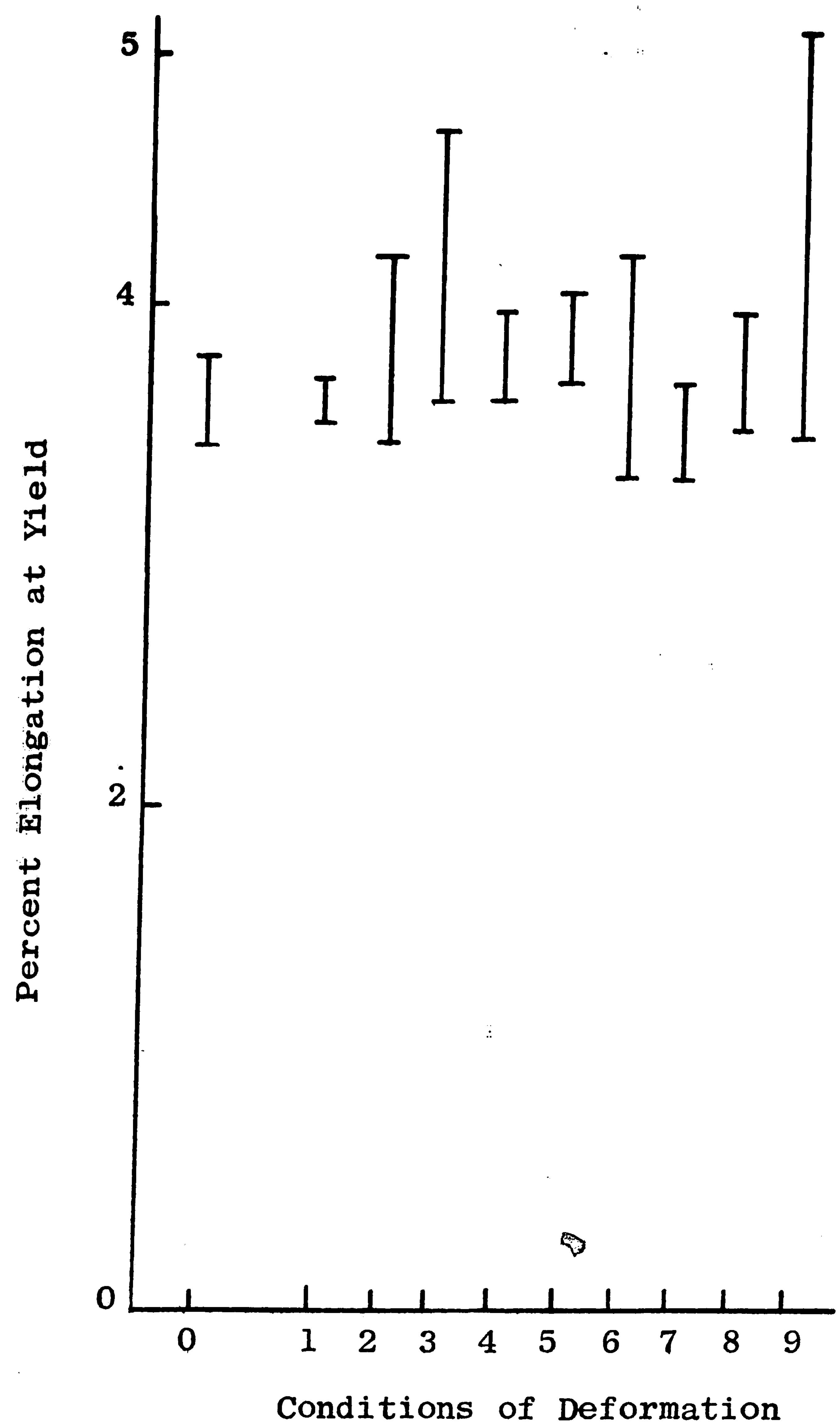


Figure 20. Percent Elongation at Yield of ABS Specimens from Top T for the Different Conditions of Deformation

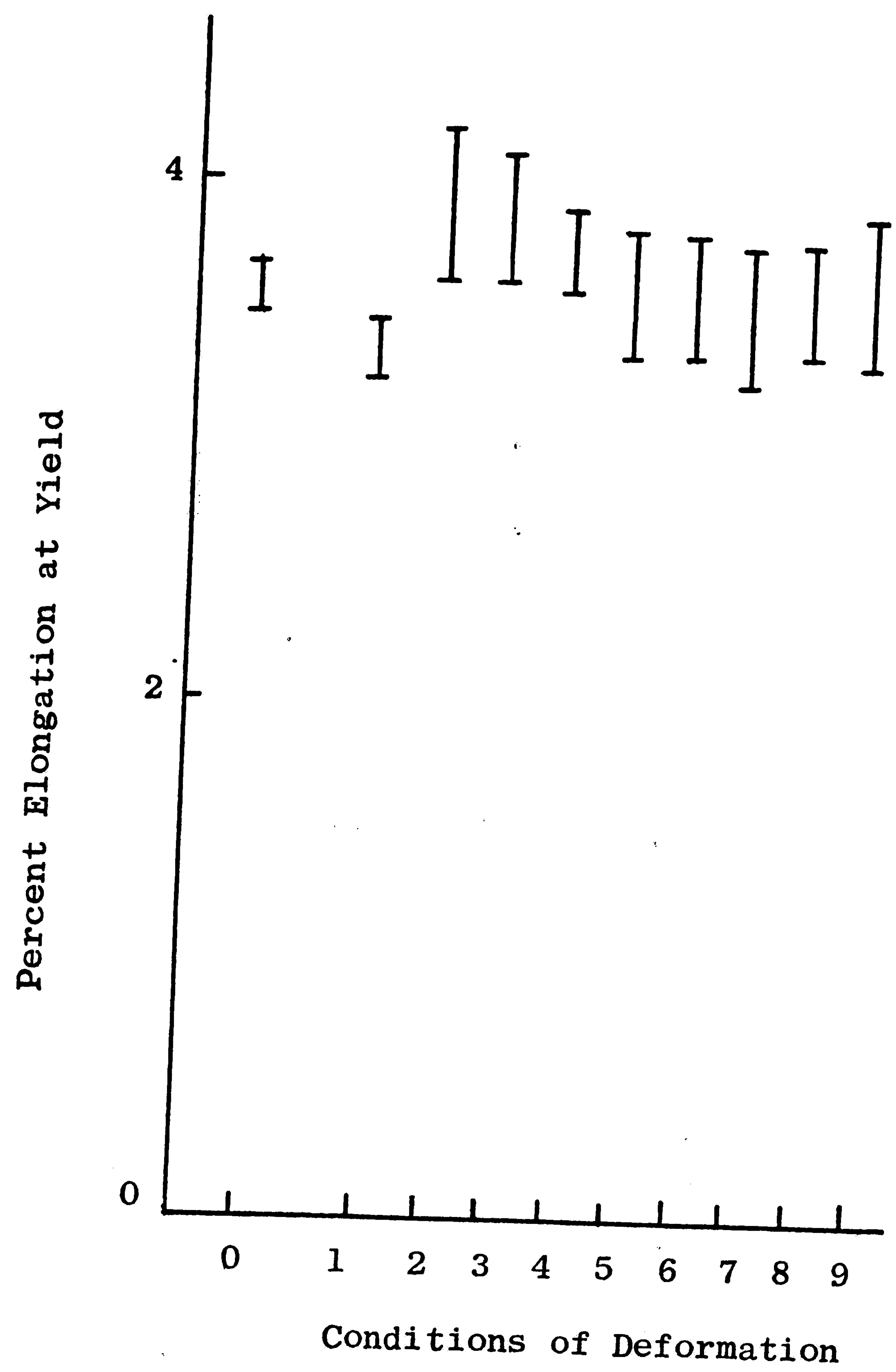


Figure 21. Percent Elongation at Yield of ABS Specimens from Top P for the Different Conditions of Deformation

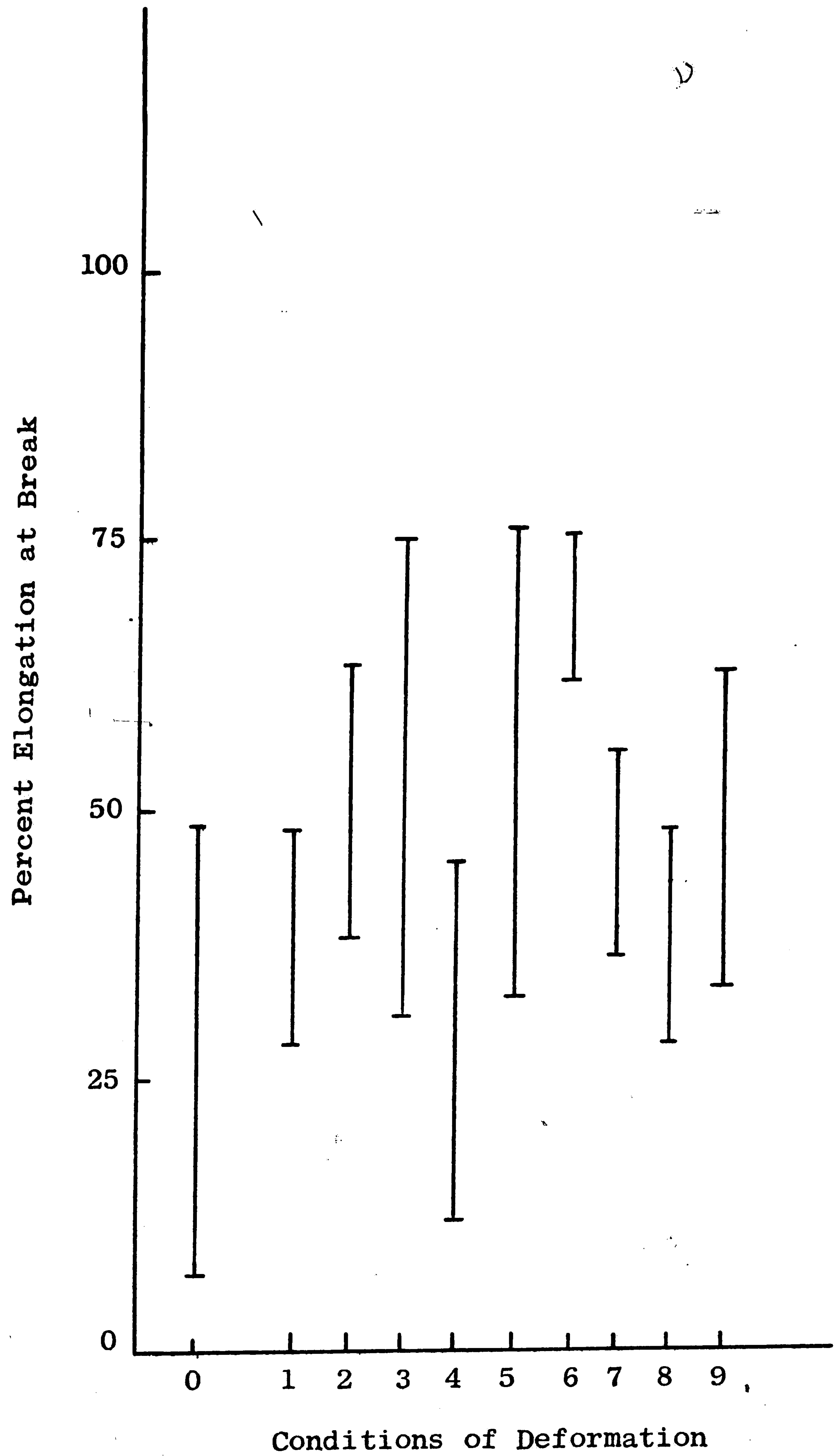


Figure 22. Percent Elongation at Break of ABS Specimens from Side T for the Different Conditions of Deformation

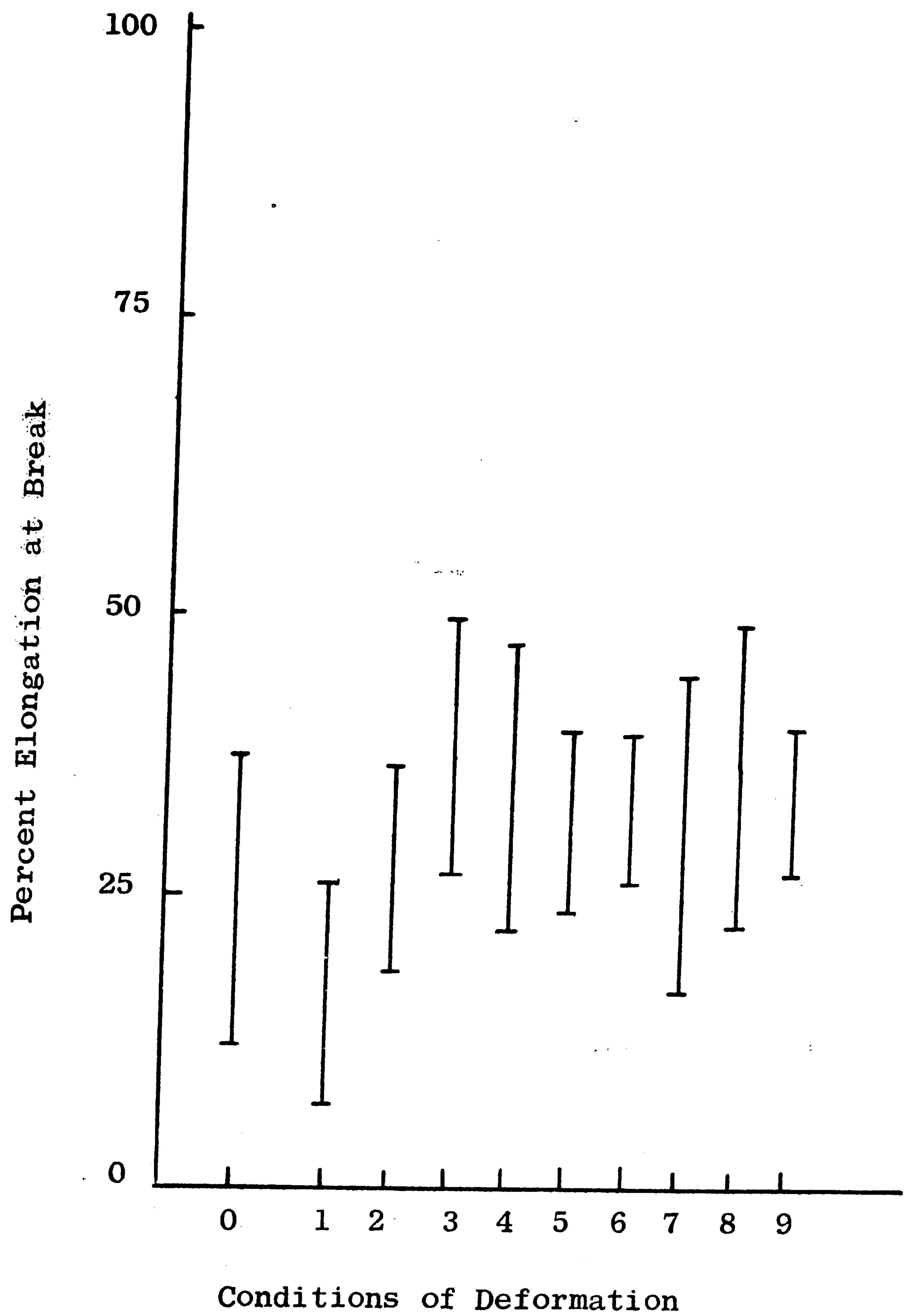


Figure 23. Percent Elongation at Break of ABS Specimens from Side P for the Different Conditions of Deformation

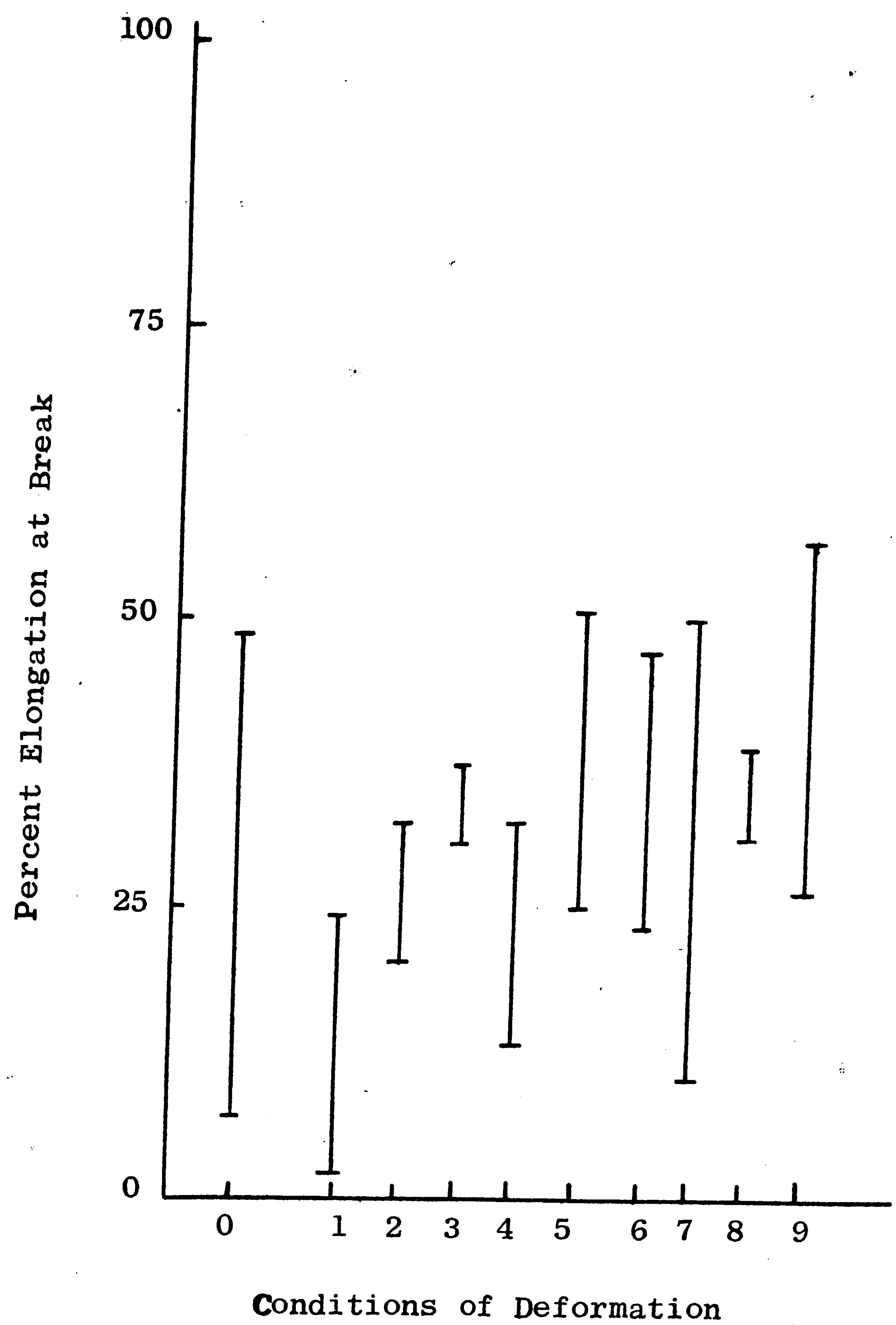


Figure 24. Percent Elongation at Break of ABS Specimens from Bend T for the Different Conditions of Deformation

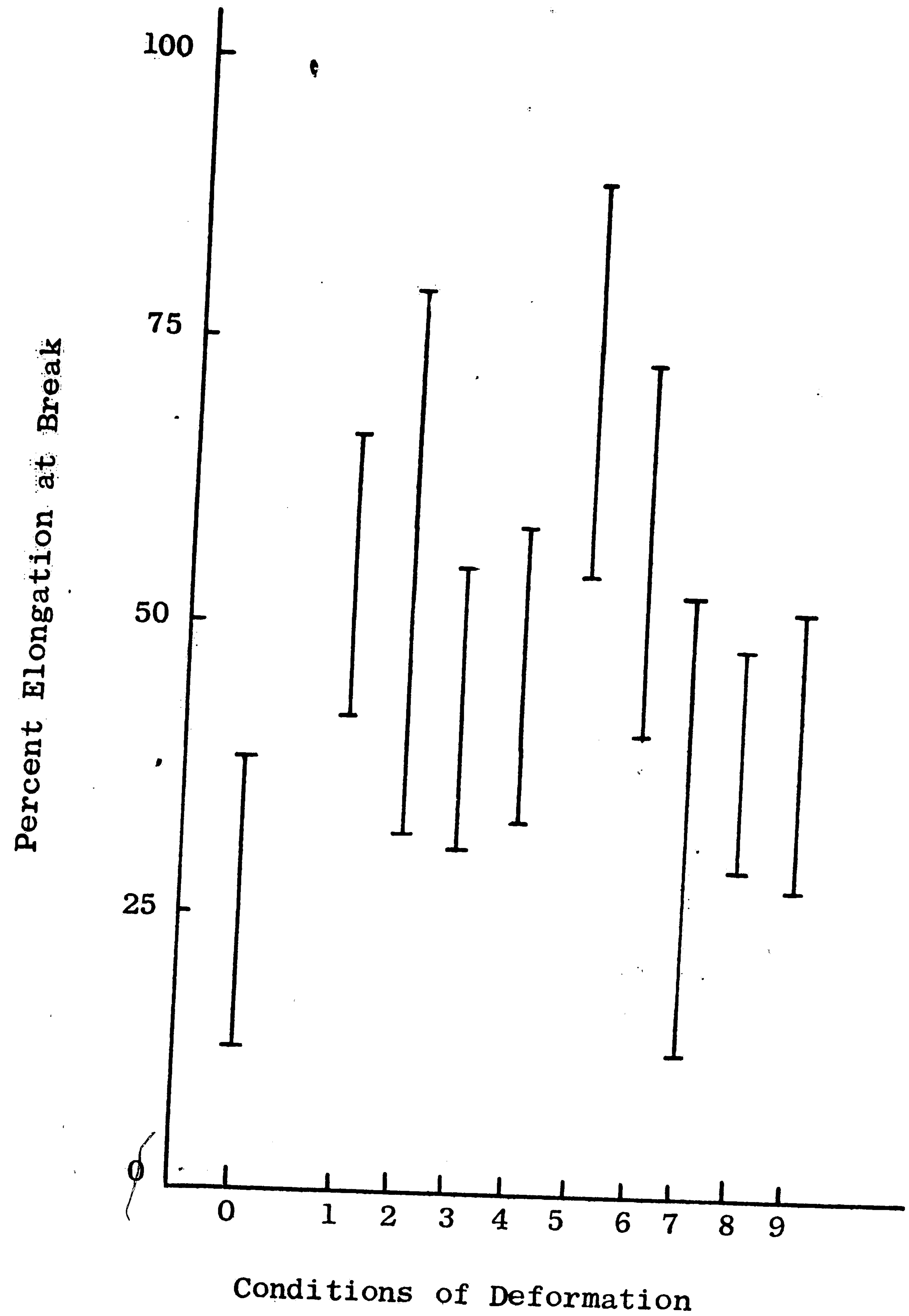


Figure 25. Percent Elongation at Break of ABS Specimens from Bend P for the Different Conditions of Deformation

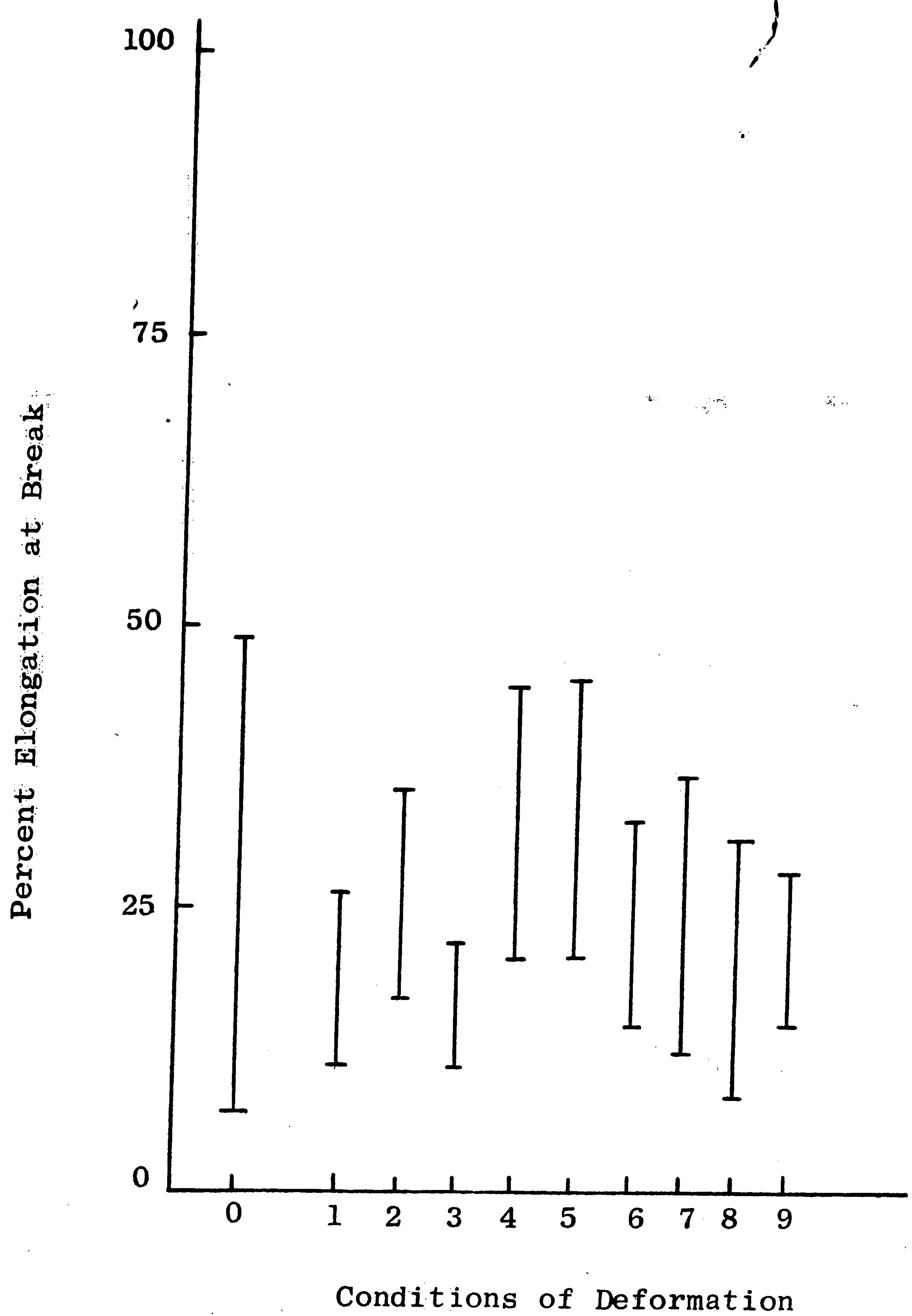


Figure 26. Percent Elongation at Break of ABS Specimens from Top T for the Different Conditions of Deformation

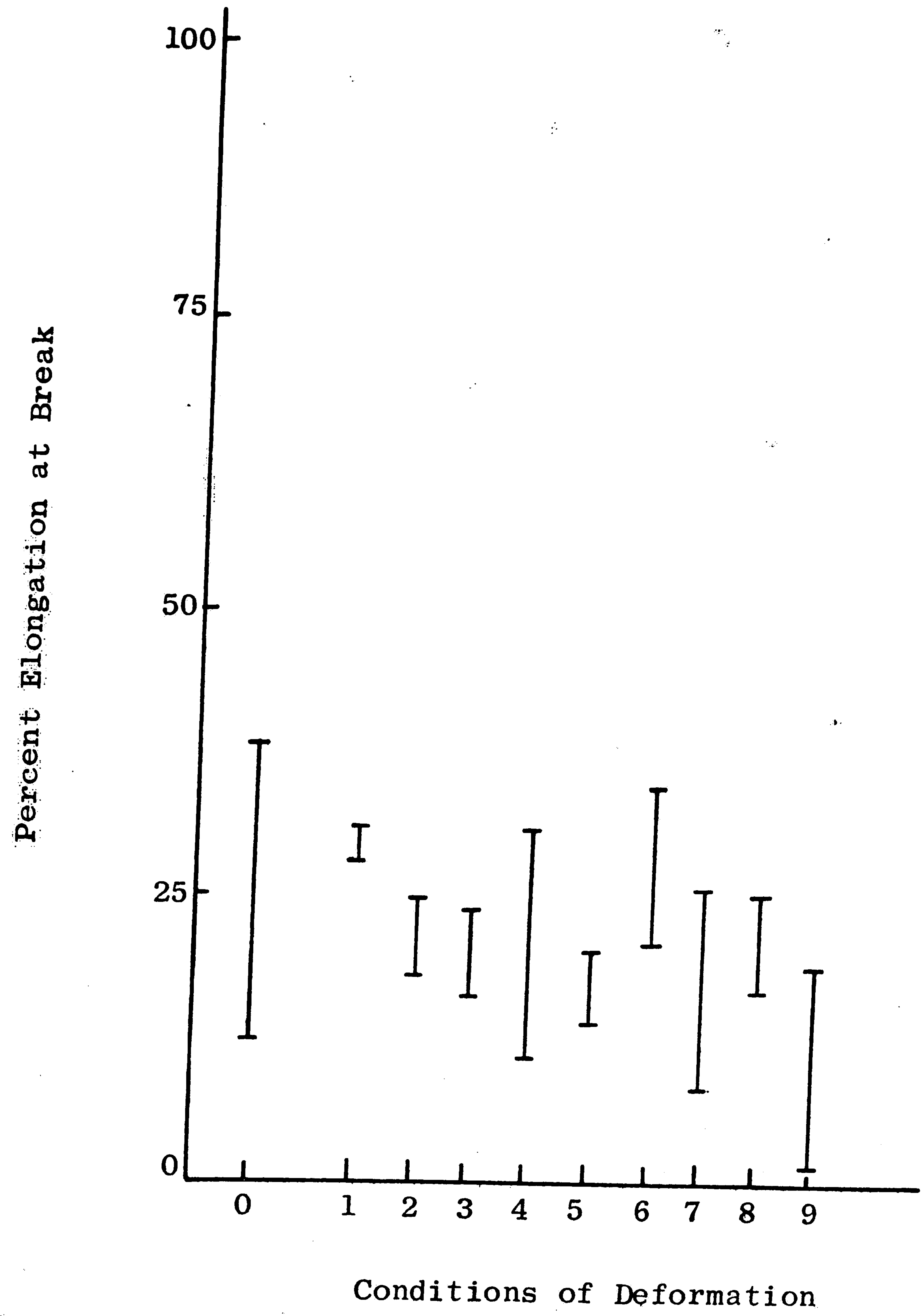


Figure 27. Percent Elongation at Break of ABS Specimens from Top P for the Different Conditions of Deformation

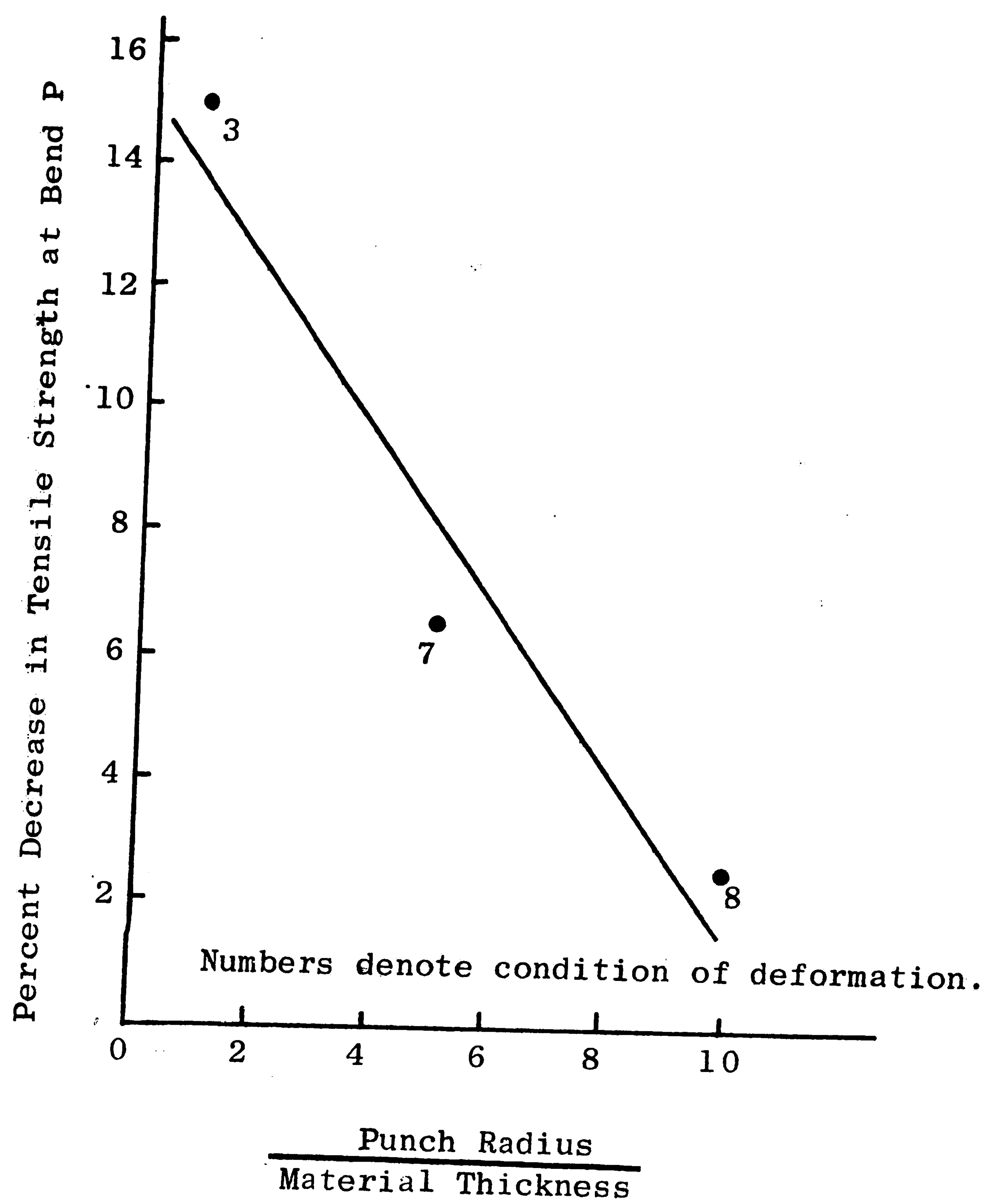


FIG. 28 Percent Decrease in Tensile Strength of ABS Specimens from Bend P as a Function of Punch Radius to Material Thickness Ratio.

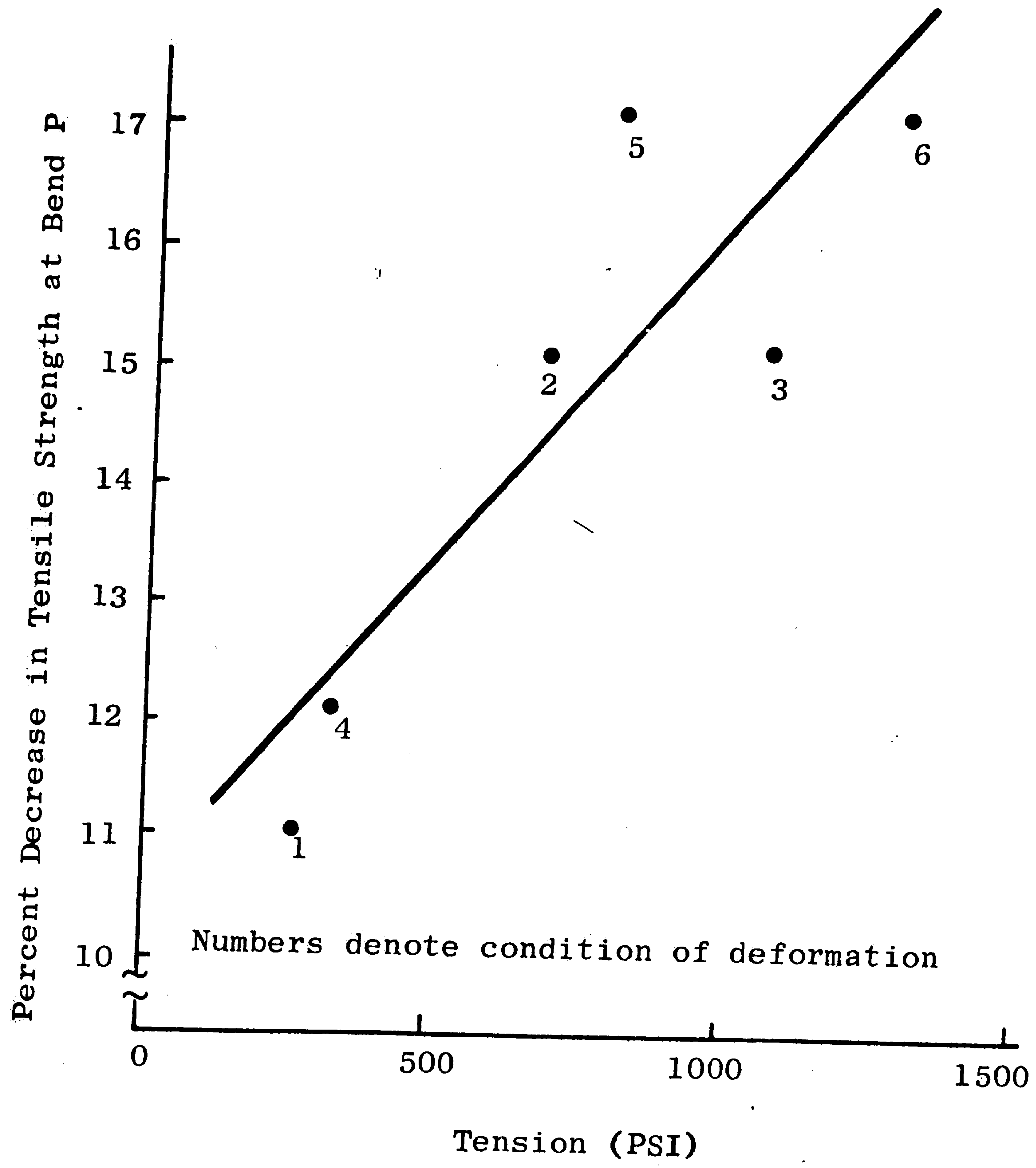


FIG. 29 Percent Decrease in Tensile Strength of ABS Specimens form Bend P as a Function of Tension

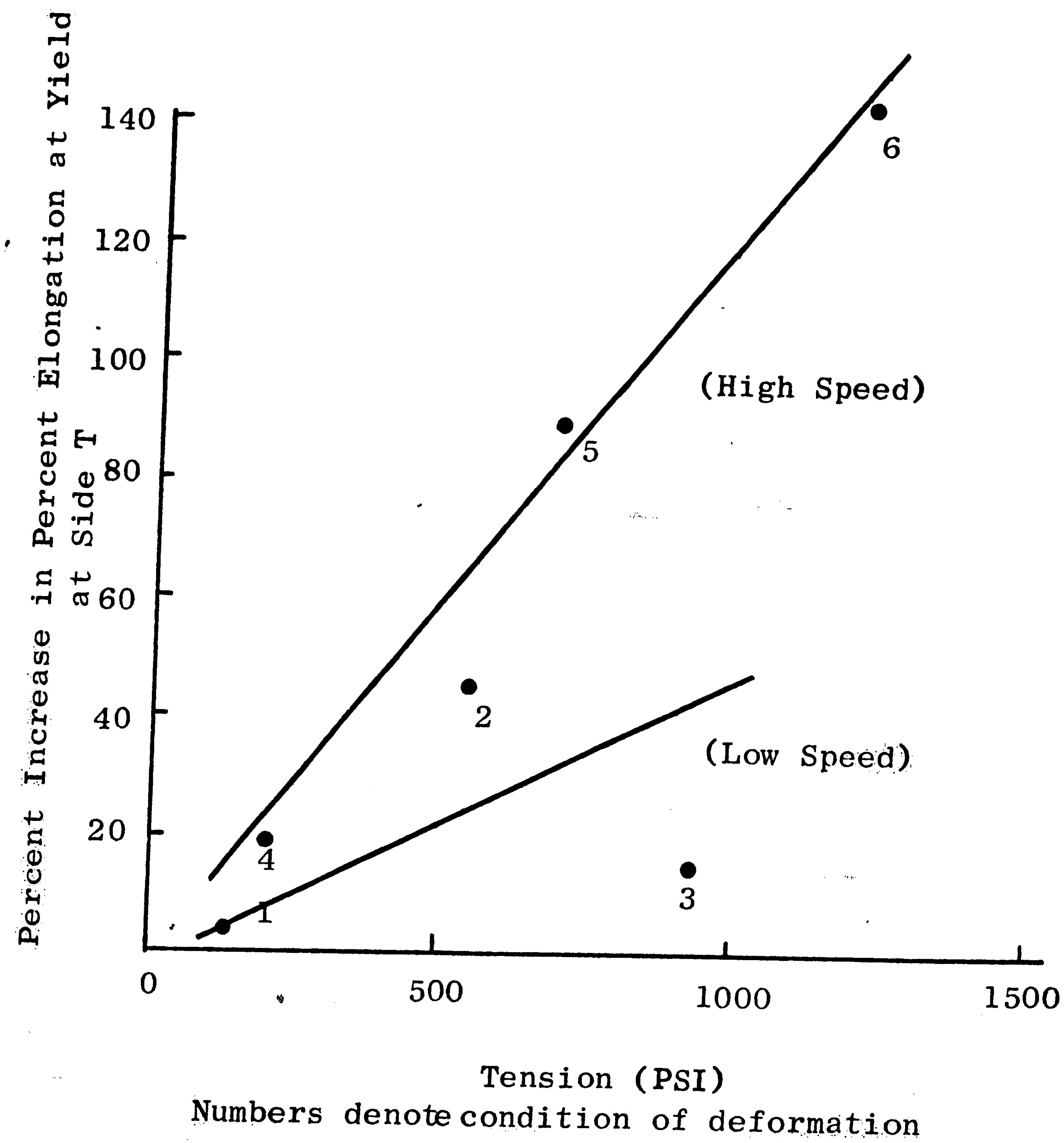


FIG. 30 Percent Increase in Percent Elongation at Yield of ABS Specimens from Side T as a Function of Tension.

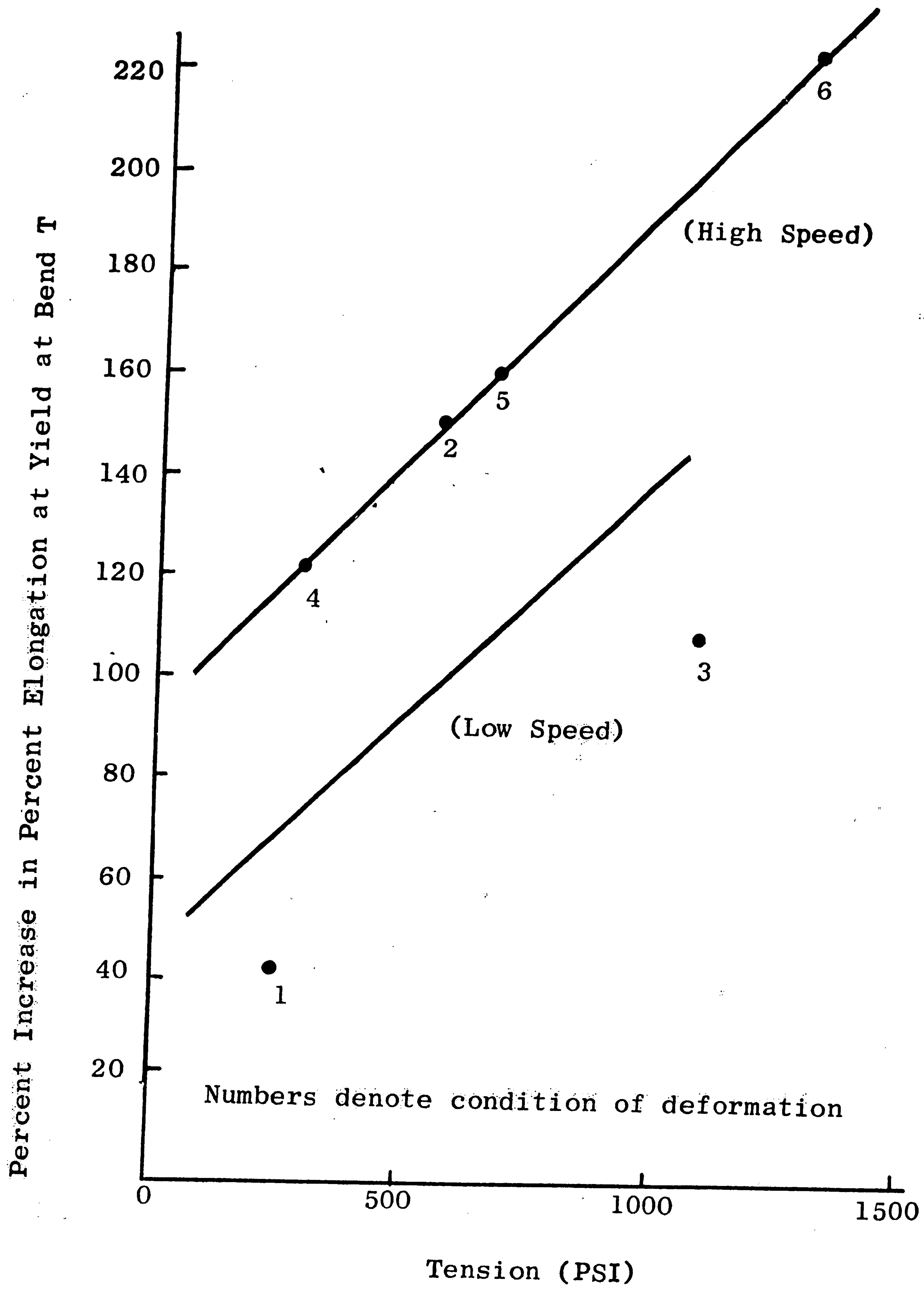


FIG. 31 Percent Increase in Percent Elongation at Yield of ABS Specimens from Bend T as a Function of Tension.

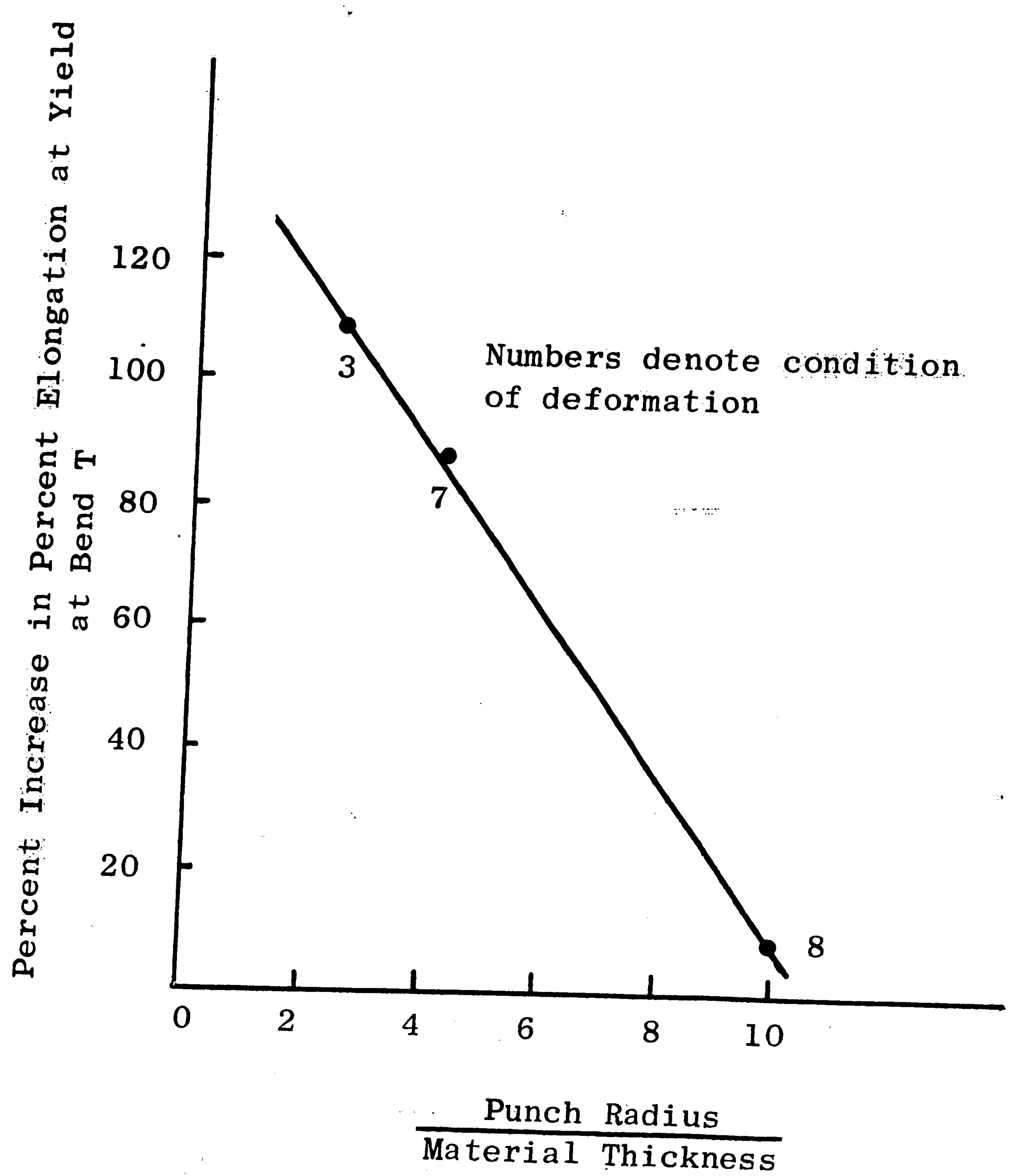


FIG. 32 Percent Increase in Percent Elongation at Yield of ABS Specimens from Bend T as a Function of Punch Radius to Material Thickness Ratio.

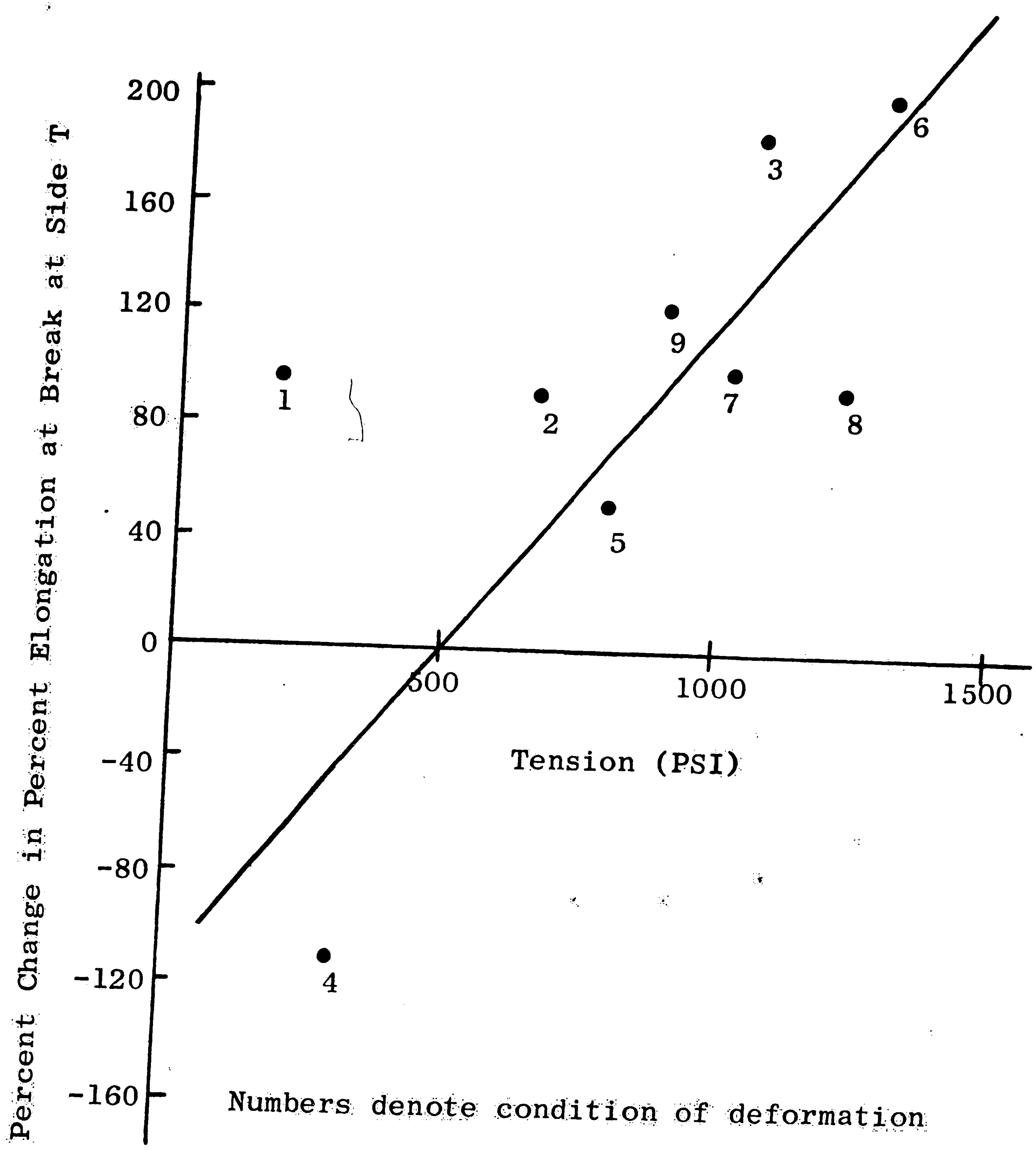


FIG. 33 Percent Change in Percent Elongation at Break of ABS Specimens from Side T as a Function of Tension

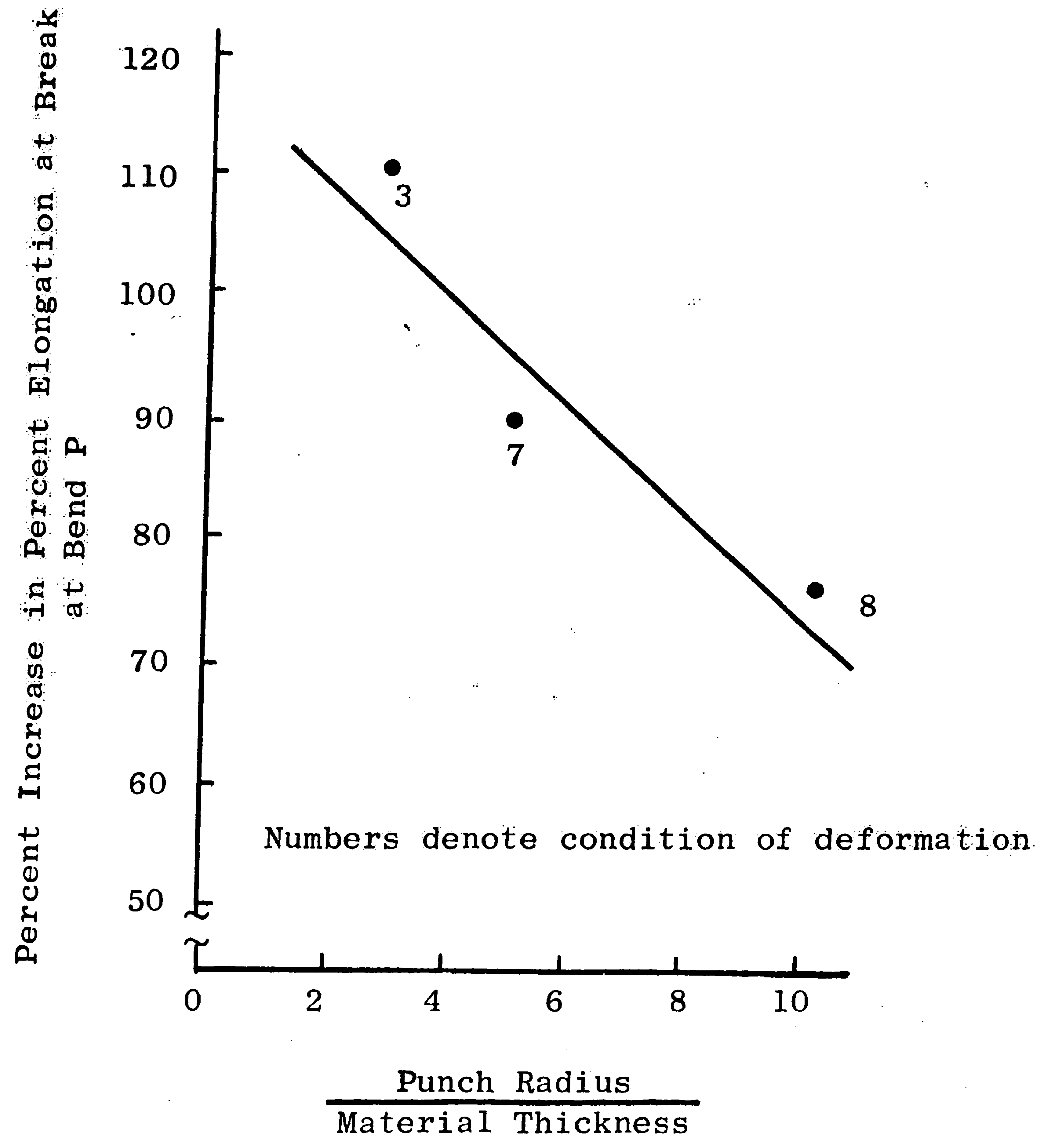


FIG. 34 Percent Increase in Percent Elongation at Break of ABS Specimens from Bend P as a Function of Punch Radius to Material Thickness Ratio.

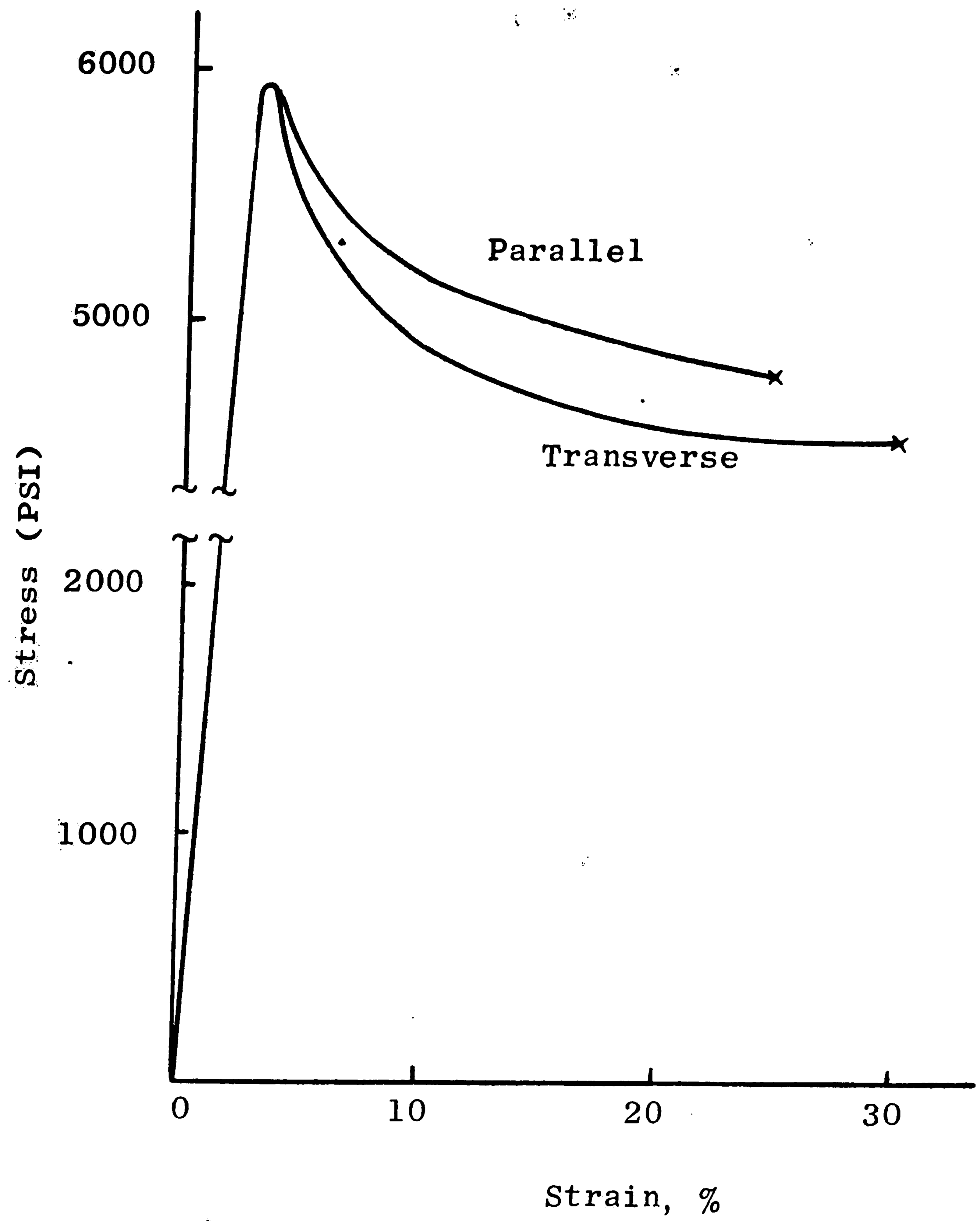


FIG. 35 Stress-Strain Relationships for Undeformed ABS

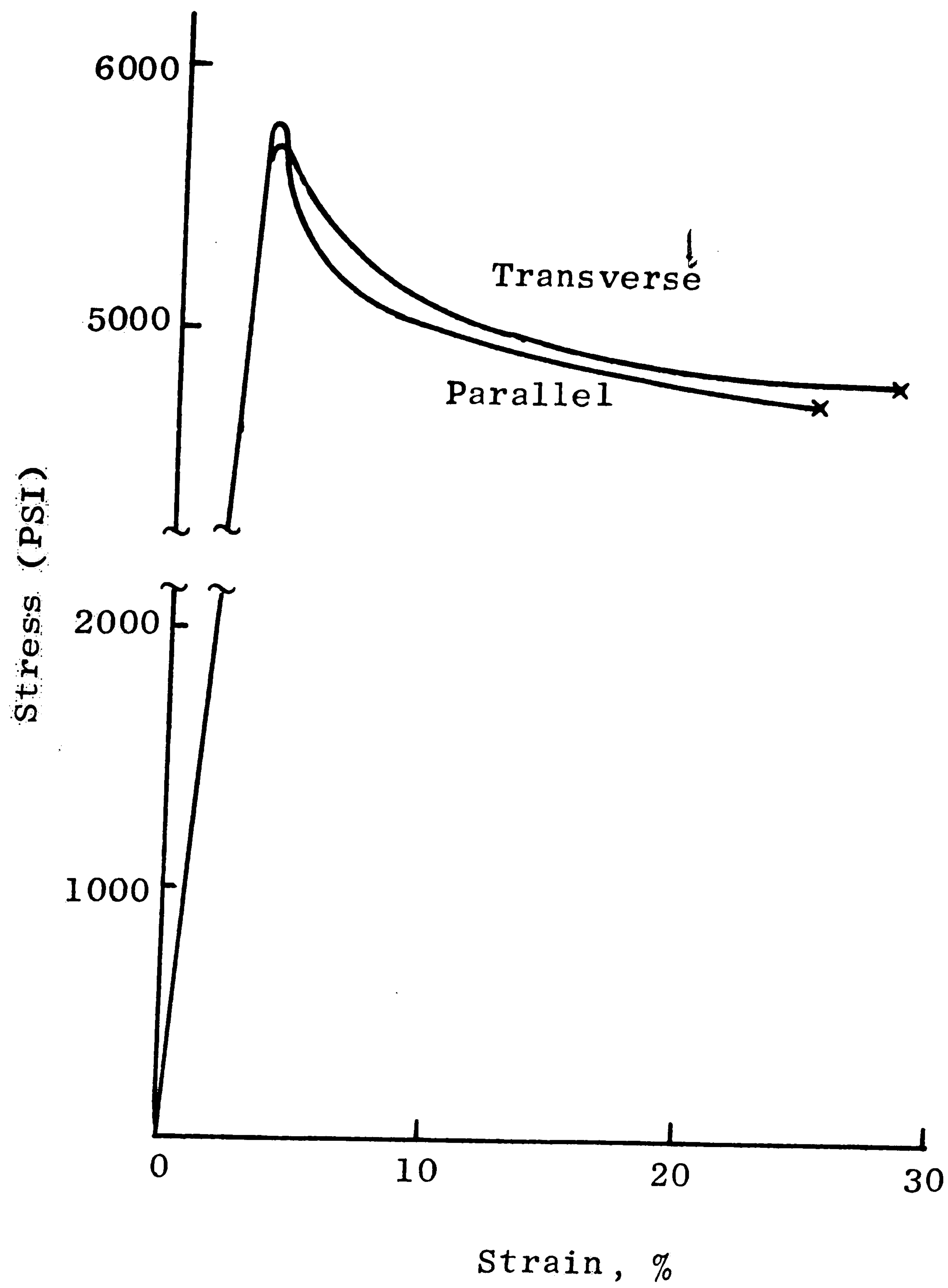


FIG. 36 Stress-Strain Relationships for ABS Specimens from the Top.

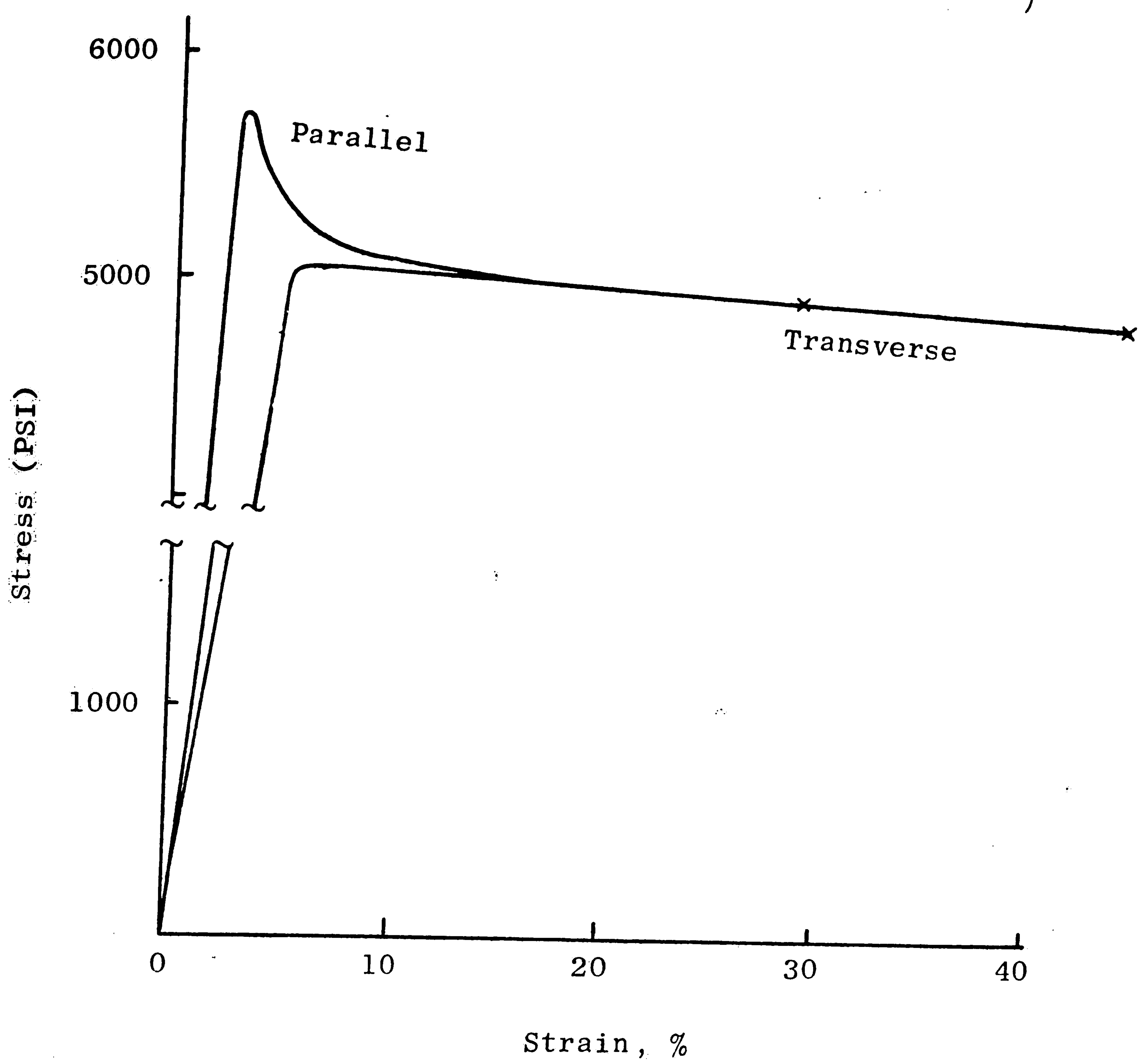


FIG. 37 Stress-Strain Relationships for ABS Specimens from the Side.

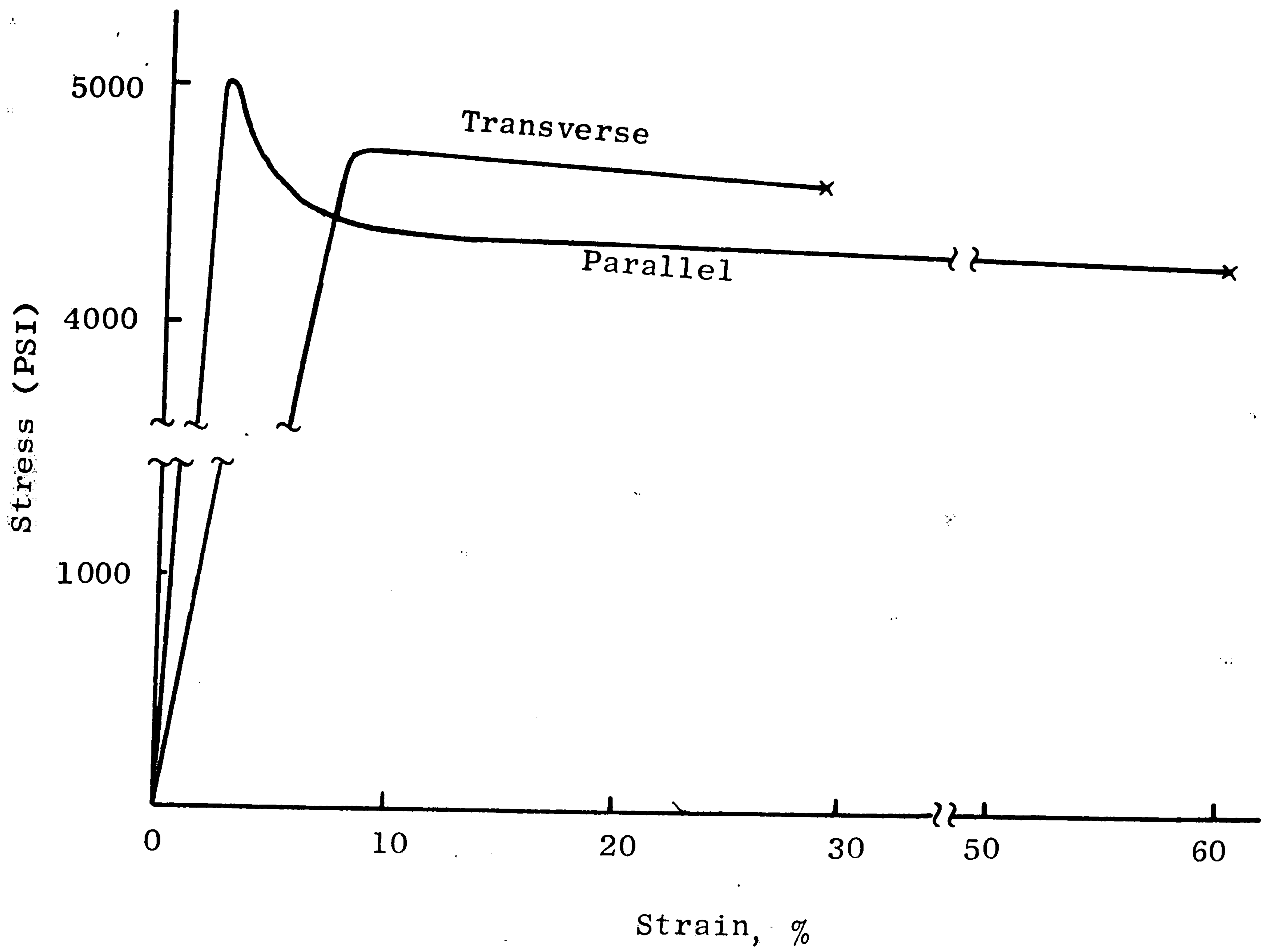


FIG. 38 Stress-Strain Relationships for ABS Specimens from the Bend

A - Undeformed
B - Undeformed
C - Top T Condition 3
D - Side T Condition 3
E - Side T Condition 3
F - Side T Condition 1

B, C, E, and F were from the same sheet of material.

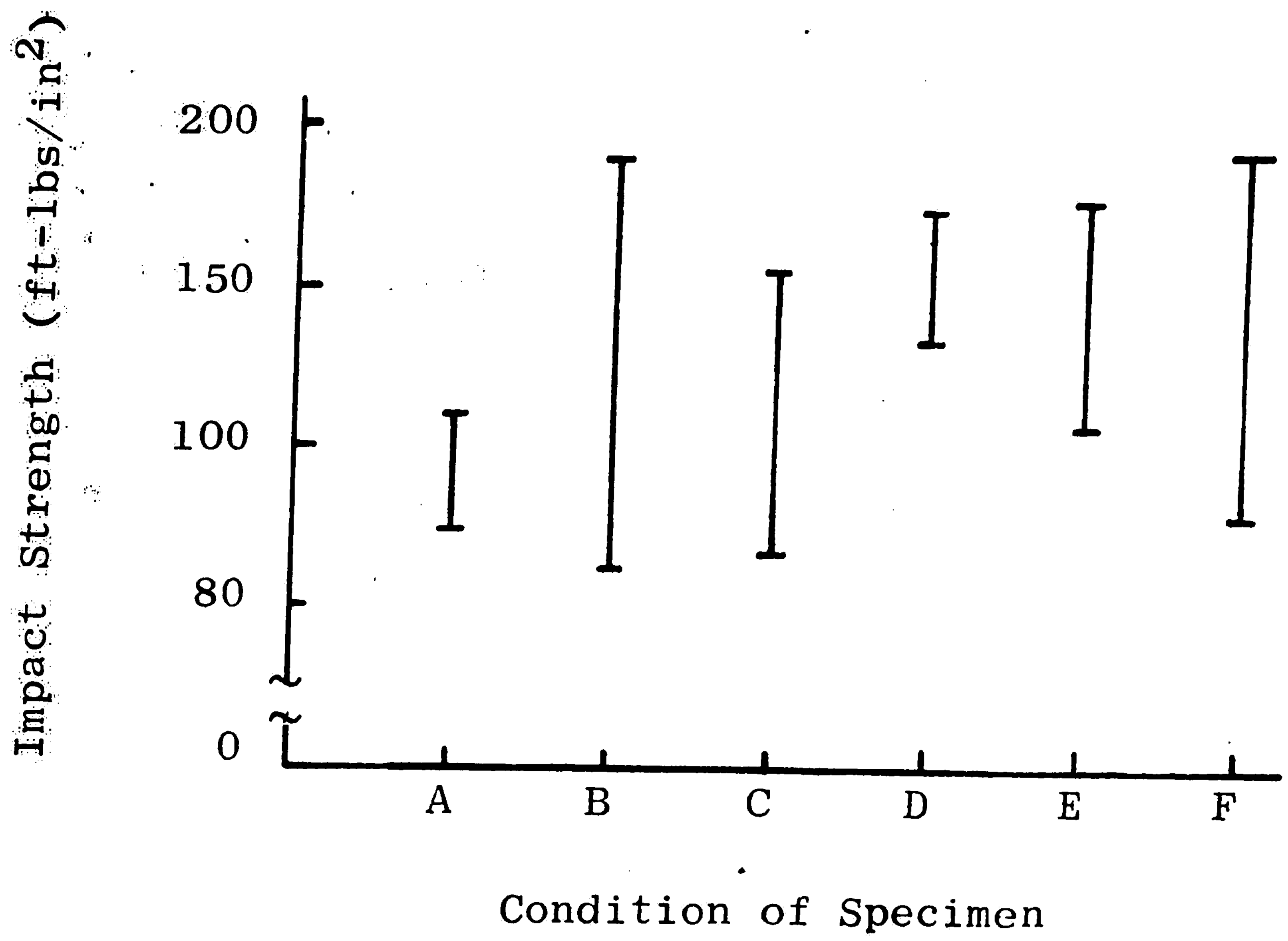


FIG. 39 Impact Strength for ABS at the Top and the Side

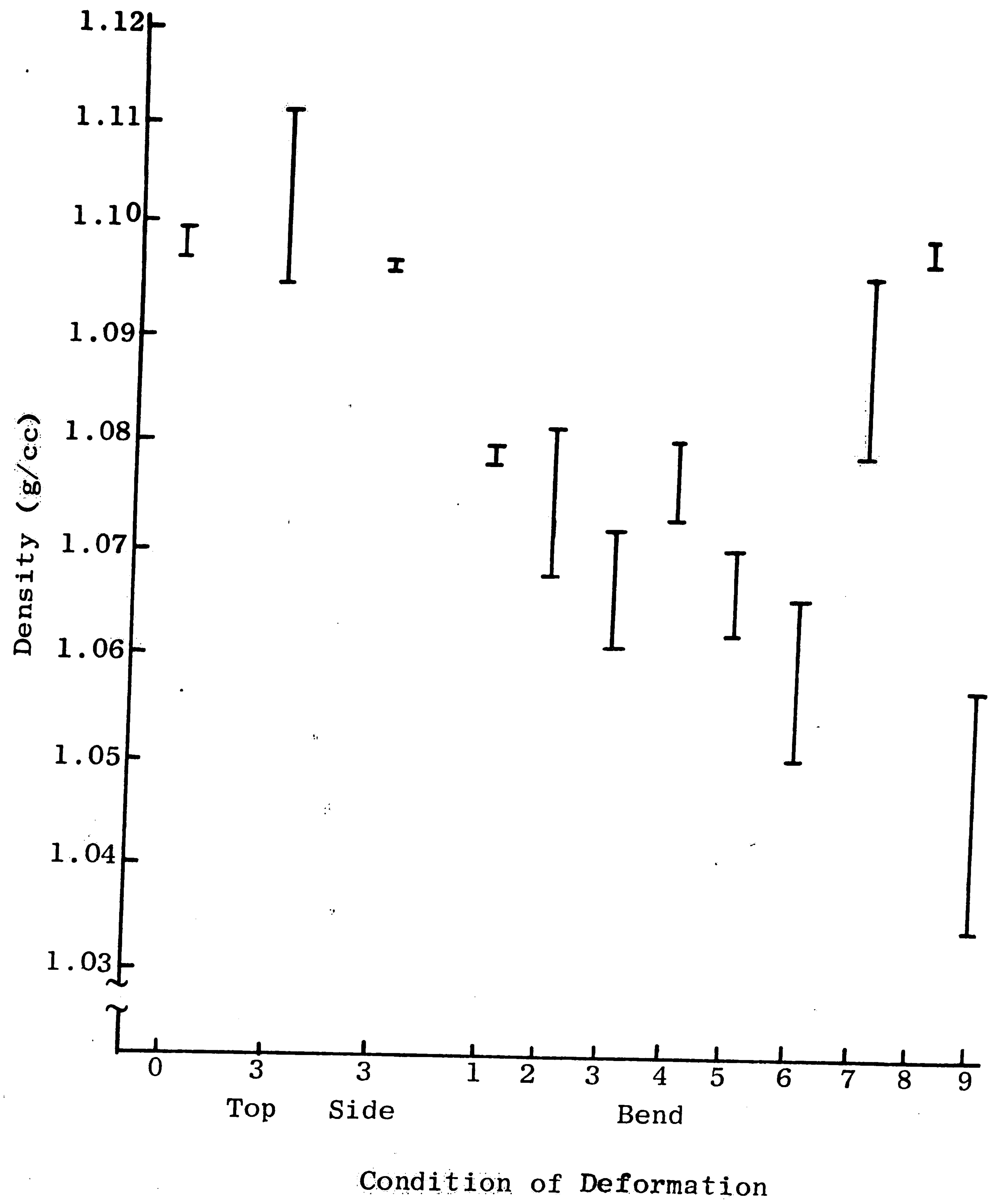


FIG. 40 Density of ABS at the Top, Side and the Bend

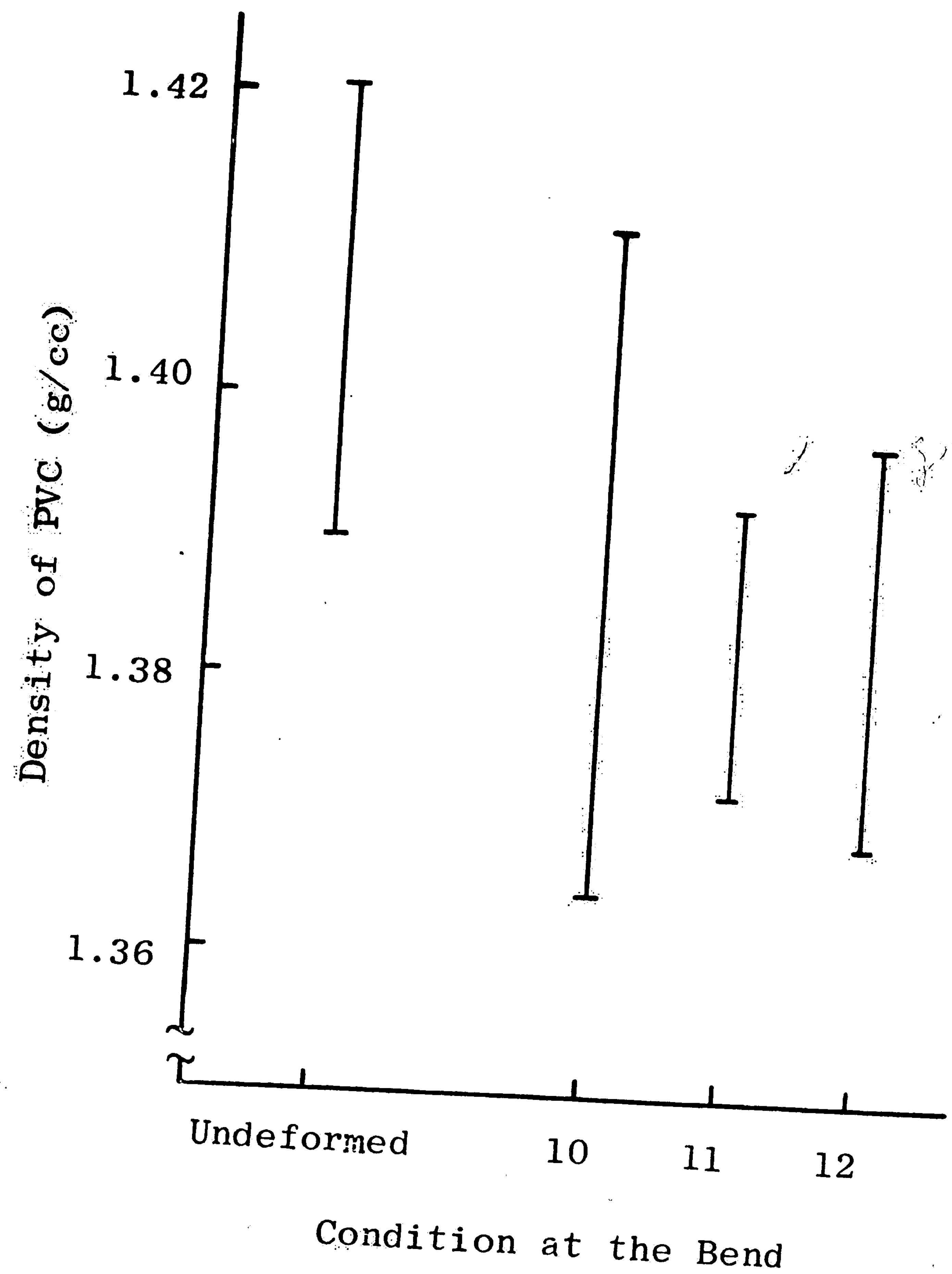


FIG. 41 Density of PVC at the Bend

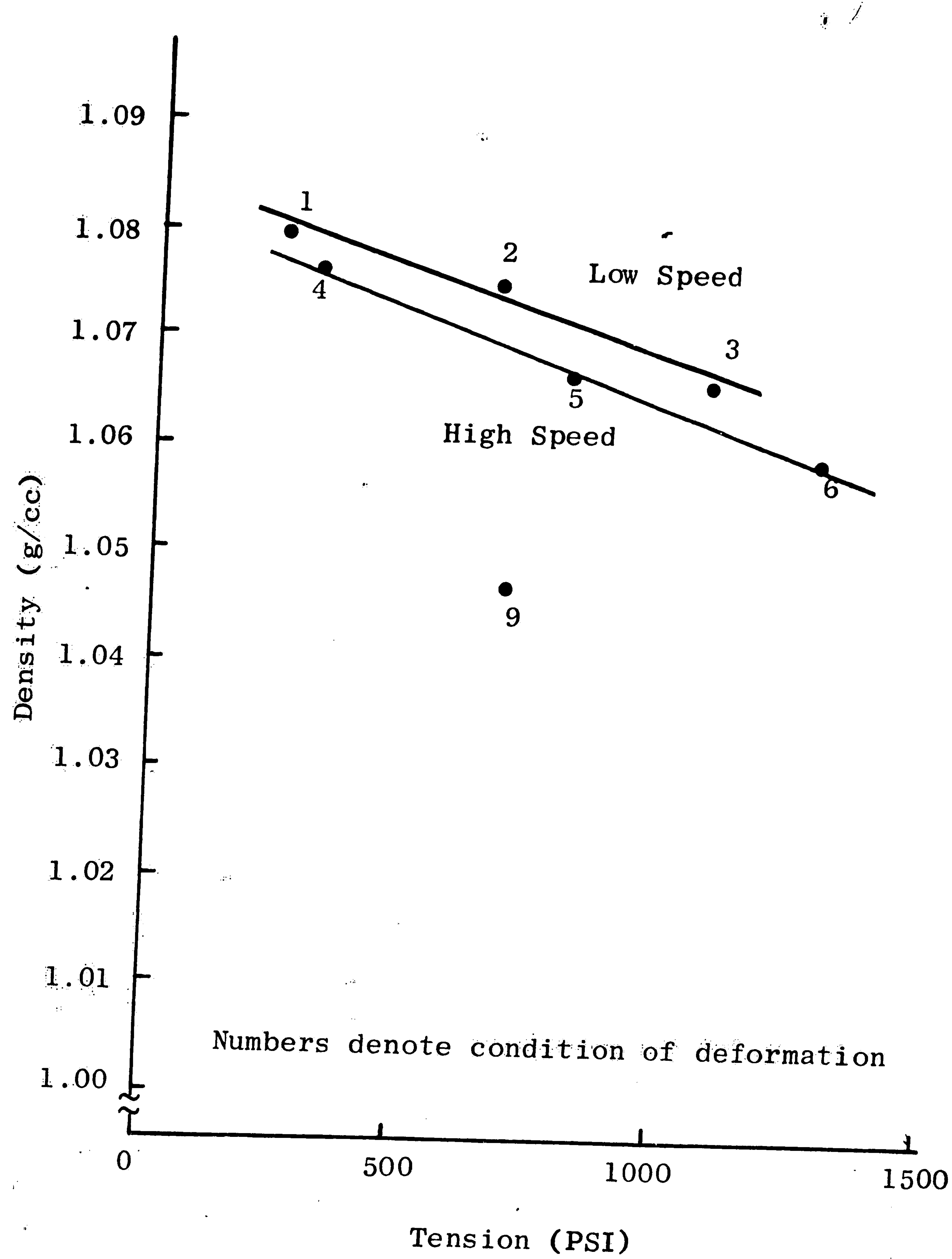


FIG. 42 Density of ABS Specimens from the Bend as a Function of Tension.

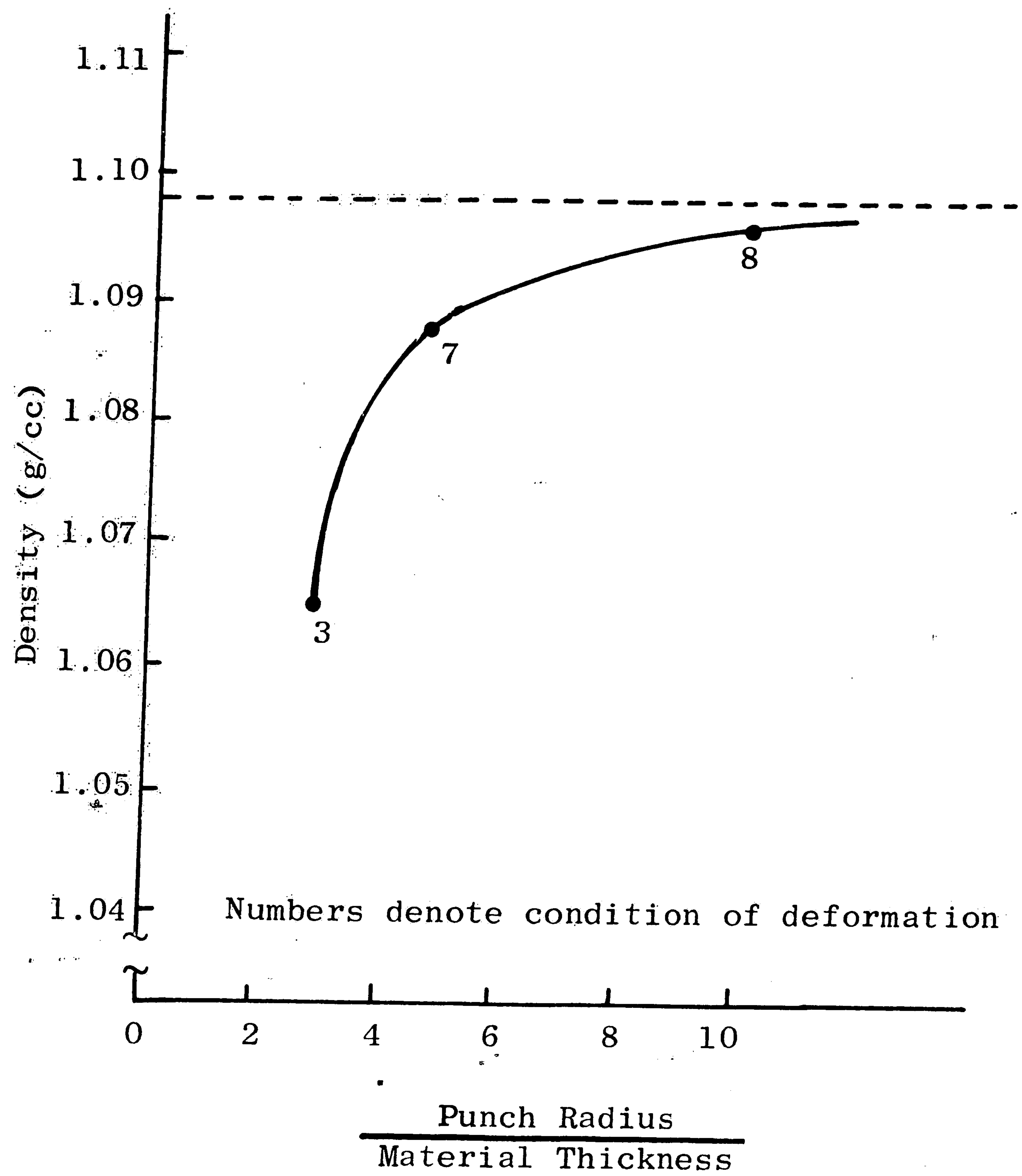


FIG. 43 Density of ABS Specimens from the Bend as a Function of Punch Radius to Material Thickness Ratio.

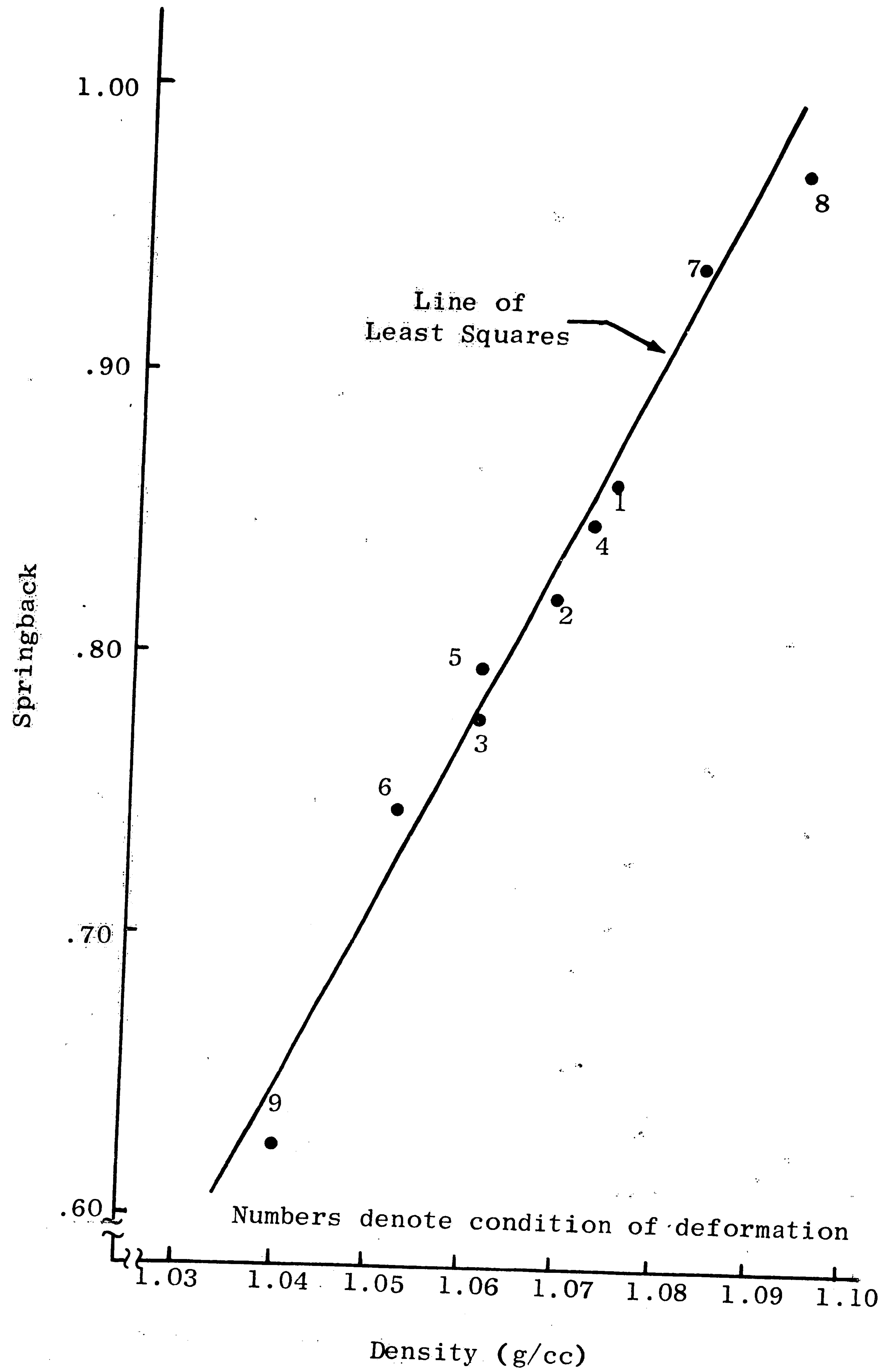
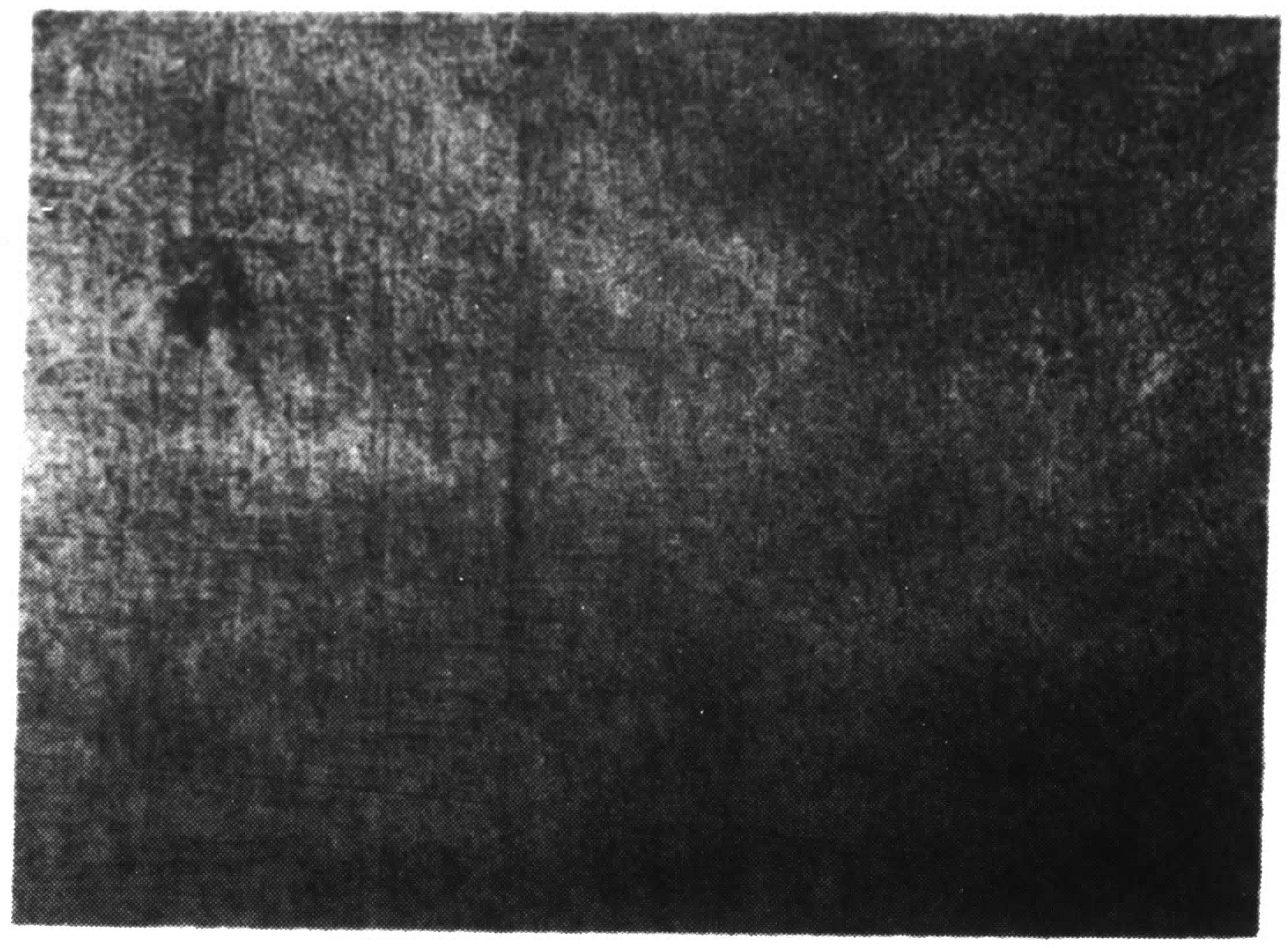
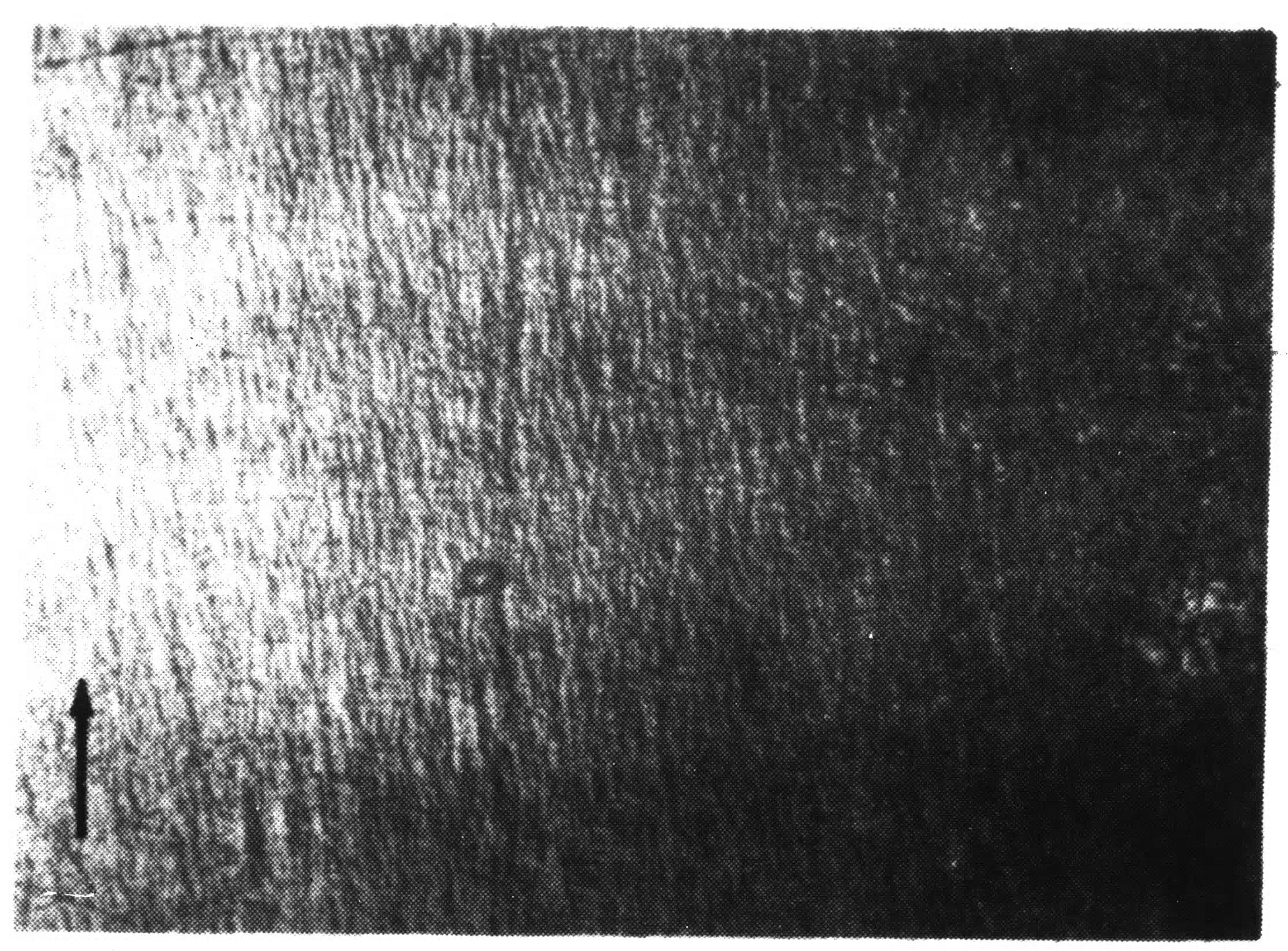


FIG. 44 Springback as a Function of the Density of ABS Specimens from the Bend



(a) Top

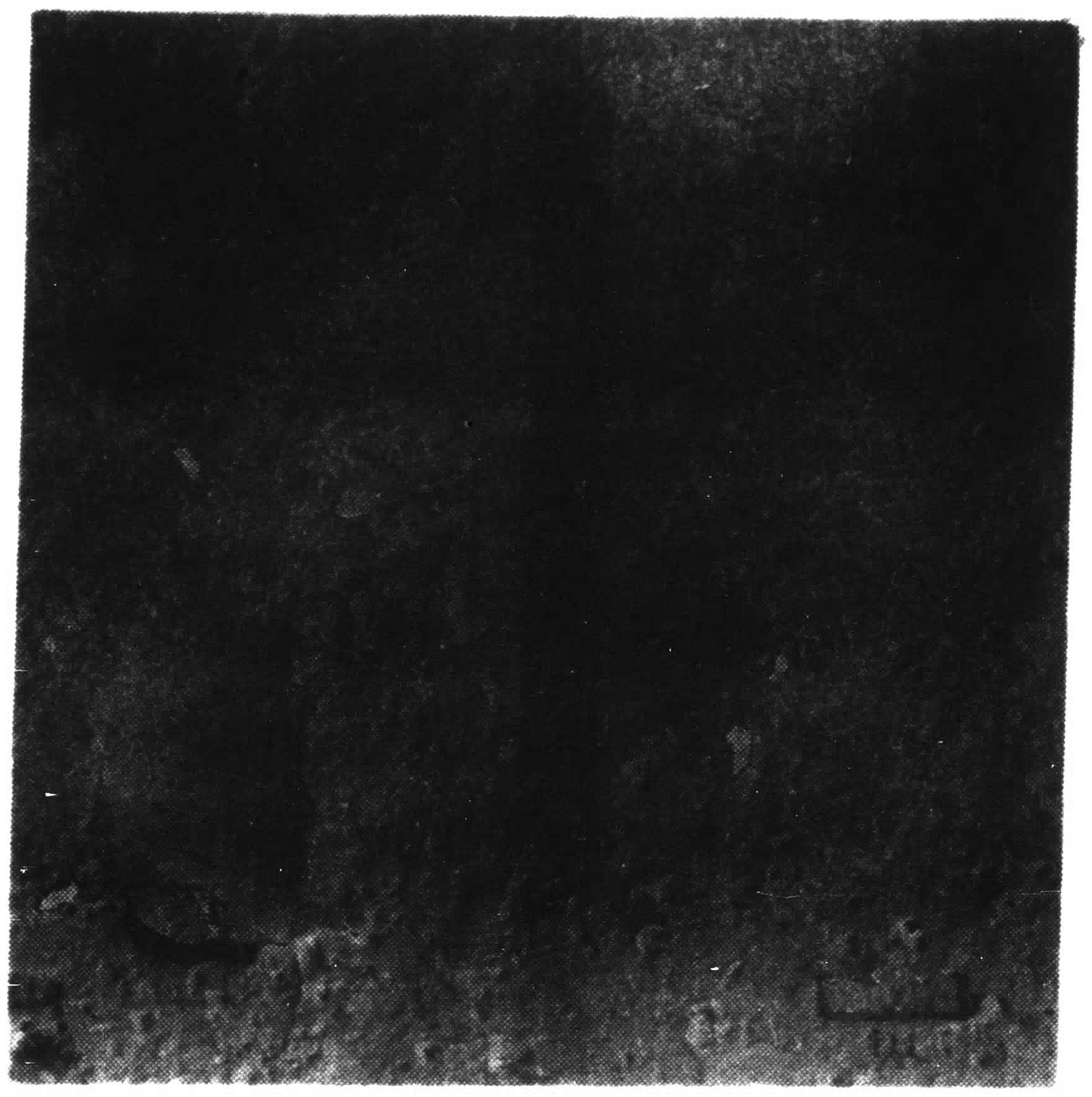


(b) Bend (Arrow designates bend axis)

FIG.45 ABS Viewed at 190X with an Interference Contrast Microscope

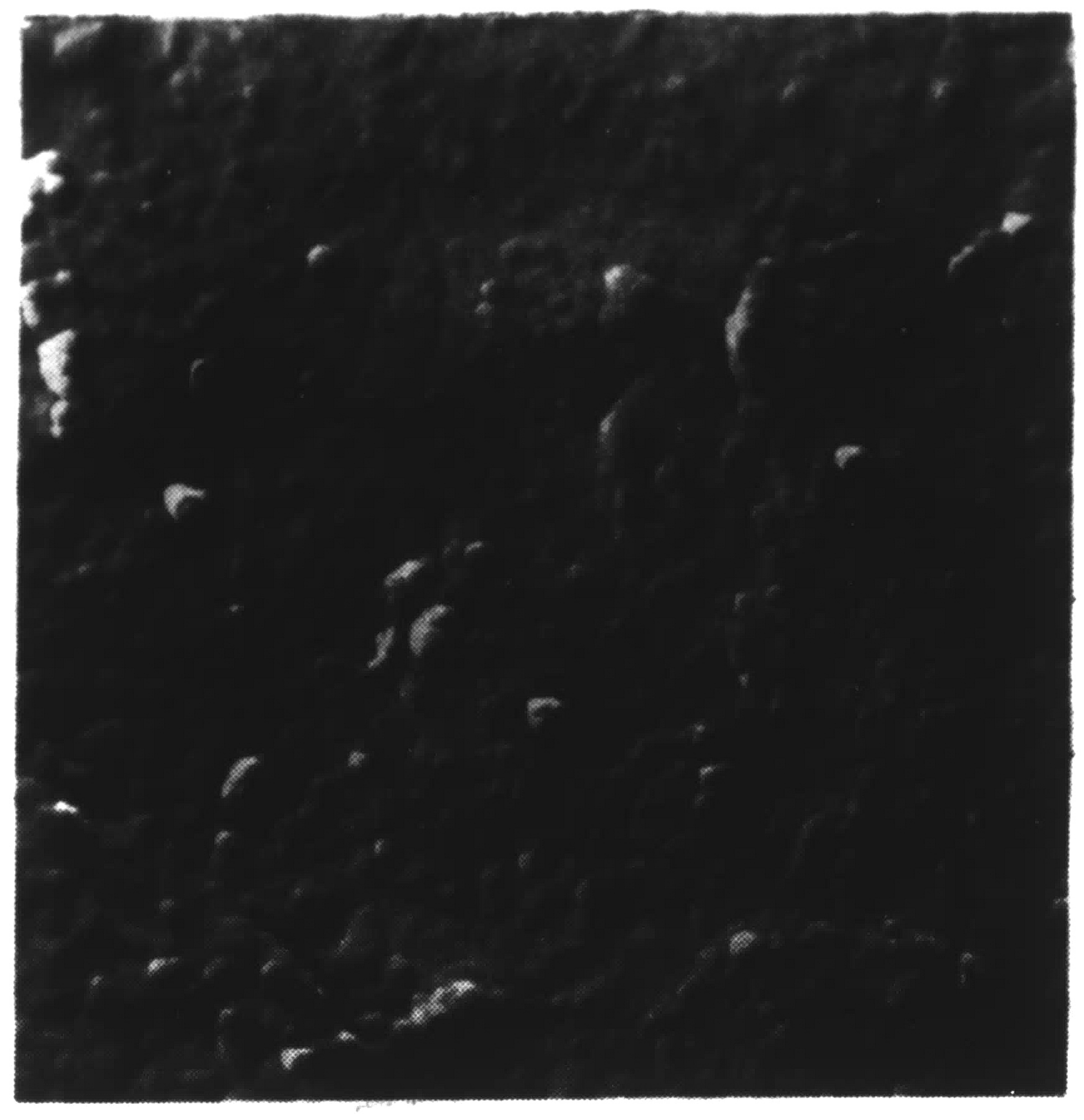
(a) Top

(b) Side



(c) Bend

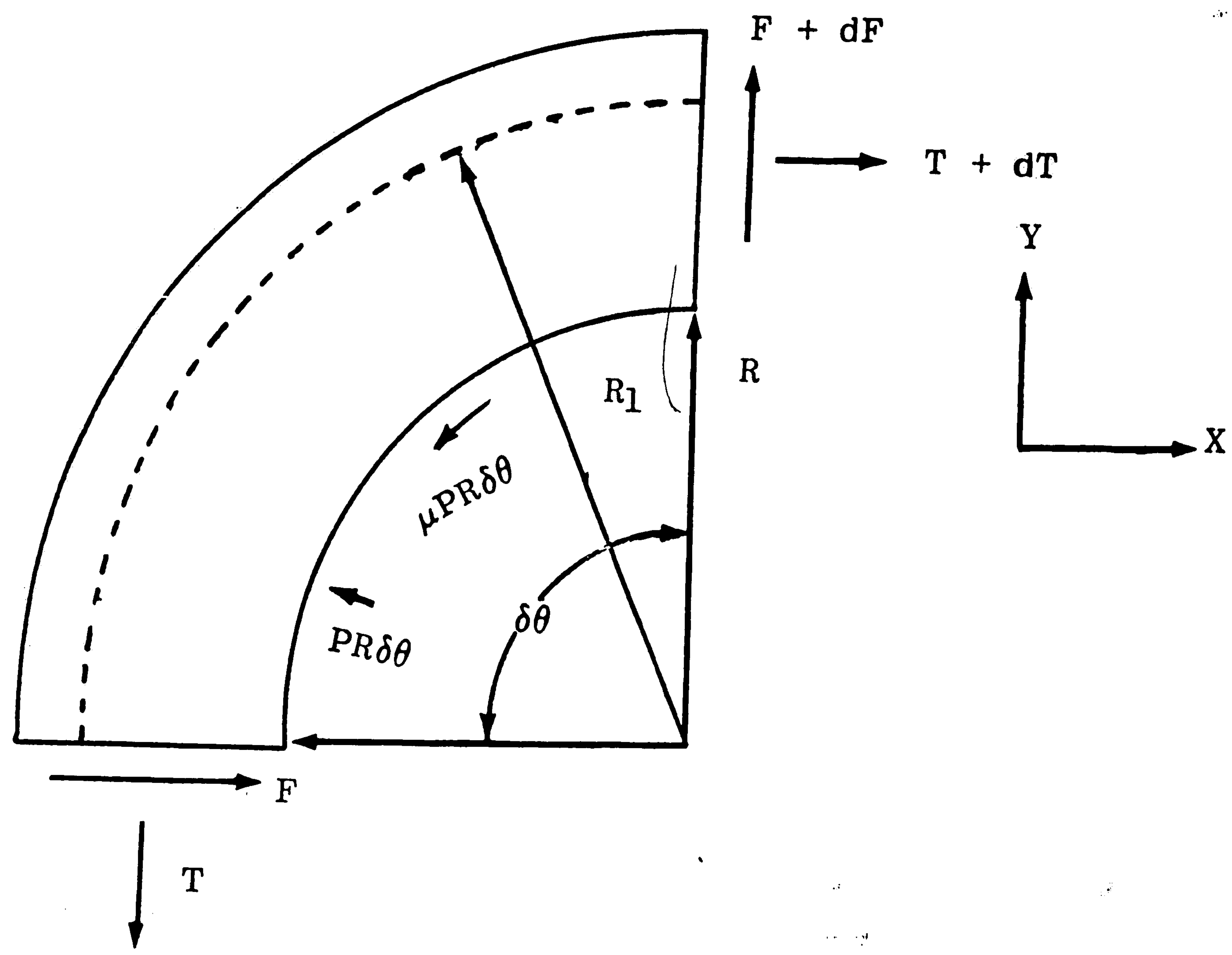
FIG. 46 Electron Micrographs of the Surface of ABS at the Top, Side and Bend



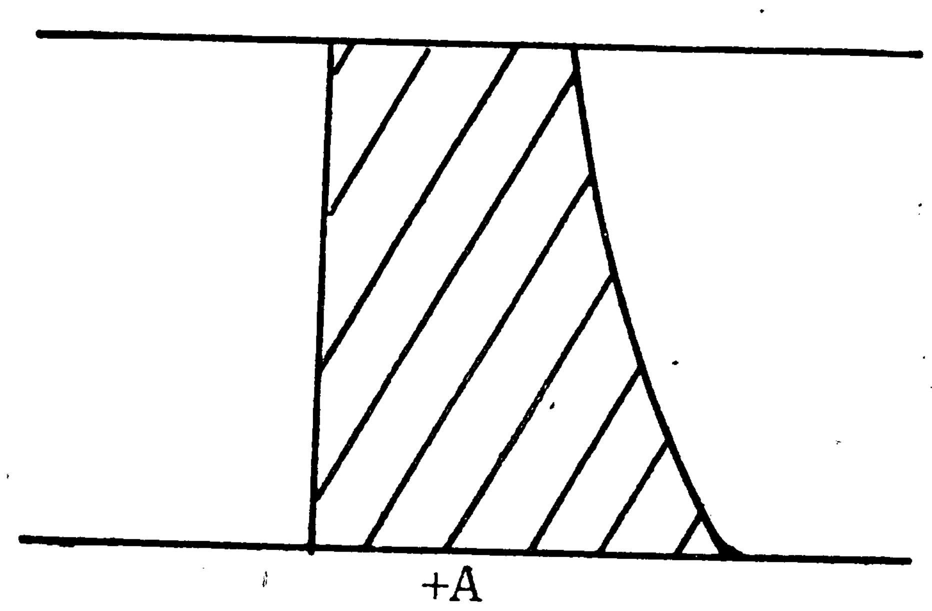
(a) Undeformed

(b) Bend

FIG. 47 Electron Micrographs of Fractured ABS



(a)



(b)

FIG. 48 Stress Associated with Tension on a Material Conforming to a Radius

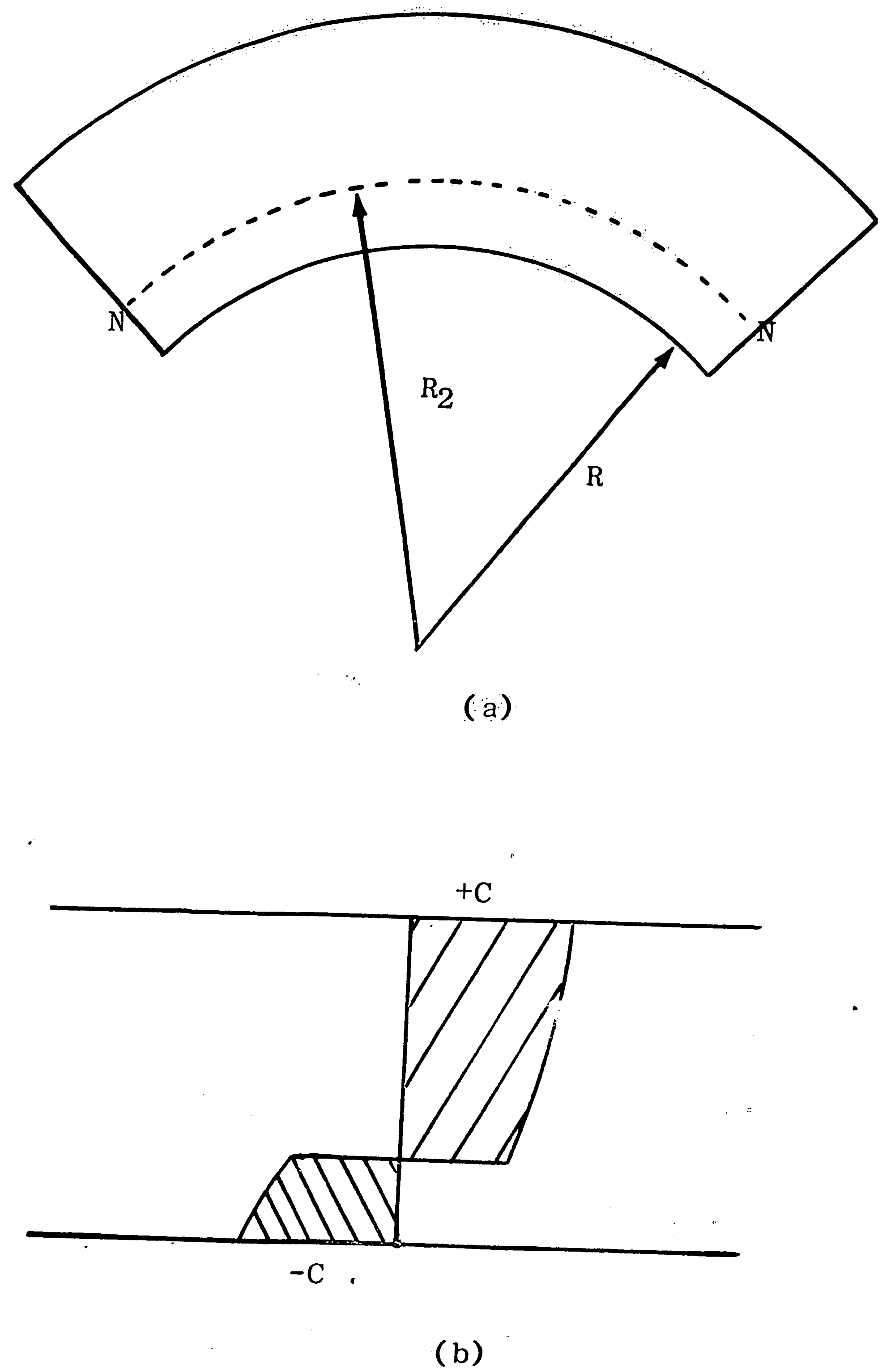


FIG. 49 Stress Associated with Bending a Material about a Radius

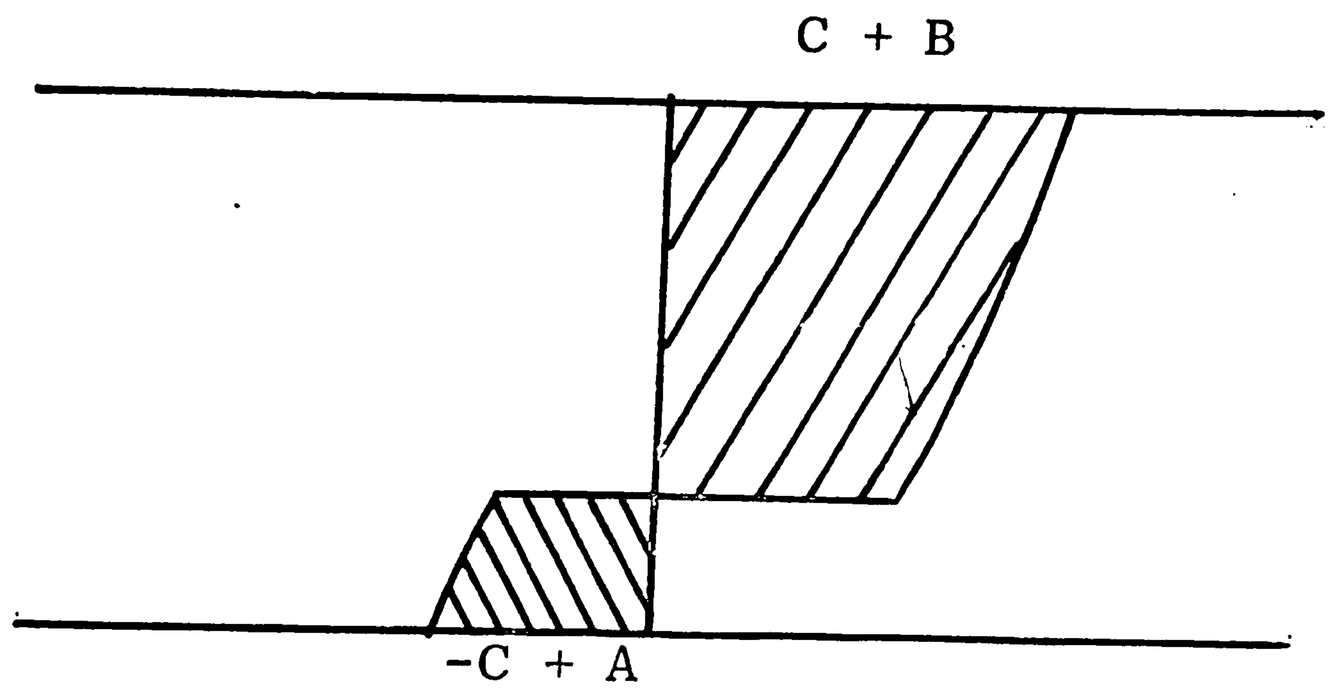


FIG. 50 Combined Stress of Material Conforming to a Radius under Tension

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