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Studies in the cold drawing of $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass and 316 stainless steel crystalline wires

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The stress necessary to draw $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires has been measured using a tensile machine, and compared with that of 316 stainless steel crystalline wires. To assess the elastic back-pull of a drawn material, variable static back-stresses have been loaded on a drawing wire. In the case of the metallic glass wires, the draw stress, σ_d, under different applied back-pulls, σ_{ab}, increases linearly with the reduction in area, R_a, up to 23% and then increases less rapidly. This tendency of the curve σ_d versus R_a is also the same in 316 crystalline wires. On the other hand, the elastic back-pull of the glassy wires is 2.05 kg mm^{-2} at zero applied back-pull and then decreases monotonically with σ_{ab}, while that of the 316 crystalline wires is 6.62 kg mm^{-2} at $\sigma_{ab} = 0$ and decreases linearly with the increase in σ_{ab}. The empirical maximum reduction in $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wire for one-pass drawing is measured to be 40% at $\sigma_{ab} = 0$ and it then decreases with increasing σ_{ab}. The resultant curves of drawing stress versus reduction in area are discussed in the light of plastic theory. The theoretical curves calculated under the assumption of small strain-hardening fits quite well with the experimental curves of $Pd_{77.5}Cu_6Si_{16.5}$ glassy wires.

1. Introduction

The cold-drawing of metallic glass wires was first studied by the author using the $Pd_{77.5}Cu_6Si_{16.5}$ alloy system and was reported elsewhere [1–2]. It has been shown that: (1) a total cross-sectional area reduction of ~90% can be easily obtained after multiple passes through dies; (2) during drawing, two families of deformation bands appear at the exit of a die, i.e. one set is inclined at a certain angle to the wire axis while the other is nearly perpendicular to it. Furthermore, it has also demonstrated that fracture stresses increase slightly and a macroscopic plastic strain increases remarkably after cold-drawing, and that a large number of fine striations are observed on the surface slip steps of the wire specimen drawn and subsequently bent. Therein, the appearance of the fine striations on the slip steps has been explained in terms of the interaction between slip systems, been attributed to work-hardening resulting from the interactions between slip systems (though the rate of work-hardening is expected to be small) [1–3].

Since metallic glasses do not have any crystallographic slip systems and are presumably structurally isotropic, they appear to be suitable for the analysis of plastic deformation under various stress conditions related to plastic theory (in which material is usually assumed as an isotropic structure). Based on this respect, in the present work, the force necessary to draw a metallic glass wire through a die is measured as a function of the reduction in cross-sectional area under various back-tensions. The resultant curves of draw stress versus reduction in area thus obtained are discussed in the light of plastic theory. For comparison, 316 stainless steel crystalline wires are also investigated in the present studies.

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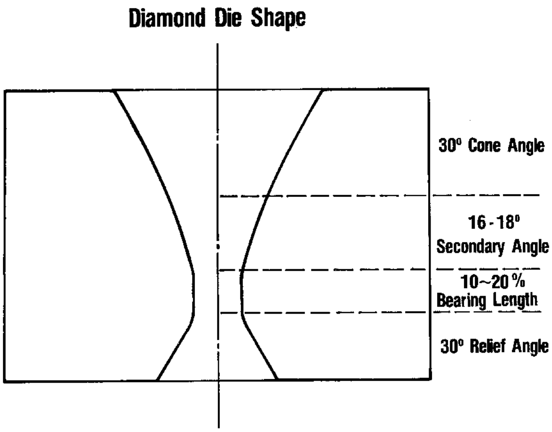

Figure 1 Schematic diamond die shape.

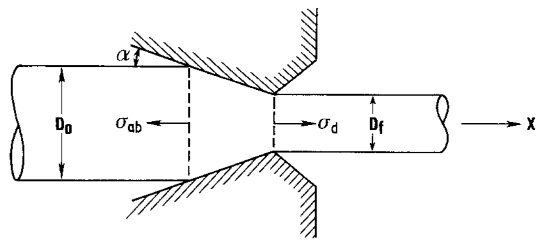

Figure 2 Schematic illustration of wire drawing.

2. Experimental procedure

$Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires with diameters of 0.290 mm were prepared by rapid quenching into water from the molten alloy. The wires thus obtained were carefully examined with X-ray diffraction techniques to confirm their glassy nature. The original diameter of as-received conventional 316 stainless steel crystalline wires is 0.277 mm. The diamond die shape used in the present study is shown schematically in Fig. 1.

Prior to tests, both the glassy and the crystalline wires were drawn down to 0.269 mm diameters, to remove surface imperfections and to ensure an accurate original diameter. A special bench for wire drawing was made and mounted on the moving cross-head of an Instron tensile machine. The die holder and the die are fastened to the drawing bench so that the drawing direction is exactly the same as the die axis. Then the loads necessary to draw a wire through dies were recorded on a recorder chart of the tensile machine. The cross-head speed used to draw a wire through the dies was 0.05 cm min^{-1}. Before and during drawing operations, machine oil lubricant was applied to the surface of a wire. In order to verify an elastic back-pull, back-tension was applied by loading a stationary weight to the end of a wire specimen during drawing. A schematic diagram of the drawing is shown in Fig. 2, in which the part of bearing length in Fig. 2 is excluded for the sake of clarity. Here, X is a drawing direction, D_o and D_f initial and final diameters, σ_d and σ_{ab} drawing stress and applied back-pull, respectively, and α the secondary angle in Fig. 1.

In order to assess the mechanical properties, the specimens prepared for drawing (0.269 mm diameter) were pulled to fracture at room temperature with a strain rate of 4×10^{-5} sec^{-1} in an Instron tensile machine.

3. Results

The mechanical properties of the wires drawn down to 0.269 mm diameter, prepared for drawing tests, are presented in Table I. The values listed are averaged over eight tensile specimens, including the standard deviations. The elastic limits of stress–strain curves are designated as apparent yield stress and strain, respectively.

3.1. 316 stainless steel crystalline wires

The experimental values of draw stress σ_d with different applied back-pulls, σ_{ab}, are plotted as a function of $(D_f/D_o)^2$ or the reduction in cross-sectional area R_a. Fig. 3 shows the resultant curves thus obtained for 316 stainless steel crystalline wires. In the figure, the draw stress first proportionally increases with reduction in area up to

TABLE I Mechanical properties of $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass and 316 stainless steel wires drawn down to 0.269 mm diameter

Sample	Apparent yield strain ϵ_Y (%)	Fracture strain ϵ_F (%)	Apparent yield stress σ_Y^a (kg mm^{-2})	Fracture stress σ_F (kg mm^{-2})	Ultimate tensile strength σ_U (kg mm^{-2})	Area reduction* R (%)
$Pd_{77.5}Cu_6Si_{16.5}$	0.89 ± 0.05	3.06 ± 0.15	63 ± 5	159 ± 3		14
316 Stainless steel	0.77 ± 0.15	2.73 ± 0.14	80 ± 14		197 ± 3	5

* Area reduction was measured as the total reduction in cross-sectional area by drawing.

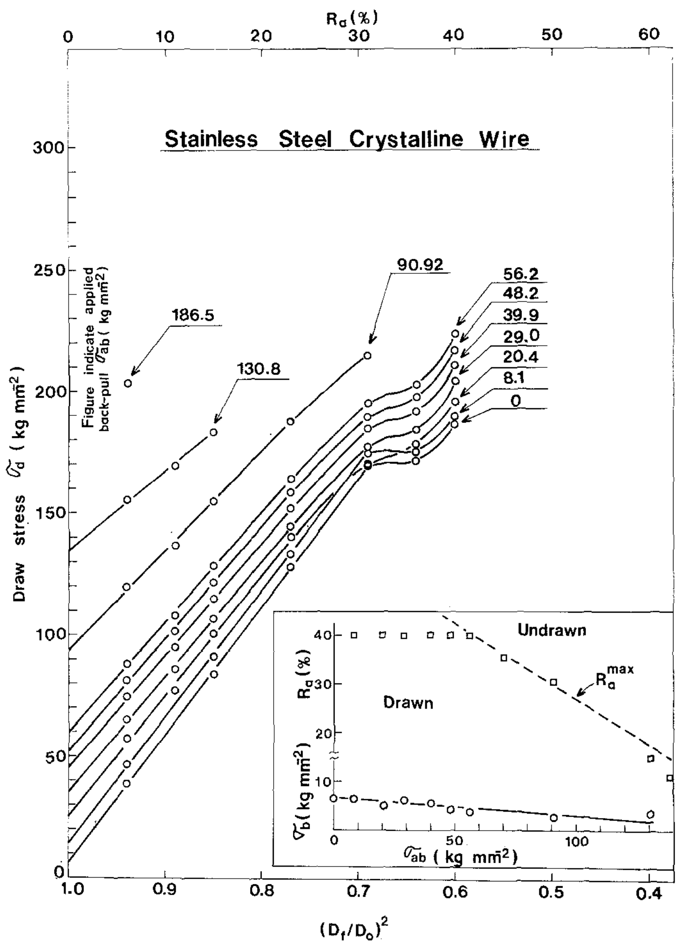

Figure 3 Effect of applied back-pull on draw stress, area reduction and elastic back-pull for 316 stainless steel crystalline wires.

$R_a = 23\%$ (except curves with the applied back-pull $\sigma_{ab} = 0$ and $8.1\,\text{kg}\,\text{mm}^{-2}$), after which the necessary stress to draw the wires increases less rapidly. Note that the draw stresses do not follow a smooth curve with area reduction above $\sim 30\%$. Such an anomalous increase in the drawing stresses is observed in all the present tests, and hence appears to be an inherent phenomenon in this particular wire. The cause of such an anomaly of the drawing stresses is not clear at present but seems to result from unstable plastic flow enhanced by heat generated by a large amount of plastic deformation due to a large reduction in area.

It should be noticed that the draw stress increases with back-pull, though by an amount less than the back-pull itself. The larger the reduction becomes, the smaller the contribution of the back-pull to the draw stress. Thus, as already well established in metal crystalline wires, this experimental fact can be reasonably deduced to the reduction in frictional losses as a result of the decrease in die pressure [3]. Hence, the difference in the draw stress extrapolated to $(D_f/D_o)^2 = 1$ (i.e. zero permanent reduction) and the applied back-pull can be interpreted as that axial stress which corresponds to the die pressure acting in the elastic regions adjacent to the die opening. To evaluate the difference designated as elastic back-pull σ_b, draw stresses extrapolated to $(D_t/D_o)^2 = 1$ were measured by applying a least-squares linear method to the linear portion of the experimental curves of Fig. 3. The elastic back-pulls thus obtained are plotted against the applied back-pull σ_{ab} and shown in the inset at the bottom right corner of Fig. 3 (lower part). The experimental elastic back-pull thus obtained under zero applied back-load yields the value of about 8% of the apparent yield stress, i.e. $6.62\,\text{kg}\,\text{mm}^{-2}$. This magnitude of elastic back-pull is the same as that of 0.58% C steel wires reported elsewhere [4]. As well as the results of other crystalline wires, the elastic back-pull of 316 stainless steel wires decreases linearly with an applied back-pull σ_{ab}. The experimental relation between σ_b and σ_{ab} can

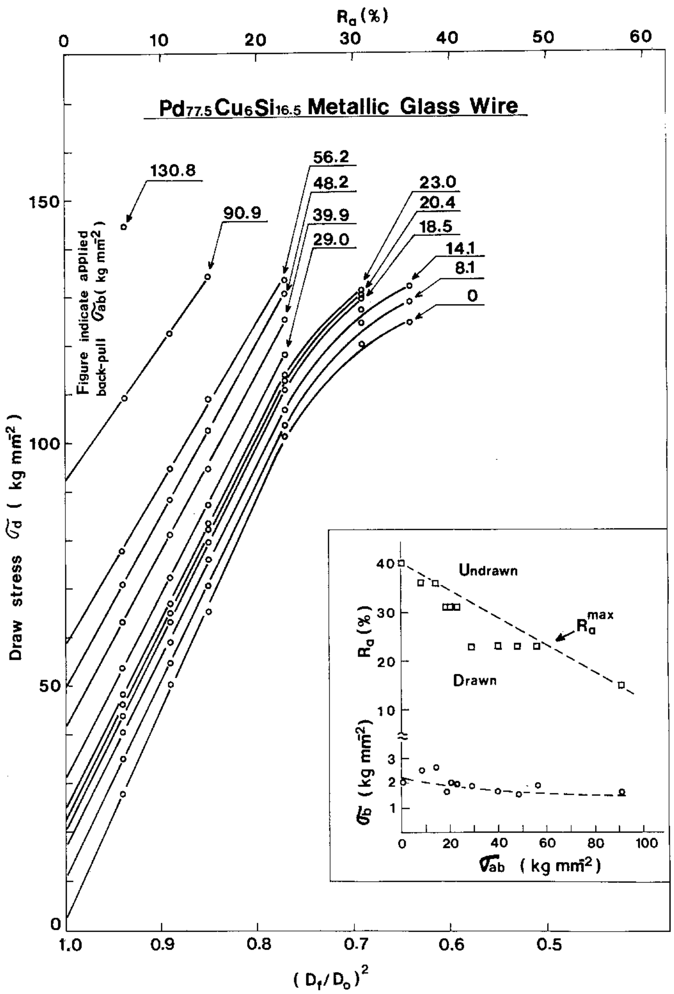

Figure 4 Effect of applied back-pull on draw stress, area reduction and elastic back-pull for $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires.

be expressed as

$$\sigma_b = -0.042\,\sigma_{ab} + 6.624.$$

From the above equation, the elastic back-pull is expected to be zero at $\sigma_{ab} \simeq 158\,\mathrm{kg\,mm^{-2}}$.

On the other hand, a maximum capable reduction in area decreases with increasing an applied back-pull. Such experimental data are shown as a function of an applied back-pull in the upper part of the insert of Fig. 3. The broken line indicates the boundary of the maximum possible reduction for one-pass drawing. Note that the maximum possible reduction in area appears to be inversely proportional to the applied back-pull.

3.2. $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires

The empirical values of a draw stress for $Pd_{77.5}Cu_6Si_{16.5}$ glassy wires are plotted in a similar manner to Fig. 3 and shown in Fig. 4. Similar to the 316 crystalline wires, the draw stress, σ_d, first linearly increases with area reduction up to $R_a = 23\%$, and then monotonically increases less rapidly. Here it should be emphasized that an elastic back-pull is also borne out during drawing a $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wire as well as existing in crystalline wires. The experimental value of elastic back-pull under zero applied back-pull, designated as a draw stress at a zero area reduction in the figure, is measured to be $2.05\,\mathrm{kg\,mm^{-2}}$, which yields 3% apparent yield stress (see Table I). This magnitude of elastic back-pull for the metallic glasses is 31% lower than that for the 316 crystalline wires ($6.62\,\mathrm{kg\,mm^{-2}}$). The empirical elastic back-pull against an applied back-pull is shown in the lower part of the insert at the bottom right corner of Fig. 3. Comparing this with the result of 316 crystalline wires, the elastic back-pull of the metallic glass does not decrease linearly with σ_{ab} but does so monotonically in a very small amount. Such a small decrease of elastic back-pull with σ_{ab} appears to indicate that the effect of an applied back-pull on the elastic back-pull is very small in $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires in comparison to the 316 crystalline wires.

As depicted in the upper part of the insert of Fig. 3, the maximum possible reduction in area for one-pass drawing increases linearly with increase in applied back-pull. The rate of decrease for the metallic glass wires is nearly equal to that for the 316 stainless steel wires. Yet, the maximum possible reduction in area for the Pd-base glassy wires is much lower than that for the 316 crystalline wires.

4. Discussion

Since metallic glasses do not have any crystallographic slip systems and are structurally isotropic, they are presumably suited for the analysis of plastic theory (in which subjected materials are usually considered as an isotropic structure). Based on this consideration, it is of interest to compare present results with theoretical values calculated from plastic theory. For this respect, Sacks [5] and Davis and Dokos [6] analyses in wire-drawing problems are employed. The former mathematical treatment is based on the assumption of an ideal yield while the latter is derived for materials which have work-hardening. In both cases, they assumed a steady state of flow for which original cross-sections remain planes. Actually, this assumption holds for a smaller angle of reduction and for a small area reduction in drawing.

Sacks' mathematical model derives the following equations, for the stress necessary to draw a material, σ_d

$$\sigma_d = \frac{1+K}{K}\sigma_o\left[1-\left(\frac{D_f^2}{D_o^2}\right)^K\right]+\sigma_{ab}\left(\frac{D_f^2}{D_o^2}\right)^K, \quad (1)$$

where D_o and D_f are original and final wire diameters respectively, σ_o and σ_{ab} are yield stress and applied back-pull and K is related to a coefficient of friction f (between a drawn material and the wall of die) and a reduced angle α, i.e. secondary angle of Fig. 1, by the following equation:

$$K = \frac{f}{\tan\alpha}. \quad (2)$$

Although the above Sacks equation was derived under the assumption of an ideally plastic material, it can also apply to materials which have a small work-hardening with single modifications [7]. This is done by simply replacing an average flow stress at the outset and at the termination of plastic flow in place of the (initial) yield stress σ_o in Equation 1. On the other hand, draw stresses calculated by Davis and Dohos are expressed as:

$$\sigma_d = \frac{1+K}{K}\left\{3w\ln\left(\frac{D_o^2}{D_f^2}\right) - \left(\frac{3w}{K}-\sigma_o\right)\left[1-\left(\frac{D_f^2}{D_o^2}\right)^K\right]\right\}+\sigma_{ab}\left(\frac{D_f^2}{D_o^2}\right)^K \quad (3)$$

where a rate of work-hardening is assumed as a constant w. It should be noted that Equation 1 can be reduced by substituting $w = 0$ in Equation 3.

4.1. Drawing of $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires

Let us consider first the experimental results of $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires. Continuous observations of the appearance of deformation bands during a tensile test of the drawn Pd-base glassy wires reveals that burst of slip lines appears over the whole peripheral surface of the specimen above the stress level of an apparent yield point [2]. Apparently, this result strongly indicates that the onset of plastic flow for a drawn metallic glass wire takes place at the apparent yield point. Since prior to the present test, as-quenched metallic glass wires were drawn down to the area reduction $R_a = 14\%$, if there is no work-hardening in the drawn glassy wires the initial yield stress σ_o should be the apparent yield stress, i.e. 63 kg mm^{-2} (see Table I). Substituting 63 kg mm^{-2} for σ_o in Equation 1, a draw stress σ_d was calculated as a function of $(D_f/D_o)^2$ for various values of K. However, all theoretical curves thus obtained show poor agreements with the experimental ones presented in Fig. 3. In a further attempt to fit theoretical curves to experimental ones, let us assume next a small work-hardening in the drawn metallic glass wires. According to Sacks' analysis, fitting Equation 1 as closely as possible to the experimental data, we obtain $\sigma_o = 159$ kg mm^{-2} as an average flow stress (i.e. tensile strength of the drawn glassy wires) and $K = 2$. These resultant curves are shown in Fig. 5 (dashed lines) and compared with representative experimental data (solid lines). Note that the theoretical curves thus obtained fall very close to the experimental ones up to the area reduction $R_a \sim 28\%$. The large deviation from the experimental data above $R_a \sim 30\%$ may suggest the limit of validity of Equation 1 to the actual draw stresses. In fact, above $R_a \sim 30\%$ the original bottom planes of the Pd-base wire

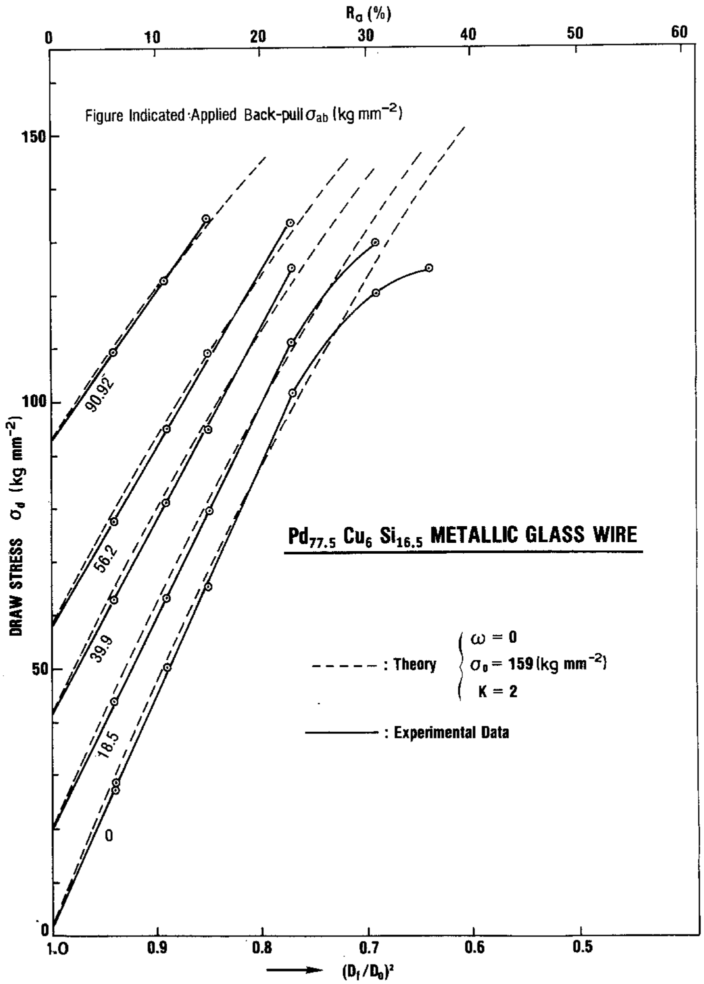

Figure 5 Draw stress versus area reduction for $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires. —— experimental curves, – – – – theoretical ones.

becomes largely concave [1], indicating that the original cross-sections do not remain planes. This means that the assumption of a steady state flow no longer holds in deriving Equation 1. On the other hand, another possible explanation for the large discrepancy is that the value of the average flow stress $\sigma_o = 159\,\mathrm{kg\,mm^{-2}}$ used in Equation 1 is overestimated above $R_a \sim 30\%$ due to the unstable flow enhanced by heat generated by a large amount of plastic deformation.

Substituting $K = 2$ (resultant value obtained above) and $\alpha = 17°$ (average secondary angle of a die used) into Equation 3, a coefficient of friction is calculated to be 0.61, which is the same order of magnitude as the value of the static coefficient of friction for diamond on metal (0.1 to 0.15). Finally, the possibility of a large work-hardening in a drawn metallic glass was evaluated by using Equation 3 in comparison to the experimental data. As a result, the theoretical curves calculated by assuming a large work-hardening show a poor agreement with the experimental data. In fact, even if we find the best parameters of Equation 3 to describe the first empirical curve, σ_d versus $(D_f/D_o)^2$, with zero applied back-pull, the theoretical curves thus calculated fall far from the experimental ones with increasing applied back-pull.

Consequently, summarizing the current considerations, the draw stress calculated under the assumption of small work-hardening falls most closely to the empirical data of $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wires.

4.2. Drawing of 316 stainless steel crystalline wires

For the case of 316 stainless steel crystalline wires, the best theoretical curves calculated from Equation 1 are shown in Fig. 6 together with the corresponding experimental ones. In the figure, only representative experimental and theoretical curves are presented. On the whole, all theoretical curves thus obtained show a poor agreement with

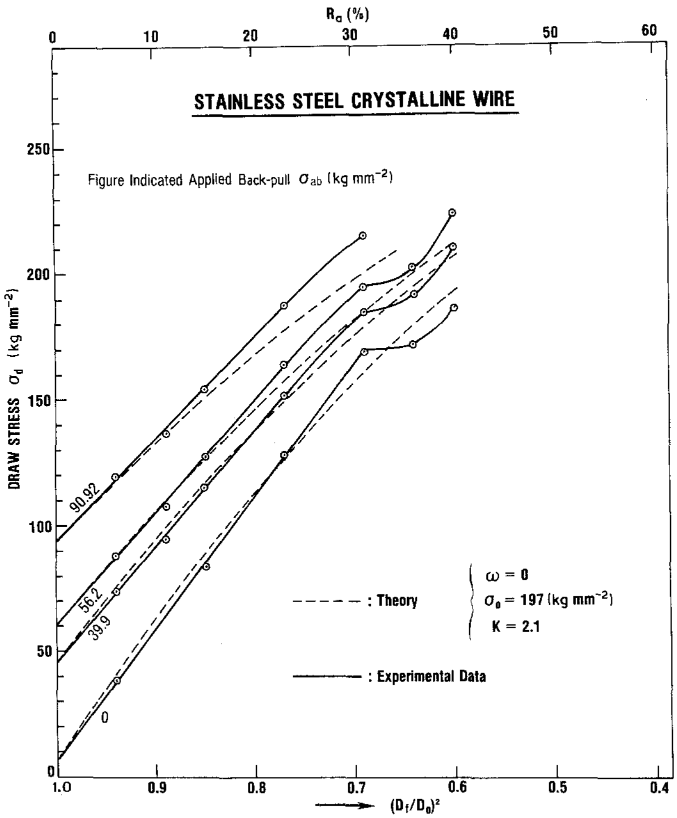

Figure 6 Draw stress versus area reduction for 316 stainless steel crystalline wires: ——— experimental curves, – – – – theoretical ones.

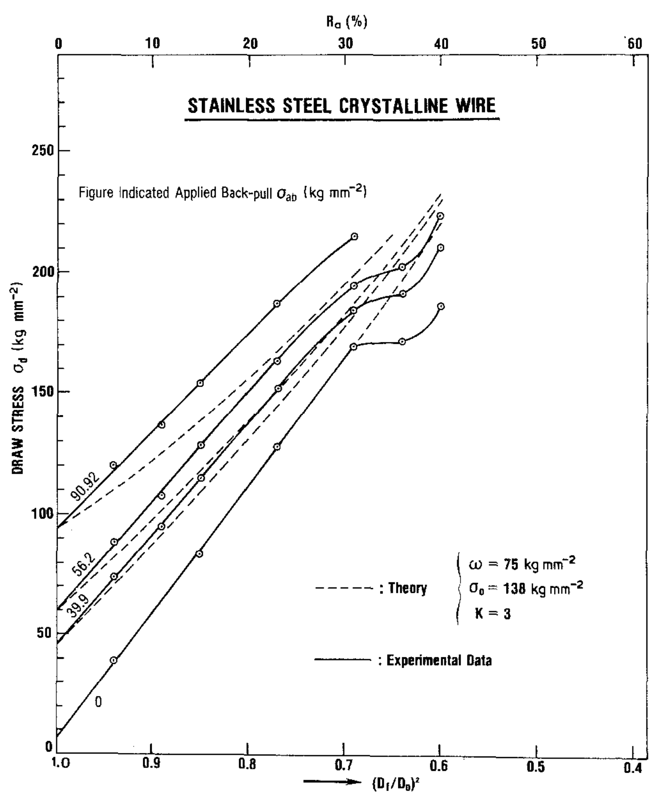

Figure 7 Draw stress versus area reduction.

the experimental results even though assuming a small work-hardening for plastic deformation. However, even curves calculated by Equation 3 are in poor agreement with the empirical ones. This typical example is presented in Fig. 7. Here the parameters w, σ_o and K were obtained by fitting Equation 3 as closely as possible to the experimental data with zero applied back-pull. Note that the discrepancy between theoretical and experimental curves increases with increasing applied back-pull. Since the stacking fault energy of 316 stainless steel is low, the rate of work-hardening can be expected to be large for plastic deformation. Therefore, failure to describe the experimental curves by using Equation 3 might suggest that the assumption of a constant rate of work-hardening in Equation 3 is somewhat simple-minded for the present 316 stainless steel crystalline wires. Thus, the poor agreement between theoretical and experimental curves might be improved by obtaining an exact formula of a work-hardening rate as a function of plastic strain, and solving a numerical integral equation derived by Davis and Dokos [6]. Such a correct mathematical treatment to describe the present experimental data requires further attention and is currently being investigated.

5. Conclusions

(1) For both $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass and 316 stainless steel crystalline wires, the draw stress σ_d under an applied back-pull σ_{ab} first increases linearly with reduction in area R_a and then increases less rapidly.

(2) The elastic back-pull of the $Pd_{77.5}Cu_6Si_{16.5}$ glassy wires in $2.05\,kg\,mm^{-2}$ under zero applied back-pull and then decreases monotonically with σ_{ab}, while that of the 316 crystalline wires is $6.62\,kg\,mm^{-2}$ at $\sigma_{ab} = 0$ and decreases linearly with σ_{ab}.

(3) The empirical maximum reduction in $Pd_{77.5}Cu_6Si_{16.5}$ metallic glass wire for one-pass drawing is 40% at $\sigma_{ab} = 0$ and then decreases as increasing σ_{ab}.

(4) The theoretical curves calculated under the assumption of small work-hardening fit quite well to the experimental curves of $Pd_{77.5}Cu_6Si_{16.5}$ glassy wires.

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