EFFECT OF DIE PROFILE ON MECHANICAL PROPERTIES OF PRODUCT IN EXTRUSION OF RODS

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Abstract In any metal forming process, both the strain rate and deformation rate depend on the die profile. The die profile also, is responsible for the non-uniformity of the deformation along the cross-section. These affect the quality and mechanical properties of the product. Therefore, if a die is designed, in which the affecting variables can be controlled spontaneously it is hoped to obtain a product with a desired quality. In this paper, the effect of the die profile on the mechanical and metallurgical properties of the product is investigated.

Key Words Tool Design, Extrusion, Redundant Shearing Strain

چکیده در فرایندهای تغییر شکل پلاستکی فلزات، هم شتاب کرنش و هم شتاب تغییر شکل بستگی به شکل هندسی قالب دارند. همچنین، شکل قالب در مقدار و نوع نایکنواختی تغییر شکل تاثیر می گذارد. این عوامل کیفیت و خواص مکانیکی محصول را تعیین می کنند. بنابر این، اگر بتوان قالبی طراحی کرد که در آن عوامل موثر به دلخواه تغییر داده شود می توان امیدوار بود که محصول با کیفیت دلخواه بدست آید. در این مقاله اثر شکل هندسی قالب روی خواص مکانیکی و متالورژیکی محصول در فرایند اکستروژن مورد بررسی قرار گرفته است.

1. INTRODUCTION

Despite a considerable advances achieved in the theoretical analysis of plasticity, the die design has developed on the basis of lengthy and costly trial and error methods. In practice, a high level of forces is used which may not be necessary for the homogeneous deformation of metal. This high level of forces may produce defects in the product and damage the tooling.

Strain is an inherent factor in any metal-forming process, whose amount in different directions defines the final shape of the product. A homogeneous strain is attained in a die less media of a specimen, for example in a simple tension testing. However, any metal-forming process consists of a series of dies, which can produce inhomogeneous strains and defects in the work piece.

In a metal deformation process, the product should be defect free, having certain mechanical properties and metallurgical structure and is produced economically. These requirements can be attained in an ideal die, which introduces a proper stress, strain, strain rate, and temperature at any point of deformation zone. If the stresses are insufficient for fully plastic flow, within the deformation zone, some of the material may not contribute to homogeneous deformation. Non-uniformly distributed stress may also, cause different internal and external types of fracture in the product. For this reason the correct tool design is the key factor in the economical metal-forming processes.

The quality of the product will depend on the strain path. Consider a specimen subjected to strain ε_a over a length X_f in a given operation (Figure 1-a). An infinite number of strain paths may be traced to join O to A, of which two different strain profiles are shown in Figure 1-b. The rate of deformation on length OB of the curve 1 is high and on length BA, is negligible. Hence, the product may have adequate time for recrystallization before leaving the die and entering into a very different environment. By contrast, curve 2 ends in length CA of a greater rate of deformation and the metal may harden as it comes to point A, without having the time for recrystallization. Consequently, the mechanical properties and metallurgical structure of the product for the paths 1 and 2 will differ widely.

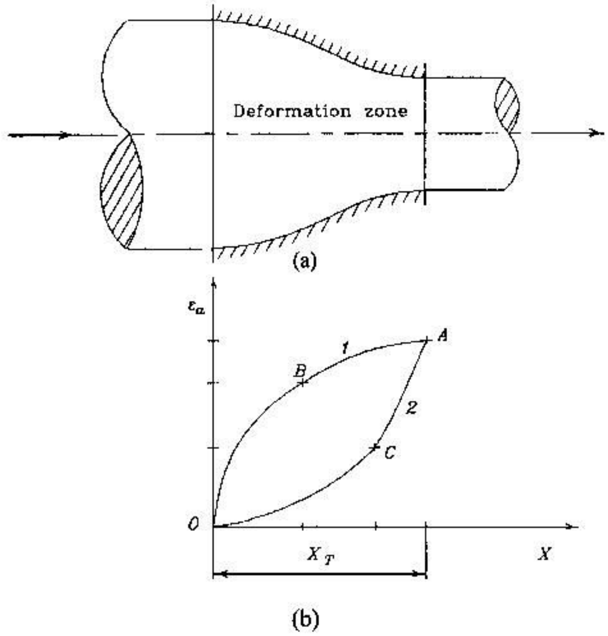


Figure 1. Different strain paths, which may be traced in a real deformation process.

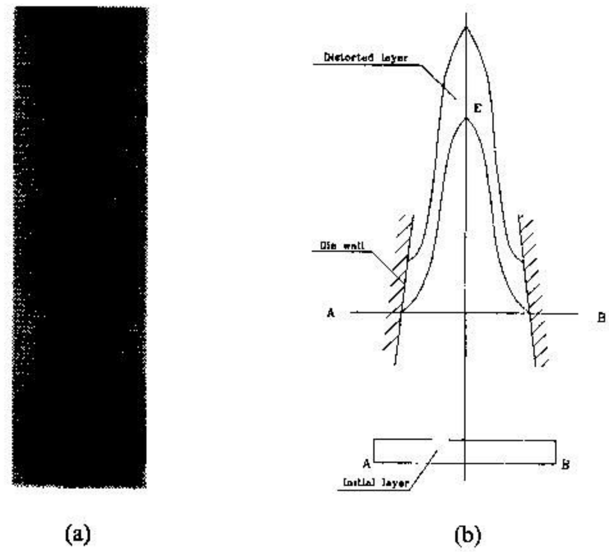


Figure 2. Typical flow pattern (a) distortion of layers in a laminated specimen and (b) a deforming layer in deformation zone.

2. FLOW PATTERN

Among the metal-forming processes, extrusion is a suitable means for theoretical study, because the process is simple, the flow effects can be displayed clearly, and the deformation readily reaches the steady state condition. In this work the extrusion was adopted for the experimental study of the flow pattern.

An ideal deformation is one, in which any plane normal to the axis remains plane and normal after the deformation. In real processes, however, the normal planes may distort and cause nonuniformity throughout the final product. A typical flow pattern of a laminated experimental specimen, using a kind of industrial wax as a model material, is shown in Figure 2-a, and a deforming layer within the deformation zone is isolated and depicted in Figure 2-b.

The normal planes are subjected to two distinct, unnecessary physical effects and distort to hyperbolic shapes [1]. Any element of the layer may suffer from a translational displacement and a shearing distortion. The final arrangement of elements, corresponding to a layer, forms the flow pattern.

In the left-half portion of Figure 3-a, a flow pattern of a layer is plotted using the data obtained from a measured specimen. The distribution of particles, considering the translational displacement only, is shown in the right-half portion. The initial plane layer is divided into n identical elements. These elements in ideal deformation should have equal lengths of l_o in the considered position. However, the i-th element may have displacements x_i, relative to the ideal position, and w_i, relative to the (i-1)th element. Although the translational displacement of the elements from the ideal position to their final positions may be associated with deformation, here further deformation of the elements is not involved. It can be noticed that in addition to the incremental displacements not being equal, (w_i constant), the lengths of the elements situated at the mid- portion between the die wall and the centre-line are longer than the rest. It means that these elements in addition to translation suffer extra extension during the deformation. But, it seems that a very thin particle at the vicinity of the die wall does not change, and remains at the original length throughout the deformation.

The axial displacement of the layer elements does not contribute to the deformation and the final shape of the product. Consequently, the energy dissipated in the movement is entirely redundant.

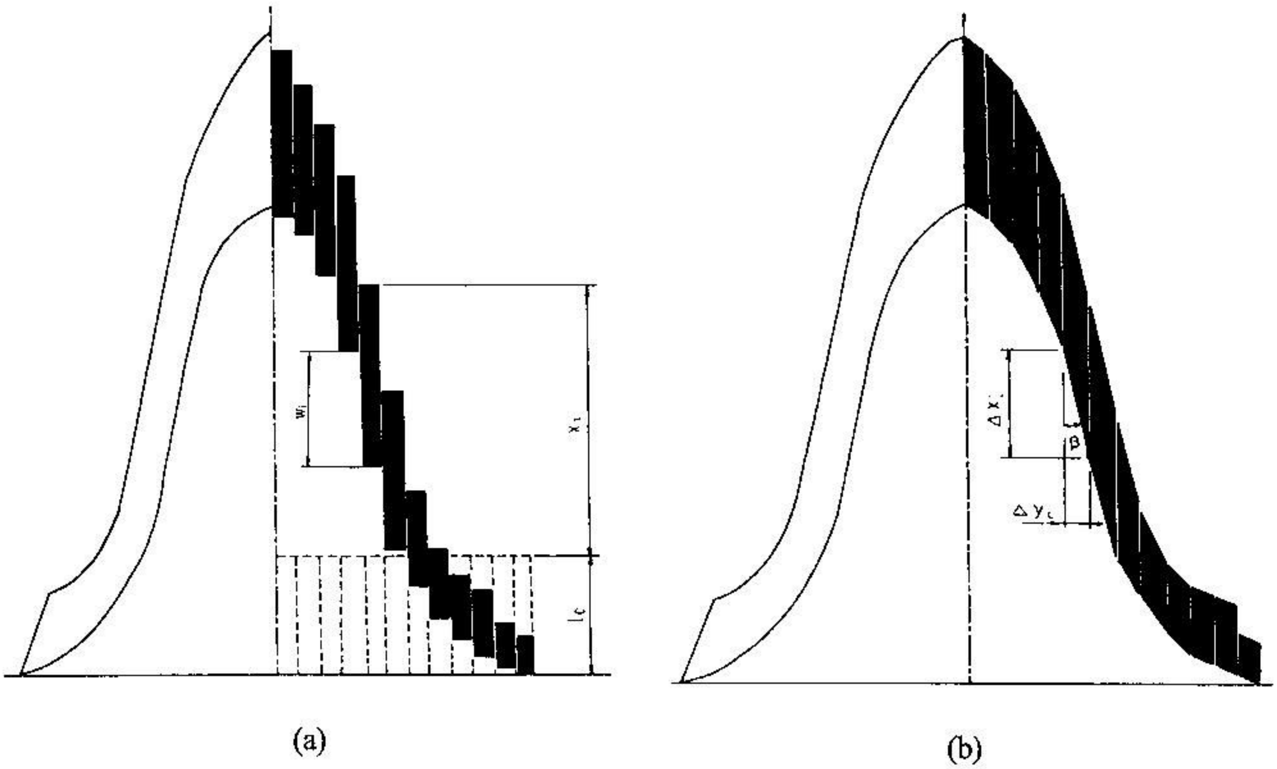


Figure 3. Analysis of a distorted layer in extrusion (a) translational displacement of particles and (b) final arrangement of element.

The second distorted effect is assumed to cause the rectangular elements to become parallelograms (Figure 3-b). The distortion is Δx_i along the axis, and it takes place in an element height Δy_i. Accordingly, a shear strain, equal to $\Delta x_i/\Delta y_i$, can be evaluated for any individual element and may be considered to be cot β. This figure reveals that the distortion of the elements is not the same. Shearing strain is higher at mid-portion between the die wall and the axis, while it is lower near the axis. The distribution of the shearing strain at the cross-section can map out the inhomogeneity in the specimen. This is shown in Figure 4. Although shearing strains do not affect the final shape of the product, they contribute to the total straining, whose nonuniform distribution results in an inhomogeneous deformation. Moreover, the product consumes energy to perform shearing strains. Accordingly the shearing energy is also redundant.

If the principal strains are denoted by ε_x, ε_y, and

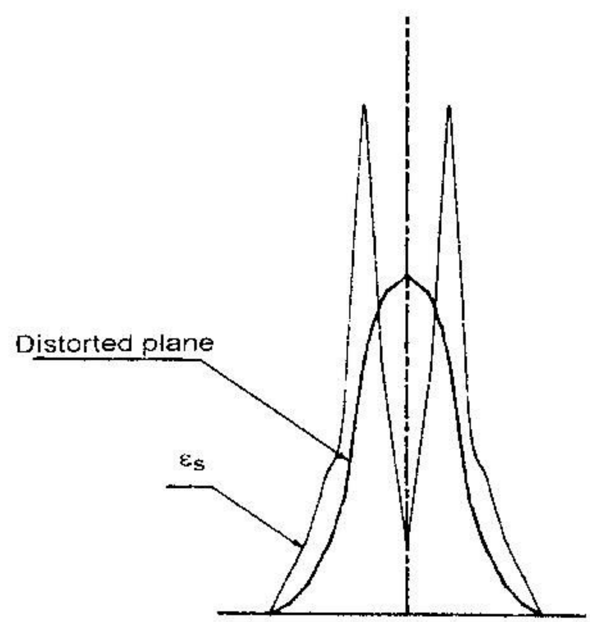


Figure 4. Distribution of shearing strain in a deforming layer.

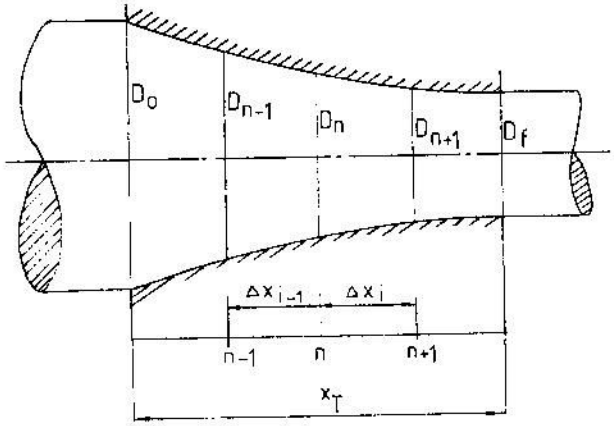


Figure 5. Die geometry in deformation zone.

ε_z, in an ideal homogeneous deformation, the strain in any element can be calculated as:

$$\varepsilon_H = \sqrt{\frac{2}{3}}\left[\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2\right]^{\frac{1}{2}} \tag{1}$$

In the existence of the redundant strains, the final strain becomes [2].

$$\varepsilon_T = \varepsilon_H + \frac{1}{2}\left(\varepsilon_l^2 + \varepsilon_t^2 + \varepsilon_c^2\right)^{\frac{1}{2}} \tag{2}$$

where, ε_l is the longitudinal strain, ε_t is the tangential strain, and e_c is the circumferential strain.

The amount of homogeneous strain can be calculated from the geometry of the deformation zone, whereas the amount of the redundant strain depends on many factors, including the material properties, geometry of the die, frictional conditions, temperature, etc.

3. EXISTING TOOL DESIGN METHODS

A considerable amount of investigations in metal forming, thus far is devoted in the area of:

- Determination of energy consumption, and the methods of its reduction,
- Reduction of product defects, and
- Increase in the tooling life.

However, not many published works can be found on the effect of die profile on the mechanical properties of the product. The advantage of curved dies over flat-faced tools is reported in some investigations [3, 4]. But, before using a specified profile, its influence on the inhomogeniety of the strains should be recognized. The major factors producing the inhomogeniety are not completely identified, but it is a proven fact that the geometry of the deformation zone has a dominating role in initiation and growth of inhomogeniety [5, 6, 7].

Most of the investigators utilize a certain series of dies, with randomly selected profiles; to evaluate the overall energy consumption, and study the quality of product, in the hope of finding an optimum die profile. Among the common geometrical shapes, the cosine, elliptic, hyperbolic concave curves as well as conical dies are utilized frequently [8, 9, 10, 11].

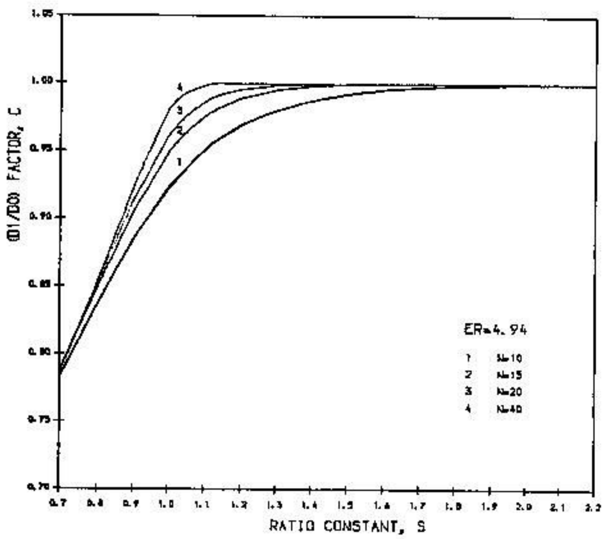
The governing role of the die pass on the inhomogeniety of deformation may lie in the fact that the strain rate, contact area, stress distribution in work-piece, possibility of recrystallization and some other influencing factors all depend on the die geometry. Among the listed parameters, it is proven that the strain rate has influence conclusively In extrusion, the mean longitudinal shearing strain is proportional to the strain rate [1].

4. C.R.S. DIES

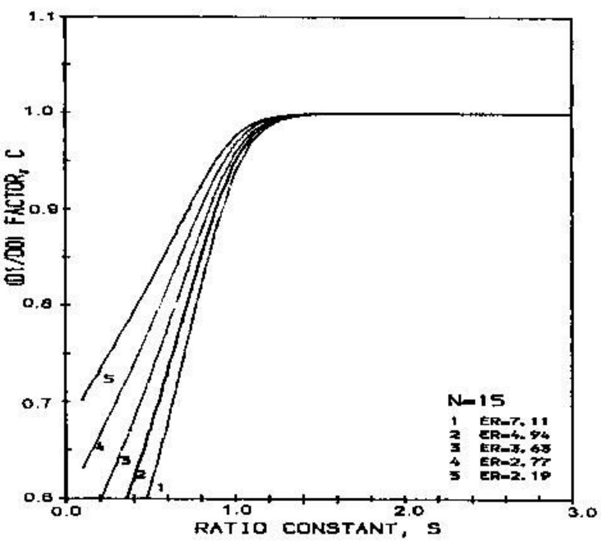
The concept for provision of curved die profiles based on the "Constancy of the Ratios of the successive homogeneous Strains" (C.R.S.), proposed by Blazynski [12], is defined as:

$$\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_1 - \varepsilon_0} = \frac{\varepsilon_3 - \varepsilon_2}{\varepsilon_2 - \varepsilon_1} = \ldots = \frac{\varepsilon_n - \varepsilon_{n-1}}{\varepsilon_{n-1} - \varepsilon_{n-2}} = s \tag{3}$$

where s- is an arbitrarily selected numerical constant. In this concept, it is assumed that the die length X_T is divided into N small distances of x (Figure 5) and homogeneous strains in individual sections are denoted by ε_1, ε_2, ε_3, ... and ε_n. In general ε_n is considered to be the finite strain between section zero (0) of the pass, i.e. where the transverse section in which plastic deformation begins, and any section (n) along the pass. The



(a)



(b)

Figure 6. Interdependence of design parameters of a die (a) dependence of C on s and number of divisions N and (b) dependence of C on s and area reduction.

general homogeneous strain can be presented in the form of:

$$\varepsilon_n = \mathrm{Ln}(Z_n) \tag{4}$$

where, Z_n- is a function that is related to the dimensions of the work-piece in section n. On substituting into Equation 3 from Equation 4 we have:

$$\frac{Z_n}{Z_{n-1}} = Z_1^{s^{(n-1)}} \tag{5}$$

The solution of this equation will provide the dimensions of the work-piece in any desired section, and will thus define the required geometry of the pass.

The constant s can take any positive number. If s = 1, a uniform rate will be expected, if s > 1 or s < 1 accelerated or decelerated rates will be obtained, respectively. The choice of the mode of the rate will depend on the severity of the operation.

If the initial and final radii (R_o and R_f) of work-piece are known, considering the homogeneous deformation in the extrusion of rod, we can find [2]:

$$R_n = R_0 C^{1+s+s^2+\ldots+s^{n-1}} \tag{6}$$

where, C- is the amount of deformation in the first divided section.

The selection of s will leave the choice of N (the total number of divisions) and C to the judgment of the designer. On the basis of experience, Blazynski [12] suggested C=0.992, s=0.8 for decelerated, s=1 for the uniform, and s=1.2 for the accelerated rates of deformation in wire drawing, irrespective of N. N, s, and C are interdependent. Figure 6-a shows the dependence of s on C with different number of divisions and the variation of s with C for different extrusion ratios is given in Figure 6-b. Again, it can be seen from these figures that the optimum value of C is about 0.99 and that of s lies in the range of 0.8 to 1.3.

It is clear from Equation 6 that the die length is not a restrictive parameter in the design and can be selected with considering other aspects. However, if the selected number of divisions exceeds a certain limit, it is seen from Figure 6-a that the higher degrees of accelerated deformation rates will not be possible.

For design purposes, if the diameters D_o and D_f are known, a rational selection of s and N can lead

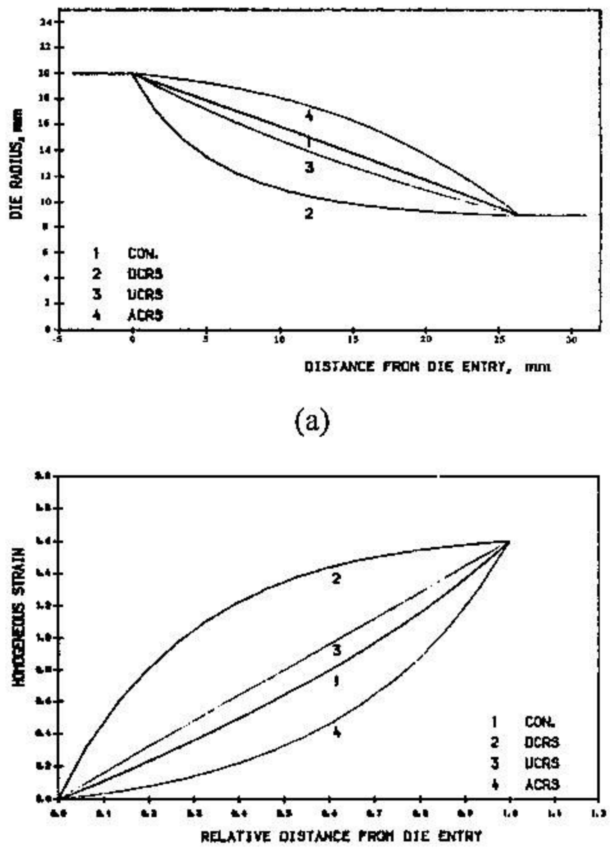


Figure 7. C.R.S. die, (a) die profile and (b) strain path.

to the calculation of the factor C from Equation 6. Typical die profiles for N = 15, s = 0.8, 1, and 1.2, with R_o/R_f = 20/9 are shown in Figure 7-a. In this figure, the conical die profile is abbreviated to CON., the accelerated profile to A.C.R.S, the decelerated one to D.C.R.S. and the uniform profile to U.C.R.S. The strain paths of these dies are illustrated in Figure 7-b. By changing the constant s, different strain paths can be obtained.

As can be noticed from Figure 7-b, strain paths are dissimilar for different dies. Consequently, the quality and the mechanical properties of the product will vary widely. In the D.C.R.S. die the strain rate is considerably high at the beginning and is negligible at the end. This trend allows the material to recrystallize within the deformation zone. By contrast, in A.C.R.S. die the strain rate is negligible at first and is noticeable towards the end. This may result in the strain hardening of the material within the die. In U.C.R.S. die a uniform strain rate is obtained.

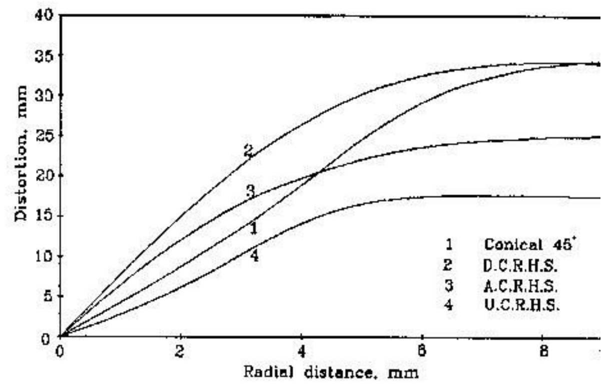


Figure 8. Distortion of plane layers in C.R.S. and Conica dies.

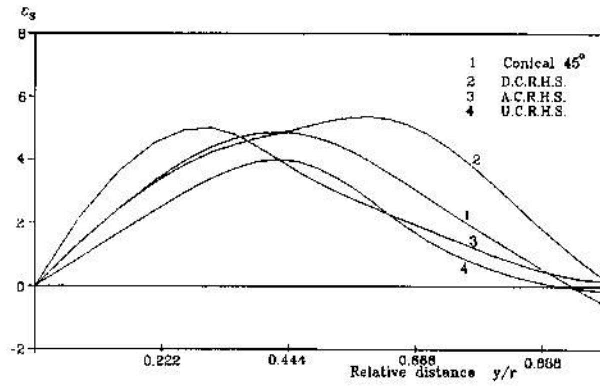


Figure 9. Distribution of shearing strain in C.R.S. and Conica dies.

Experiments on C.R.S. dies were conductec using a kind of industrial wax as model material The observations agree very well with expecte results. In the conical dies the extrusion ratio, di length, and contact area is not independent of eac other. For this reason, it was impossible to stud the effect of any of these variables in the absenc of the others.

Unlike the conical dies, the parameters are mor controllable in tools with the C.R.S. concept. Th die geometry dictates the mode of variation o strain and strain rate. It also determines the contac length and should control the material flow, b dominating the frictional effect. These governin elements are all under control in the C.R.S. dies.

The distortion of layers normal to the die axis i illustrated in Figure 8, and the distribution c

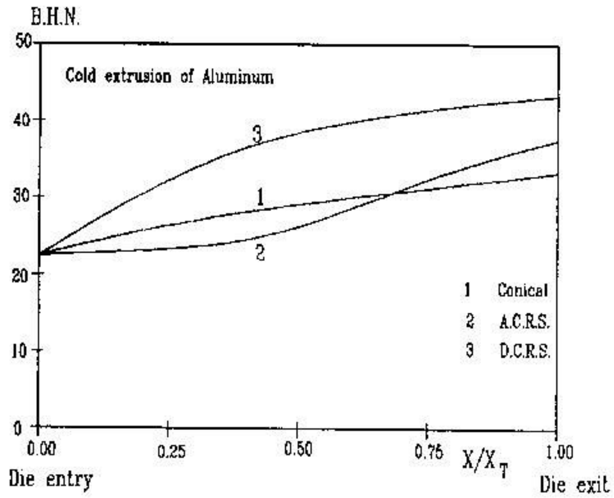


Figure 10. Distribution of hardness along the die pass in cold extrusion of Aluminum.

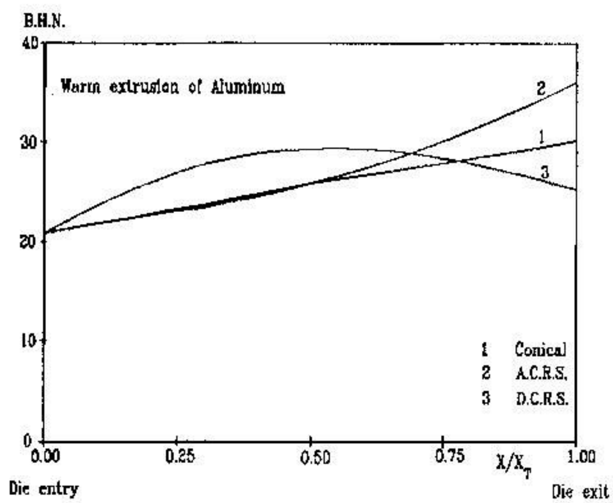


Figure 11. Distribution of hardness along the die pass in warm extrusion of Aluminum.

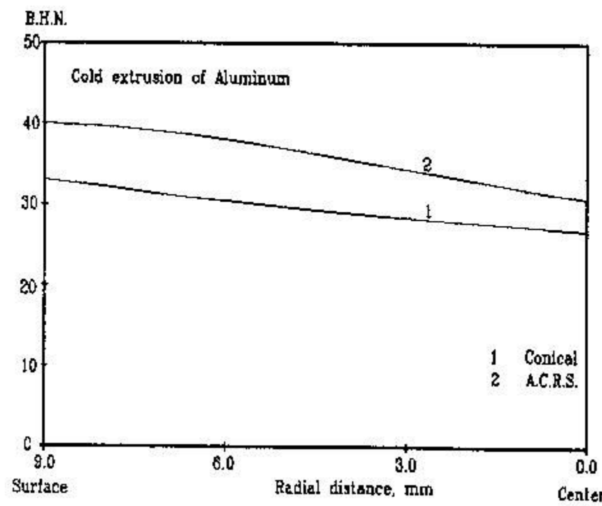


Figure 12. Distribution of hardness along the radius of Aluminum specimens after extrusion.

redundant shearing strains ε_s on the cross-section of rod is shown in Figure 9. This distribution will determine the homogeneity of the product in radial direction. Accordingly, it is expected that the product extruded from each of these dies should have a harder surface and a softer core, which is more significant for A.C.R.S. tools. On the other hand, uniformity of the product will be guaranteed using the U.C.R.S. dies. This theory is also applicable for processes other than extrusion, including drawing, rolling and piercing.

5. FURTHER EXPERIMENTS

Many researchers studied the mechanical properties of materials extruded through conical dies, see for example references [13, 14]. Their findings can be readily interpreted by the above discussion.

Further experiments were conducted using aluminum specimens. The specimens were divided in two groups, one of which were extruded cold and the other were warmed up to 350 °C and extruded through the same dies. Measurements of hardness were made on the deforming part of the specimens, on the cross-sections cut in equal distances along the die length, after cooling the work-pieces. The results are shown in Figures 10 and 11. As can be seen, the strain hardening and recrystallization effects are clearly evident, in accordance with the discussion made for the strain path.

Hardness testing also was made along the radius of the work-piece, on the final products extruded through different dies, shown in Figure 12, which is in close agreement with the work of Osakada and Niimi [13].

6. CONCLUSIONS

Using a rational die design method, such as C.R.S. analysis, it is possible to find any desired tool profile in which the metalworking variables are controllable. It may lead the process to minimize the power consumption, reduce the product defects, increase the tooling life and obtain products with specified mechanical properties. Conversely, when the die profile is obtained, this study enables the prediction of mechanical properties, and metallurgical structure of the product.

7. GENERAL NOTATION

C amount of deformation in the first section
D_f die exit diameter
D_o die entrance diameter
ER extrusion ratio
L_o expected thickness of a layer after extrusion, according to homogeneous deformation
N total number of divisions of die length
n number of considered section of the die
s rate of deformation
w_i relative displacement of two successive elements of a distorted layer
X_T total length of die
ε strain
ε_c circumferential shearing strain
ε_H homogeneous strain
ε_l longitudinal shearing strain
e_T total strain
ε_t tangential strain
ε_s redundant shearing strain

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