

Experimental simulation of intercrystalline sliding and fracture in metals

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SIMPLE experimental two-dimensional models of polycrystalline structure of metals with simulated grain boundaries are deformed plastically in order to investigate the possible effect of the strength of grain boundaries and the intercrystalline sliding and fracture on the behaviour of polycrystalline metals. The grain boundaries are simulated by prepared rows of holes forming a regular array of hexagons in a solid block of a ductile aluminium alloy. The behaviour of the models is compared with the properties of an analogous theoretical model.

Proste dwuwymiarowe modele symulujące polikrystaliczną budowę metali poddano próbie ściskania w celu zbadania możliwego wpływu wytrzymałości granic ziaren oraz poślizgów i pęknięcia międzykrystalicznego na zachowanie się metali o strukturze polikrystalicznej. Granice ziaren w modelach są symulowane przez rzędy otworów tworzących w próbce wykonanej z ciągliwego stopu aluminium regularny układ sześciokątnych bloków. Zachowanie się tych modeli porównano z własnościami analogicznego modelu teoretycznego.

Простые двумерные модели, имитирующие поликристаллическое строение металлов, подвергнуты испытанию сжатия с целью исследования возможного влияния прочности границ зерен, а также скольжений и межкристаллического разрушения на поведение металлов с поликристаллической структурой. Границы зерен в моделях имитируются рядами отверстий, образующих в образце, изготовленном из тягучего сплава алюминия, регулярную систему шестиугольных блоков. Поведение этих моделей сравнено со свойствами аналогичной теоретической модели.

1. Introduction

THE MECHANISM of intergranular sliding and fracture has been widely discussed in papers devoted to the creep phenomenon in metals (see [1, 2]). It is observed, however, (see for example [3]) that in some alloys at certain conditions the generation of grain boundary cavities is connected with the plastic strain and not necessarily with creep deformation. For example, intergranular fracture has been observed in wolfram tested under simple tension at the temperature of 2200°C [4]. It is well known that in some polycrystalline ordered alloys fracture is intergranular [5]. The grain boundaries being discordant provide the easier fracture path. Also the vacuum melted iron can exhibit intergranular brittleness at low temperatures [6].

In order to obtain a deeper insight into the mechanics of intergranular internal fracture and the plastic deformation of the polycrystalline aggregate due to the grain boundary sliding, in the previous works [7, 8] two-dimensional idealized theoretical and experimental mechanical models of the structure of polycrystalline metals were considered.

The present work is mainly devoted to a more extensive experimental study of the behaviour of idealized models of the structure of metals. In these models the grain boundaries are simulated by means of prepared rows of holes forming the hexagonal array

of quasi-grains. In order to simulate grain boundaries of different strengths the specimens were prepared in such a manner that the ratio of the diameter of holes to the spacing between the mwas different in the consecutive specimens of each series. Moreover, in order to study the influence of the orientation of grain boundaries with respect to the direction of the loading force, the rows of holes were prepared at three different angles of inclination to the edges of specimens.

Specimens prepared in this manner allow us to study the possible role of intercrystalline sliding and fracture in the phenomena of softening and hardening of metals undergoing plastic deformation. It is observed that the models with the weak simulated grain boundaries display remarkably unstable behaviour of the force-deformation diagram. These instabilities in the form of sudden drops of the compressive force followed by the recovery of the carrying capacity are caused by the decohesion process along these rows of holes which are inclined at a small angle to the direction of the compressive force. It is interesting to notice that such unstable behaviour is also predicted by a simple idealized theoretical model of polycrystalline metals discussed at the end of the paper.

2. Specimens and experimental technique

Altogether seven specimens were prepared from a rolled bar 14 mm thick of a ductile AlMg2 aluminium alloy (alloy PA2N according to Polish standards). Dimensions of specimens are given in millimeters in Fig. 1. The rows of holes form a regular array of

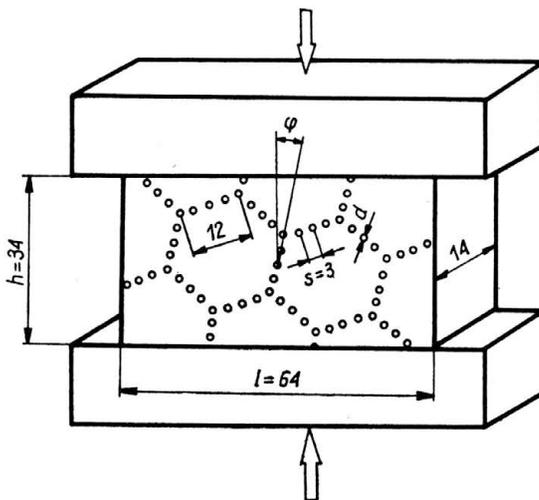


FIG. 1.

hexagons inclined at the angle φ to the vertical axis. The side of each hexagon is equal to 12 mm and is the same in all specimens. Also the spacing s between the holes is the same in all specimens and is equal to 3 mm.

As a preliminary test a specimen with the angle $\varphi = 0^\circ$ was investigated and next two series of specimens each with a different angle φ were tested. In the first series of three specimens the angle φ was equal to 10° and in the second series it was equal to 20° . In

each specimen of the two series the diameters of holes were different and were consecutively equal to $d = 2.0$ mm; 2.3 mm and 2.6 mm. In this manner the “grain boundaries” of various strengths were simulated. Their strength depends on the value of the dimensionless strength parameter ξ defined as the ratio of the ligament width between the holes ($s-d$) to the spacing s . Thus we have

$$(2.1) \quad \xi = \frac{s-d}{s}.$$

For the three chosen values of the diameters of holes the strength parameter in the consecutive specimens of each of the two main series takes the values $\xi = 0.333$, $\xi = 0.233$ and $\xi = 0.133$, respectively.

All specimens were compressed uniaxially as shown in Fig. 1 on the Instron testing machine with the conventional strain rate of the order of $-5 \cdot 10^{-4} \text{ s}^{-1}$ (the conventional strain was defined as $\varepsilon = \Delta h/h$ — see Fig. 1). For each test the force-displacement Δh diagram was recorded. In order to minimize the friction on the contact surfaces, a thin teflon sheet was placed between the specimen and the compressing plates.

3. Experimental results

Figure 2 presents the deformed specimen used for the preliminary test. In this case the angle φ was equal to zero and the “grain boundary” strength factor $\xi = 0.200$. The

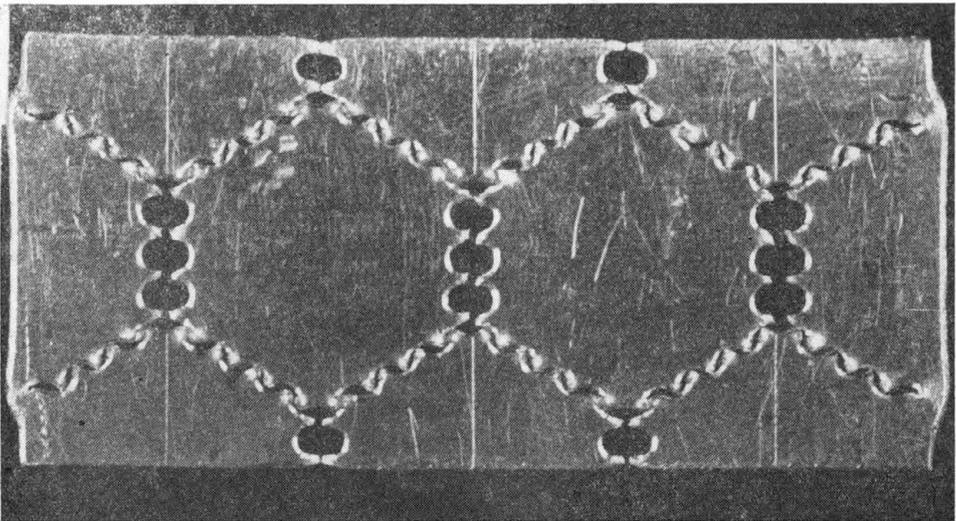


FIG. 2.

specimen was deformed up to the permanent conventional strain in the vertical direction $\varepsilon_p = -0.103$. Total separation of ligaments between the holes in vertical rows is clearly visible. There is no such decohesion along the inclined rows of holes where only strong shear deformation simulating grain boundary sliding is observed.

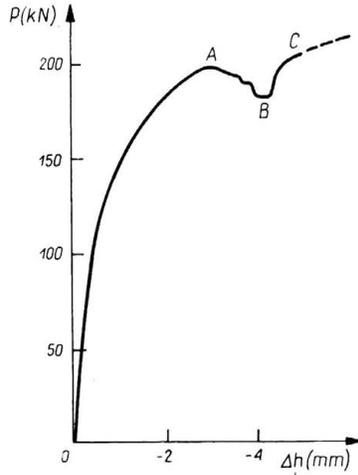


FIG. 3.

In the force-displacement diagram shown in Fig. 3, there appears clearly visible instability between the points *A* and *B*. This instability is connected with the process of decohesion along the vertical rows of holes. After total separation along the vertical rows the compressive force increases. This must be attributed to the hardening effect along the inclined rows of holes caused by the complex process of shearing along them.

This simple test was treated as a preliminary one. A more extensive experimental study is presented below for specimens with the inclination angle $\varphi = 10^\circ$ and $\varphi = 20^\circ$ and various values of the strength parameter ξ .

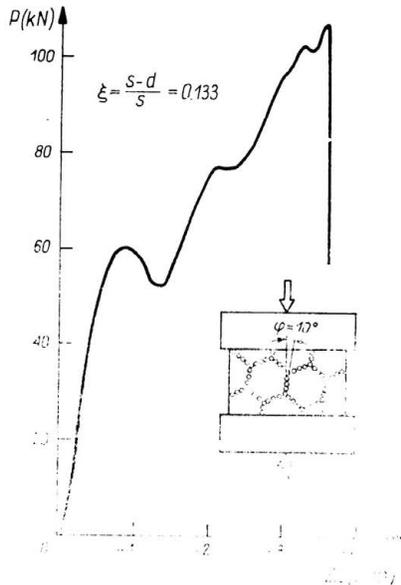


FIG. 4.

Figure 4 presents the force-displacement diagram for the first specimen of the set of specimens characterized by the angle of inclination $\varphi = 10^\circ$. The “grain boundary” strength parameter of this specimen is $\xi = 0.133$. Thus the simulated boundary between adjacent hexagons was rather weak. The strongly unstable behaviour of the model during the compression test is clearly visible. These instabilities are connected with the progressing process of decohesion along the rows of holes inclined at the angle $\varphi = 10^\circ$ to the direction of the compressive force. The phenomenon of decohesion along these rows of holes was observed during the test. Figure 5 presents the specimen deformed plastically up to the

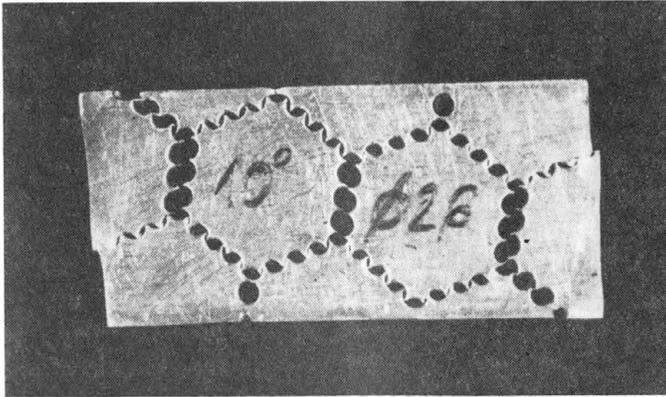


FIG. 5.

end point of the compression diagram shown in the previous figure. Along the “grain boundaries” more inclined to the direction of compression we observe the quasi-sliding. Along the “boundaries” inclined at the angle $\varphi = 10^\circ$ very advanced separation of the adjacent hexagons takes place.

Each step in the force-displacement diagram corresponds to the separation process along the consecutive rows of holes inclined at the angle $\varphi = 10^\circ$ to the direction of compression. The separation does not occur at the same time for all three rows because the two outer hexagonal blocks can move in the lateral direction in a much easier way than the two central blocks. After each step in the force-deformation diagram the compressive force increases. This may be attributed to the hardening effect on the sliding surfaces between blocks connected with the complex process of plastic deformation taking place there. In the next section we will show that a simple theoretical model very close to the experimental models discussed here also displays unstable behaviour in the initial part of the deformation process.

Similar unstable behaviour has been observed for the specimen with slightly stronger “grain boundaries” with the strength parameter $\xi = 0.233$. Remarkable drops of the compressive force can be seen in the initial portion of the compression diagram (Fig. 6). These drops of the force are followed by the increase of the compressive force due to the hardening on the sliding surfaces. Also the deformation mode of the present specimen (Fig. 7) is similar to that of the previous specimen with the weaker “grain boundaries”.

It is interesting to notice that for still stronger “grain boundaries” the behaviour of our experimental models is completely different. Practically there is no instability in the

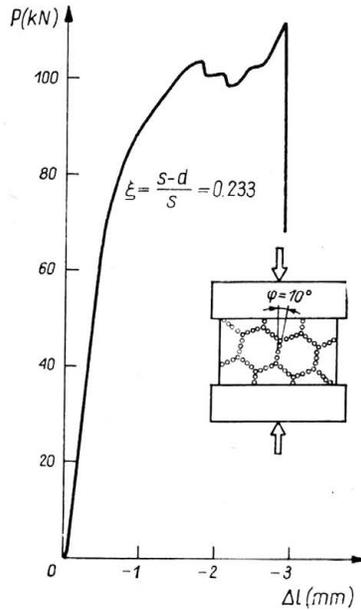


FIG. 6

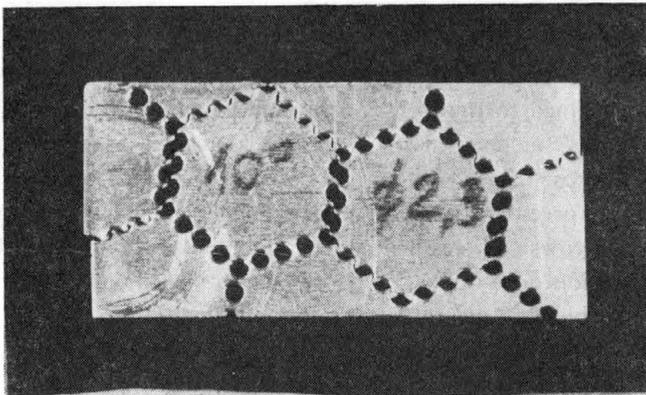


FIG. 7.

force-displacement diagram shown in Fig. 8. This diagram was obtained for the specimen with the “grain boundary” strength parameter $\xi = 0.333$. Thus this simple experiment indicates how strongly the behaviour of real technical polycrystalline metals may depend on the strength of the grain boundaries.

The strong influence of the strength factor ξ of the rows of holes separating hexagonal blocks in the tested experimental models has been confirmed by the next series of compression tests with the use of specimens characterized by the inclination angle $\varphi = 20^\circ$.

Very strongly marked instability is observed in the behaviour of the specimen with the weak “grain boundaries” characterized by the strength parameter $\xi = 0.133$ (Fig. 9). This specimen behaves similarly to the specimen with the angle $\varphi = 10^\circ$ and the same

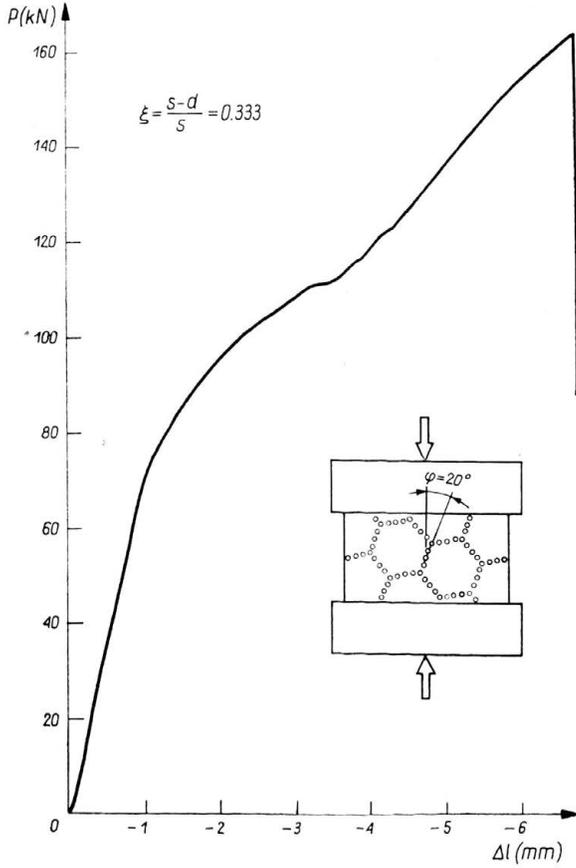


FIG. 8.

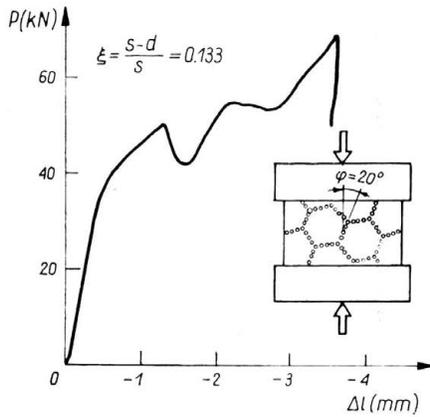


FIG. 9.

strength factor $\xi = 0.133$ (compare Fig. 4). Also the deformation mode (Fig. 10) corresponding to the end point of the compression diagram is similar to the one in the previous case (Fig. 5).

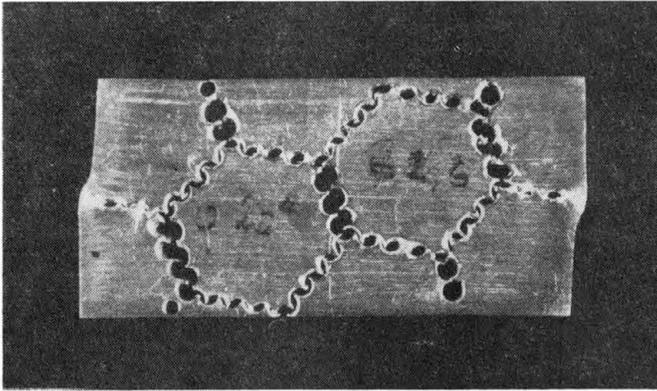


FIG. 10.

The next specimen with the “grain boundary” strength parameter $\xi = 0.233$ displays unstable behaviour during the initial period of the compression test (Fig. 11). Also in this case fracture takes place along the rows of holes slightly inclined to the direction of the compressive force (Fig. 12).

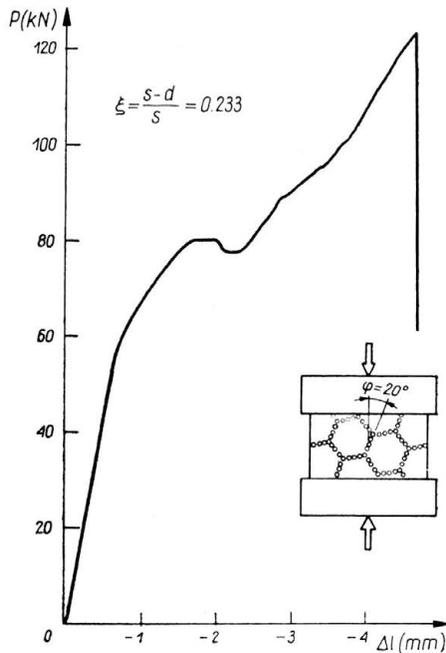


FIG. 11.

No instability is observed in the behaviour of specimens with a still larger strength parameter $\xi = 0.333$ (Fig. 13). In this case there is no separation along the rows of holes slightly inclined to the direction of compression even for the conventional permanent strain in the direction of compression as large as $\varepsilon_p = -0.197$. This is clearly seen in

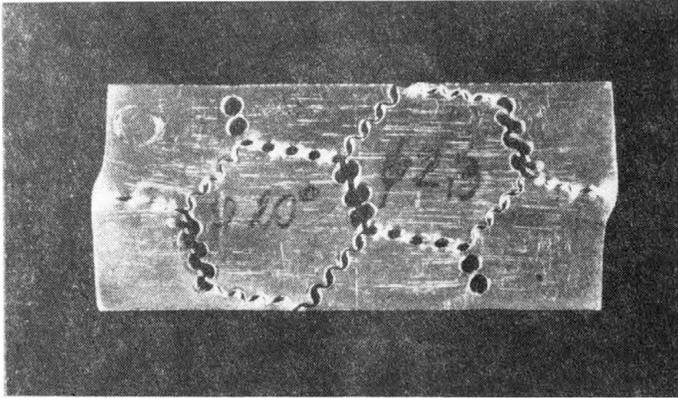


FIG. 12.

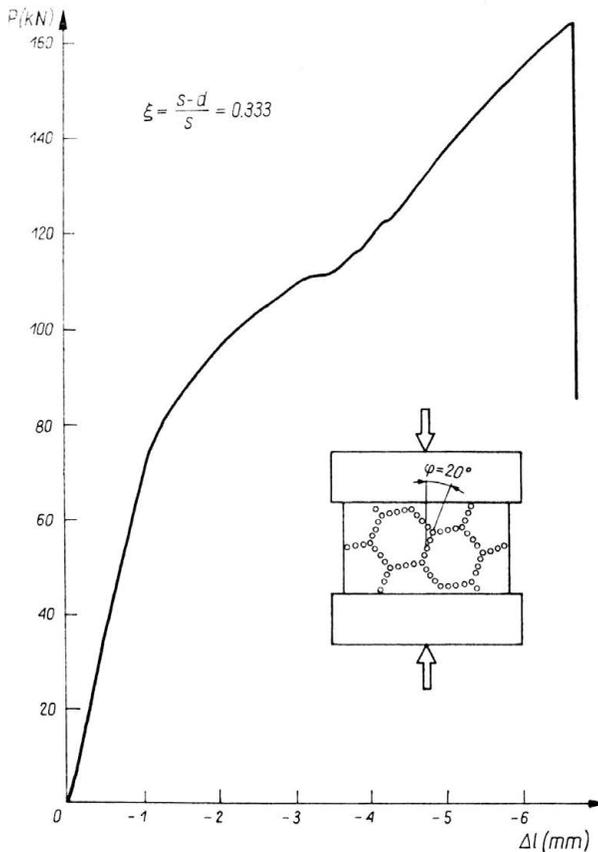


FIG. 13.

Fig. 14 in which the deformed specimen is shown. Note that in this case the hexagonal “grains” have been themselves considerably deformed plastically. Let us notice that one of the previous specimens shown in Fig. 10 in which total separation along the mentioned

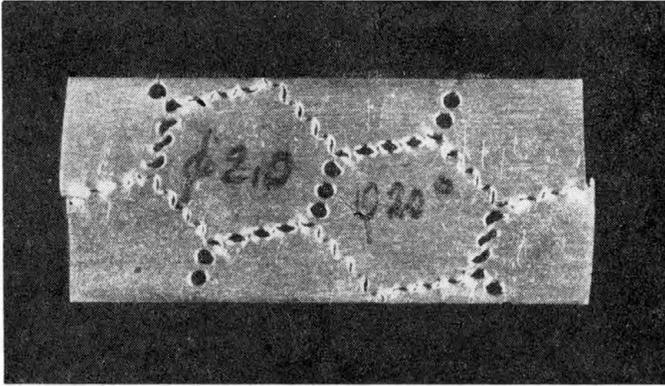


FIG. 14.

rows of holes takes place has been compressed until the permanent strain $\varepsilon_p = -0.138$, that is considerably less than the specimen under consideration. These simple experiments were performed in order to demonstrate that the strength of grain boundaries may play an important role in the deformation and internal fracture processes of polycrystalline metals.

4. Simple theoretical analysis

In order to explain the unstable behaviour of our experimental models, a simple theoretical structural model composed of n rigid regular hexagons in horizontal rows and m hexagons in vertical rows as shown in Fig. 15a was considered in the previous work

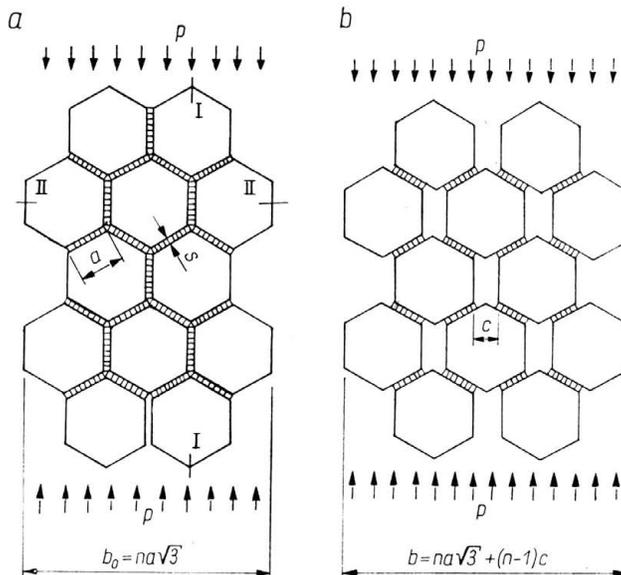


FIG. 15.

[7]. Such a configuration of the model corresponds to the particular case of the inclination angle $\varphi = 0^\circ$. The hexagons simulating grains in a polycrystalline structure of metals are assumed to be joined together by thin layers of the thickness s simulating the grain boundaries. In this model the hexagons are assumed to be rigid. Thus our model may be used for simulation of the behaviour of materials with weak grain boundaries. In order to make this paper sufficiently self-contained the properties of this model will be shortly analysed here for the particular case of uniaxial compression corresponding to the loading used in the experimental part of the paper.

Let us note that similar theoretical models of polycrystalline structure were considered in several works, for example by DYSON [9] and KELLY [10], in the analysis of the growth of grain boundary cavities during creep. A similar model was used by DRUCKER [11] for the analysis of the strength of sintered carbides.

The hexagons in the model are taken as rigid. The ratio s/a is assumed to be small. The material of the layers between hexagons is taken as rigid-plastic with strain hardening. Figure 16 presents the configuration of four hexagons after a certain amount of deforma-

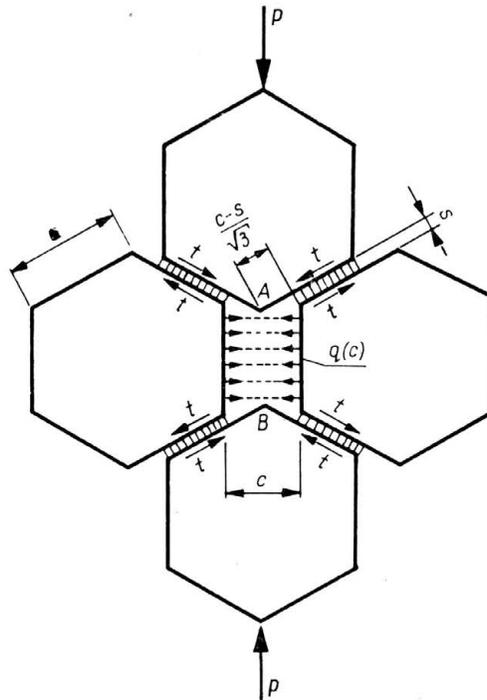


FIG. 16.

tion defined by the distance c between vertical edges ($c > s$). Let us assume that in each layer between the hexagons there exists a system of voids or cracks perpendicular to the respective edge of the hexagon. Thus the layer may be treated as a system of individual elements of limited strength in tension. Therefore the stress $q(c)$ along the boundary AB may be taken as uniformly distributed up to the limit value c_0 of the distance c between

the edges of the hexagons by which the cohesion forces decrease to zero. This means that $q(c_0) = 0$ and moreover, that $q(c = s) = q_0$.

Let us assume a linear strain hardening relation between the shear stress t on the inclined surfaces of hexagons and the average conventional strain ε of the entire aggregate of hexagons in the lateral direction. Thus we may write

$$(4.1) \quad t = t_0(1 + r\varepsilon),$$

where r is the strain hardening factor and

$$\varepsilon = \frac{c-s}{s+a\sqrt{3}}.$$

Writing the equation of virtual work for small deformations ($s < c < c_0$), we arrive at the following relation between the compressive unit load p and the lateral strain ε

$$(4.2) \quad pn(m-1) = [m(n-2) + (m-1)(n-1)]q(c) + \frac{4}{\sqrt{3}}(m-1)(n-1)(1+r\varepsilon)(1-\varepsilon)t_0.$$

The cohesion force per unit length $q(c)$ along AB changes its value from q_0 at the beginning of the deformation process ($c = s$) to zero for $c = c_0$. Thus the first member of the right hand side of the yield condition (4.2) changes its value from

$$[m(n-2) + (m-1)(n-1)]q_0$$

for $c = s$ to zero for $c = c_0$.

Our theoretical model displays, therefore, the phenomenon of the upper and lower yield point in the initial stage of the deformation process. This is shown in Fig. 17 in which the diagram compressive stress versus lateral strain of the aggregate is presented.

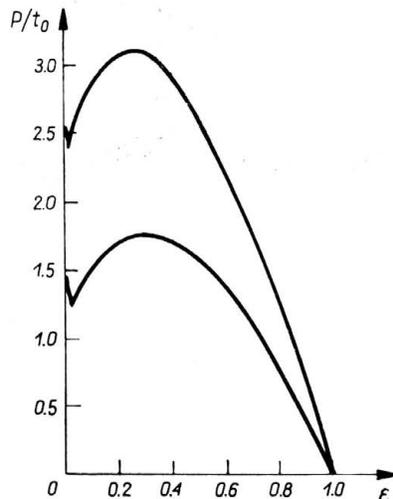


FIG. 17.

For the advanced stage of deformation the first member of the right hand side of the condition (4.2) vanishes and we obtain the following relation between the compressive stress p and the lateral conventional strain ε :

$$(4.3) \quad p = \frac{4}{\sqrt{3}} \frac{n-1}{n+(n-1)\varepsilon} (1+r\varepsilon)(1-\varepsilon)t_0.$$

This relation is graphically represented in Fig. 17 for the particular value of the strain hardening factor $r = 5$ and for two values of n , namely for $n = 2$ and $n = \infty$, respectively. These stress-strain diagrams display two kinds of instability. At the beginning there appears a remarkable sudden decrease in stresses connected with the decohesion process along the vertical boundaries between hexagons. This initial unstable behaviour of the model has been discussed above. It corresponds closely to the unstable behaviour of experimental models investigated in the previous section.

The second type of instability appearing in the advanced stage of deformation results from the reduction of the contact area along the inclined boundaries where sliding takes place. The physical significance of this second type of instability seems to be doubtful. It should be rather treated as the property of our idealized theoretical model without connection with the phenomena taking place in real polycrystalline metals.

Comparing the initial parts of the theoretical stress-strain diagrams with the force-displacement diagrams obtained for the experimental models and presented in the previous section, we see that the two models, the theoretical and experimental one, predict unstable behaviour at the beginning of the deformation process followed by the recovery of the carrying capacity due to the strain hardening on the sliding grain boundary surfaces.

The condition (4.3) and Fig. 17 show how strongly the yield stress in our theoretical model depends on the number n of hexagons in horizontal rows. This problem was discussed in detail in the previous paper [7]. However, in the present work this phenomenon has not been investigated experimentally.

5. Conclusions

Basic continuum concepts concerning plastic deformation of metals accompanied by progressing microfracture have been in numerous works analysed at the level of the microstructure of the material. The simple two-dimensional experimental models investigated in the present paper have been used in an attempt to demonstrate the possible role of intercrystalline fracture and grain boundary sliding. These models display unstable behaviour during the incipient plastic flow connected with the fracture along certain "grain boundaries". A strong influence of the "grain boundary" strength on the behaviour of the model has been observed.

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