Grain boundary sliding of copper in the rolling process

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SUMMARY

In the case of severe wear of copper rubbing against SAE 1045 steel it has been assumed that grain boundary sliding as well as sliding in the grains may be an essential deformation mechanism. This assumption has been verified in heavily cold rolled copper by means of grain thickness measurements using the linear intercept method.

1. INTRODUCTION

With the energy balance of the severe wear process of the sliding couple oxygen free, high conductivity (OFHC) copper against steel SAE 1045, it was shown\(^1\) that in addition to sliding within grains another deformation mechanism must be present, otherwise the geometric form of the worn material would not be possible. The mechanism responsible for this phenomenon, viz. grain boundary sliding, is known and may occur in creep\(^2\). However in creep, deformation and deformation rates are small compared to those in wear.

The object of this investigation was to show that grain boundary sliding may also occur with large deformation and deformation rates (compared with the creep process) and may assume high values. For the investigation, a deformation process was chosen (viz. rolling) which is accompanied by great deformation, and, which offered the possibility of separating unequivocally the two deformation mechanisms. Besides macroscopic deformation determined from test-piece dimensions before and after test, the process allows the determination of both sliding in the grains and in the grain boundaries by means of grain thickness measurements. Such measurements require to be carried out by an indirect technique, viz. the linear intercept method. In this method, lines are drawn on a photomicrograph of an etched cross-section of the material. The chords cut off by these lines from 2 successive grain boundaries appear to be representative of the grain thickness of the material. This method is elucidated below for a random grain form.

2. THE INFLUENCE OF THE ROLLING PROCESS ON THE DISTRIBUTION OF CHORD WIDTHS

In a real metal grains of various forms and thicknesses are present, and
by applying to these an infinite number of equidistant parallel lines, the distribution of frequencies of the linear intercepts is representative of the metal testpiece considered.

Consider, before the rolling process from this distribution of frequencies a random chord of length $C_{ib}$. The lines from which the chords originate are chosen at right angles to the rolling plane. If the chord length after the rolling process is $C_{ie}$, then, if only shear occurs in the crystals:

$$\rac{C_{ib}}{C_{ie}} = \frac{d_b}{d_e}$$

where $d_b$ is the initial thickness of the testpiece, and $d_e$ the thickness after rolling.

It is assumed that a two-dimensional deformation condition occurs in which deformation parallel to the axis of the rolls equals zero (in practice, it appears to be negligibly small) and that deformation is homogeneous (this applies to thin strips as used here). The mean thickness of chords may generally be said to be

$$\bar{C} = \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} C_i$$

From eqns. (1) and (2) it follows for the mean thickness of chords after rolling:

$$\bar{C}_e = \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} C_{ie} = \frac{d_e}{d_b} \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} C_{ib} = \frac{d_e}{d_b} \bar{C}_b$$

Assuming in the case of copper that the distribution of the linear intercepts is represented by a log normal distribution\(^3\), (proved below), then the mean $\mu_e$ of this log normal distribution is

$$\mu_e = \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} \log C_{ie}$$

Substituting eqn. (1) in eqn. (4) yields

$$\mu_e = \log \frac{d_e}{d_b} + \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} \log C_{ib}$$

Using

$$\mu_b = \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} \log C_{ib}$$

eqn. (5) becomes

$$\mu_e = \log \frac{d_e}{d_b} + \mu_b$$

The standard deviation $\sigma_e$ after rolling now becomes:

$$\sigma_e = \lim_{n \to \infty} \left( \frac{1}{n-1} \sum_{i=1}^{n} \{\log C_{ie} - \mu_e\}^2 \right)^{1/2}$$

With eqns. (1) and (7), eqn. (8) now becomes

$$\sigma_e = \lim_{n \to \infty} \left( \frac{1}{n-1} \sum_{i=1}^{n} \{\log C_{ib} - \mu_b\}^2 \right)^{1/2} = \sigma_b$$
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where $\sigma_b$ represents the standard deviation of the log normal distribution of the linear intercepts before rolling. From eqn. (9) it follows that the standard deviation of the log normal distribution of chords remains unchanged during rolling. Formulae (1) to (9) apply strictly when only shear occurs in the grains.

3. PREPARATION OF TESTPIECE AND EXPERIMENT

Before rolling, OFHC copper rods, $150 \times 30 \times 20$ mm were annealed in a vacuum of approx. $10^{-5}$ torr for 3 h at 750°C to remove residual stresses cold rolling-generated during manufacture and to impart a uniform initial structure. The annealed copper was rolled in a simple Bühler two-high mill (rolls of 160 mm diam). After a certain number of reductions, pieces were cut from the material for comparison with the initial material to determine the degree of deformation, grain thickness, hardness and tensile strength. Cooling between every two rolling runs prevented the materials from becoming more than hand-hot.

In order to determine the chord length, a silver–carbon WO$_3$ replica was made of a polished and etched cross-section at right angles to the rolling plane and the direction of rolling of the test piece. The grain structure was recorded photographically by means of an electron microscope (Fig. 1) as the resolution of the light microscope was too low. In these pictures each time one line was drawn (at right angles to the rolling plane), the distance between two successive points of intersection of line and grain boundary supplied one of the chords. Hardness and tensile tests were carried out within 48 h after the rolling process, the material being kept in a deep-freezer as long as practicable during this time to prevent a too rapid recovery. The Vickers microhardness measurements were carried out on a Leitz Durimet and the pressure was 0.25 N. The tensile tests were performed on a Hounsfield tensometer using flat tensile test bars.

4. RESULTS AND DISCUSSION

4.1.

If it is assumed that only sliding in the grains occurs, then, because $C_b$ and $d_b$ are constant for one particular initial material, eqn. (3) becomes

$$\frac{C_e}{d_e} = \frac{C_b}{d_b} = \text{constant}$$

(10)

This means that the ratio $(C_e/d_e)$ is independent of the reduction in thickness $(-d_b/d_e)$. In Fig. 2 this relation is represented by a line $a$. If on the other hand, it is assumed that only sliding at the grain boundaries occurs, i.e. that the grain thickness remains constant, in other words that $C_e$ is constant, then one may write for $C_e$

$$C_e = C_b$$

(11)

Using logarithms for eqn. (11) we obtain, after reduction,

$$\log \frac{C_e}{d_e} = \log \frac{d_b}{d_e} + \log \frac{C_b}{d_b}$$

(12)

where $\log \frac{C_b}{d_b} = \text{constant}$. 
Relation (12) represents a straight line in the \((\log C_e/d_e, \log d_b/d_e)\) co-ordinate system with slope 1. In Fig. 2 this relation is represented by line b. Plotting in Fig. 2 the values determined experimentally results in curve c which up to a reduction in thickness of approx. 10 corresponds with line a, i.e. sliding in the grains, but which, above this reduction has the shape of the straight line b, i.e. sliding at the grain boundaries. The regression analysis of the second part of curve c does not, as follows from eqn. (12), result in a directional coefficient equal to 1 but to 0.86. Thus in this area sliding at the grain boundaries does not occur exclusively. It follows from curve c that the transition from sliding in the grain to grain boundary sliding takes place gradually.

4.2.

If one applies a cartesian co-ordinate system in such a way that the \(x\)-axis is in the direction of rolling, the \(y\)-axis in the rolling plane and at right angles to the direction of rolling, and the \(z\)-axis perpendicular to the rolling plane, then
from the experimental datum deformation parallel to the rolls is negligibly small, i.e. a two dimensional deformation condition prevails
\[ d\delta_y = 0 \] (13)

From the constancy of volume in the case of plastic deformation
\[ d\delta_x + d\delta_y + d\delta_z = 0 \] (14)

it follows, with eqn. (13), that
\[ d\delta_x = -d\delta_z \] (15)

Using the definition of effective incremental deformation
\[ d\delta = \frac{1}{\sqrt{3}} (d\delta_x - d\delta_y)^2 + (d\delta_y - d\delta_z)^2 + (d\delta_z - d\delta_x)^2) \] (16)

it follows, with eqn. (12) and after integration and considering the boundary condition, that
\[ \delta = \frac{2}{\sqrt{3}} \ln \frac{d_b}{d_e} \] (17)

Fig. 2. The theoretical and experimental relationship between the relative mean chord and the reduction in thickness of rolled copper, both for shearing along and across the crystals.

Fig. 3. Experimental relationship between Vickers hardness and effective deformation after rolling of copper.

Figure 3 shows that starting from a particular effective deformation, hardness assumes a constant value indicative of a new process. A similar hardness effect has been found for other copper test pieces.

4.3.

The determination of the yield point (=effective stress= \( \bar{\sigma} \)) after various
Fig. 4. Experimental relationship between effective stress and effective deformation after rolling of copper.

Fig. 5. Histograms of the chord width and corresponding relative cumulative frequency diagrams of the chord width for certain rolling reductions.

degrees of rolling (to be transformed into an effective deformation via eqn. (17) by means of the tensile test) produced a relation as illustrated in Fig. 4. Tensile test bars of material subjected to a high reduction in thickness, broke before plastic deformation was observed. At these degrees of rolling the maximum stress perpendicular to the fracture face was taken as the effective stress, also when the frac-
ture face was not perpendicular to the axis of the test bar. The effective stress at higher deformation ($\delta > 2.3$) remains constant and the hardness in this area does not appear to increase (Fig. 4). This complies with the work of Ramaekers\textsuperscript{5}. A deviation between the $\bar{\sigma} - \delta$ and the $\delta$-H.V. curve lies in the $\bar{\sigma} - \delta$ curve if $\delta = 2.3$. Figure 2 shows that this point lies in the transition area of shearing in the grains and shearing along the grain boundaries. Probably this transition is the cause of the deviation. A similar deviation has been reported\textsuperscript{6}.

4.4.

It was assumed that in the case of copper the distribution of the length of chords may be represented by a log normal distribution. To verify this, in Fig. 5 the $x$-axis and the $y$-axis have been so transformed that each log normal distribution produces a straight line (logarithmic probability scale). Plotting (a) the distribution of the length of chords of the initial material and various random reductions in thickness (viz. 5 and 20) in the scale mentioned, as well as (b) the histograms belonging to these distributions provided Fig. 5. A regression analysis of the straight lines of Fig. 5 gave correlation coefficients of 0.982, 0.997 and 0.998. From which it may be concluded that the assumption made earlier was

| TABLE 1 |
| SEVERAL MEASUREMENTS AS A FUNCTION OF DEFORMATION DURING ROLLING |
| $d_{e}$ [mm] | $\delta$ [N/mm\textsuperscript{2}] | $\bar{\sigma}$ [N/mm\textsuperscript{2}] | H.V. | $C_{e}$ [$10^{-3}$ mm] | $\sigma_{e}$ | number of measurements |
| Series I |
| 20 | 0 | — | 71 | 14.5 | 0.41 | 121 |
| 8.007 | 1.05 | 342 | 116 | 4.6 | 0.36 | 118 |
| 4.035 | 1.84 | 404 | 125 | 2.1 | 0.31 | 161 |
| 2.047 | 2.62 | 462 | 119 | 1.5 | 0.28 | 122 |
| 1.050 | 3.39 | 423 | 128 | 1.2 | 0.29 | 164 |
| 0.507 | 4.23 | 413 | 121 | 0.5 | 0.21 | 191 |
| 0.239 | 5.06 | 414 | 127 | 0.48 | 0.25 | 93 |
| 0.124 | 5.87 | 418 | 124 | 0.53 | 0.25 | 99 |
| 0.067 | 6.56 | 422 | 124 | 0.38 | 0.24 | 143 |
| 0.029 | 7.5 | — | 122 | 0.35 | 0.21 | 104 |
| Series II |
| 5.03 | 1.59 | 388 | 122 | 2.4 | 0.29 | 93 |
| 4.00 | 1.86 | 396 | 126 | 2.1 | 0.27 | 137 |
| 3.001 | 2.19 | 413 | 123 | 1.3 | 0.22 | 160 |
| 2.025 | 2.65 | 462 | 123 | 1.0 | 0.20 | 165 |
| 1.032 | 3.42 | 395 | 122 | 1.0 | 0.20 | 87 |
| 0.502 | 4.24 | 413 | 126 | 0.63 | 0.19 | 157 |
| 0.266 | 4.96 | 401 | 127 | 0.70 | 0.20 | 70 |
| 0.135 | 5.75 | 402 | 126 | 0.51 | 0.20 | 114 |
| 0.065 | 6.56 | 390 | 126 | 0.44 | 0.21 | 137 |
| 0.050 | 6.9 | 397 | 125 | 0.46 | 0.17 | 92 |
| 0.0273 | 7.6 | — | 122 | 0.39 | 0.16 | 374 |
justified. Figure 5 also shows that the standard deviation $\sigma_e$ (proportional to the directional coefficient of the straight lines) of the log normal distribution decreases with increasing degree of rolling (Table I). This phenomenon is in contradiction with eqn. (9), i.e. this cannot be caused by shearing in the grains. It can be only explained if the big grains undergo a larger reduction in thickness than the small ones. Assuming the coherence of the material to remain unchanged, the greater reduction is only possible if the small grains undergo grain boundary sliding.

CONCLUSIONS

(1) Analogous to creep, grain boundary sliding can also take place by relatively high deformation rates and relatively low temperatures.

(2) During large deformation the relative decrease in thickness of large grains is much larger than that of small grains.

(3) The assumption, that grain boundary sliding can occur during severe wear, has been confirmed.

REFERENCES