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Surface Roughness Caused by Metal Forming

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There is a direct effect of the surface roughness on the functionality and quality of produced parts. Hence it appears that an improved control of surface roughness as it arises from forming operations must be considered to be of great importance. It is generally known that the roughness in a free surface due to plastic deformation of the substrate depends on grain size, effective deformation, initial roughness and anisotropy.
This paper deals with the influence of the stress state or more specifically the each to each proportion of the principal stresses. The basic assumption for modelling is that surface roughness is caused by grains or parts of grains being sheared or pushed out of the surface. With elements form plasticity theory and the Taylor model for metal deformation can this shear be estimated in its ratio to the total amount of deformation. As a consequence roughness can be derived as a function of deformation. The model was tested for different stress states. Experimental results support the model.

INTRODUCTION.

It is well known that deformation of a free surface causes surface roughness[1-6]. This is one of the main variables which governs the true contact area between tool and workpiece in dry or lubricated contact. Its control and predictability are important for the functionality, costs and quality of produced parts. In the sheet metal forming industry, for example, a high value could cause problems in lacquering, a low value could indicate that the quality of the workpiece (material) and the costs are too high. The more so as we know that about half of the costs of mass produced parts are brought in by the material. An overview of literature in this field is given by Thomson and Nayak [4]. Summarizing, it can be said [1-6] that surface roughness depends on the:

- grain diameter of the workpiece material,
- effective deformation,
- initial roughness of the workpiece material,
- anisotropy [5].

It has been reported in a former publication [7], that it is also influenced by the state of stress. In this contribution a general model is developed. It is based on the assumption that roughness is due to the shear in the planes of maximum shear stress. This assumption covers the real physical surface behaviour, which consists of different shear directions scattering around 45° degrees with the surface [8,9]. The model leads to a relation between a roughness parameter and the ratio of the principal stresses in the surface. For a representation of the surface roughness the standardized roughness parameter R_a is used [10]. The theory has been tested for two plain carbon steels under different stress conditions. Experiments have been carried out with tensile, torsion, stretch and bulge tests. Experimental results appeared to be in agreement with theory.

MODEL.

Figure 1 represents an element of a free surface with Cartesian co-ordinates for the principal stress directions.

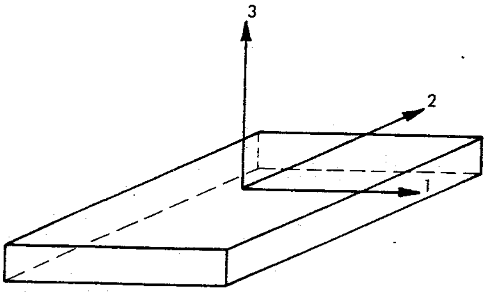

Fig. 1. Part of a free surface with Cartesian co-ordinates.

Axes 1 and 2 are in and axis 3 is perpendicular to the free surface, so $\sigma_{33}=0$.
Further it is assumed that the roughness is proportional to the maximum shear strain out of the surface [7].
The stress components parallel to the surface are:

$$\sigma_{11}=x \quad \text{and} \quad \sigma_{22}=ax \tag{1}$$

where $\sigma_{22} \leq \sigma_{11}$, so

$$-1 \leq a \leq 1 \tag{2}$$

The Levy von Mises relations for the principal directions may now be written as

$$\begin{aligned} d\varepsilon_{11} &= d\lambda\left(\sigma_{11}-\frac{\sigma_{22}}{2}\right) \\ d\varepsilon_{22} &= d\lambda\left(\sigma_{22}-\frac{\sigma_{11}}{2}\right) \\ d\varepsilon_{33} &= d\lambda\left(-\frac{\sigma_{11}+\sigma_{22}}{2}\right), \end{aligned} \tag{3}$$

with $d\lambda$ is an instantaneous non-negative constant of proportionality which may vary and $d\varepsilon_{jj}$ are the incremental strain components.

The definition for the incremental effective strain is:

$$d\bar{\varepsilon} = \sqrt{\frac{2}{3}\left(d\varepsilon_{11}^2+d\varepsilon_{22}^2+d\varepsilon_{33}^2\right)} \tag{4}$$

In general it holds for the maximum shear strains:

$$\begin{aligned} d\varepsilon_{12} &= \frac{d\varepsilon_{11}-d\varepsilon_{22}}{2} \\ d\varepsilon_{31} &= \frac{d\varepsilon_{33}-d\varepsilon_{11}}{2} \\ d\varepsilon_{23} &= \frac{d\varepsilon_{22}-d\varepsilon_{33}}{2} \end{aligned} \tag{5}$$

Combination of Eqs. 1 - 5 gives:

$$\begin{aligned} d\varepsilon_{12} &= \frac{3}{4}\frac{a-1}{\sqrt{a^2-a+1}}\,d\bar{\varepsilon} \\ d\varepsilon_{31} &= \frac{3}{4}\frac{1}{\sqrt{a^2-a+1}}\,d\bar{\varepsilon} \\ d\varepsilon_{23} &= -\frac{3}{4}\frac{a}{\sqrt{a^2-a+1}}\,d\bar{\varepsilon} \end{aligned} \tag{6}$$

According to the assumption it holds for the roughness Δx

$$\Delta x \sim \text{maximum of } \left|\frac{d\varepsilon_{31}}{d\bar{\varepsilon}}\right| \text{ and } \left|\frac{d\varepsilon_{23}}{d\bar{\varepsilon}}\right| \tag{7}$$

Figure 2 shows the values at the right as a function of the principal stress ratio a.
Some characteristic points are:

$a = -1$; this means $\sigma_{11} = -\sigma_{22}$ → torsion test
$a = 0$; this means $\sigma_{22} = 0$; $\sigma_{11} \neq 0$ → tensile test
$a = 1$; this means $\sigma_{11} = \sigma_{22}$ → bulge test

The relation between the ratio of the incremental principal strains and a is given in Fig. 3.

EXPERIMENTAL PROCEDURE.

Two test materials were used:

1) Plain carbon steel sheet (Werkstoffnr.1.0330) [7]. It was used for the bulge test (Fig. 4).

The effective deformation measured in the top of the bulge is given by:

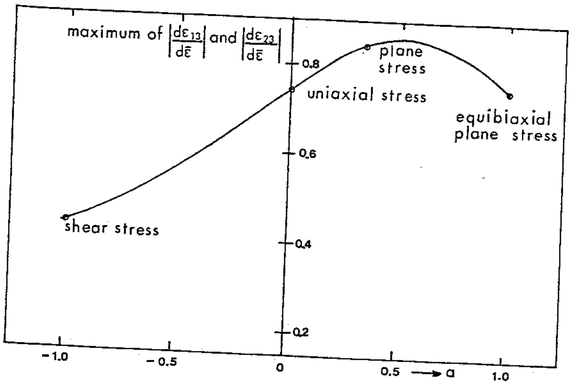

Fig. 2. The ratio of the maximum shear strain out of the surface and the effective strain as a function of the principal stress ratio.

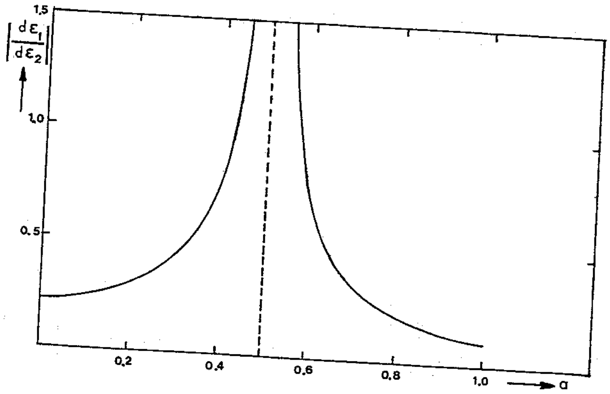

Fig. 3. The relation between the ratio of the incremental principal strains and stress ratio a.

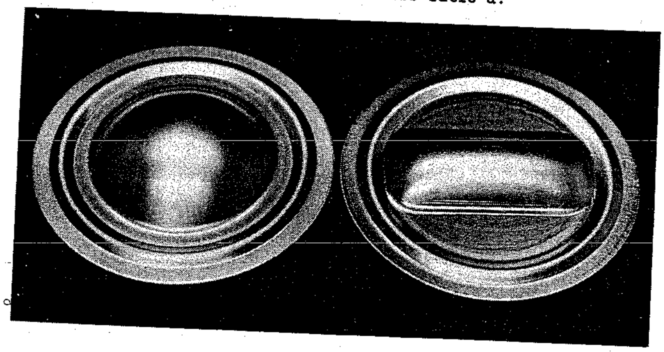

Fig. 4. Testpieces from the stretch and bulge test.

$$\bar{\varepsilon} = \ln \frac{t_o}{t} \tag{8}$$

with t_o = initial thickness
t = final thickness.

On the same material also tensile tests are carried out. Untill necking the effective deformation is

$$\bar{\varepsilon} = 2 \ln \frac{t_o}{t} \tag{9}$$

After prestraining ($\bar{\varepsilon}_o \approx 0.1$) the same material has been used for the stretch test (Fig. 4). This shape provides a value of a between 0 and 1 in Figure 2. The effective deformation is determined by the change of the dimensions of a marked circle on the top of the bulge. Tensile tests are carried out for the same material. For the bulge tests etc. a hydraulic test machine and blanks of 100 mm diameter have been used.

2) Plain carbon steel bar (Werkstoffnr.1.0036) [7]. This material was used in the torsion and tensile tests. The effective deformation in the surface of the torsion test piece is:

$$\bar{\varepsilon} = \frac{n \pi d}{l\sqrt{3}} \tag{10}$$

where n = the number of revolutions for the marked measuring length
d = the diameter of the test bar
l = the measuring length.

The effective deformation in the tensile bar can again be determined by Eq.(9) if it is replaced by d.
The roughness measurements are made with a Rank-Taylor Hobson apparatus [10] and are represented by the roughness parameter R_a. The measuring length was 3.8 mm . The signal was filtered by a double R-C filter. All the measurements are performed with the same tip and tip velocity. The roughness measurements have been carried out for different deformation levels of every test piece and five at a time. In order to get an impression of the scatter of the values mean and variance have been computed. The deformation rates have been kept equally as well as possible. The number of specimens for every test was 5.

RESULTS.

The curves in figures 5-8 have been determined by linear regression of the experimental results.

- Figure 5 presents the mean and variance of the roughness parameter R_a as a function of the effective deformation for the tensile and torsion tests. The roughness cut-off lengths were chosen parallel to the testpiece axes. According to our model represented in Fig. 2 and Eq.(7) the results for these two stress conditions are obviously different.
- Figure 6 shows analogous results for the bulge and tensile tests. The roughness of the bulge has been measured on the top in arbitrary directions. On the tensile test pieces the cut-off length was taken parallel to the tensile axis. Equal results were acquired in accordance with Fig. 2 and Eq.(7).
- The workpiece material of Fig. 7 had a strain history with $\bar{\varepsilon} \approx 0.1$. The roughness measurements were carried out 5 times in each of two perpendicular directions: for the tensile testpieces parallel and perpendicular to the tensile axis; for the bulge testpieces in two arbitrary perpendicular directions on the top of the bulge.

The mean and variance of these 10 $R_a$measurements are represented as a function of the additional effective deformation for both of the tests. Again the results appear to be in agreement with the model: all test results can be represented rather well by one curve.

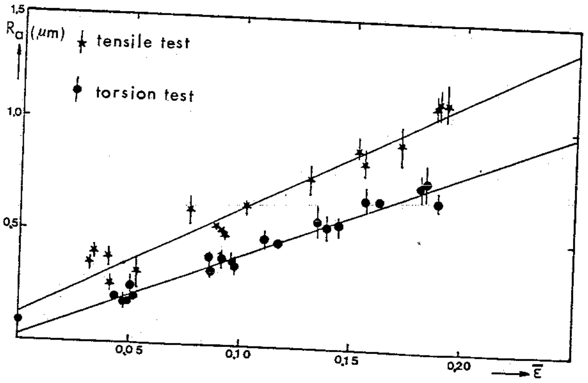

Fig. 5. The mean and variance of the roughness parameter $R_a$as a function of the effective deformation for the tensile and torsion tests.

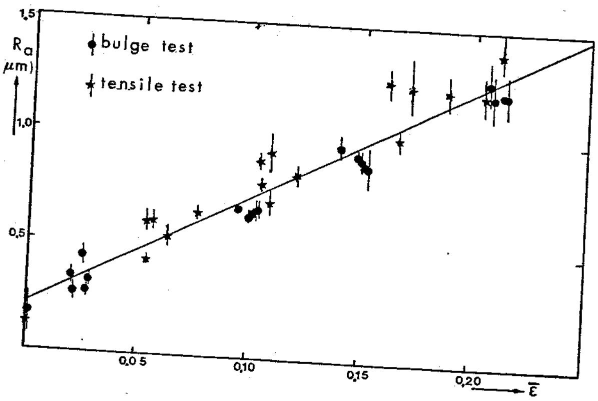

Fig. 6. The mean and variance of the roughness parameter R_a as a function of the effective deformation for the bulge and tensile tests.

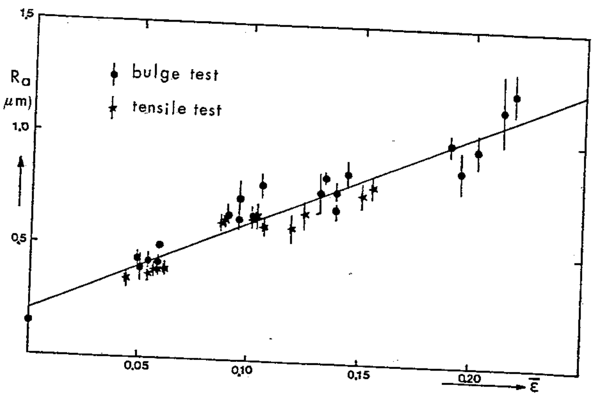

Fig. 7. The mean and variance of the roughness parameter R_a as a function of the additional effective deformation for tensile and bulge tests. The workpiece material had a predeformation $\bar{\varepsilon}_o \approx 0.1$.

- The same workpiece material and roughness measurement method have also been used for the experiments represented in Fig.8. It shows the mean and variance of R_a as a function of the additional effective deformation in the tensile and stretch tests. The value of a for the stretch tests varied for the incremental steps from 0.1 to 0.55. By accounting only for the begin - and end deformation the value is between 0.33 to 0.36. According to Fig. 4 and Eq.(7) the difference between both curves should not be too large. An objective method to prove whether the experimental results should be represented by two curves instead of one can be found in comparing the correlation coefficients for both cases. For the two separate curves it is 0.91 and 0.95; for one combined curve it is 0.87. It seems to be in agreement with the model.

The correlation coefficient for every curve in Figs. 5-8 is better than 0.93.

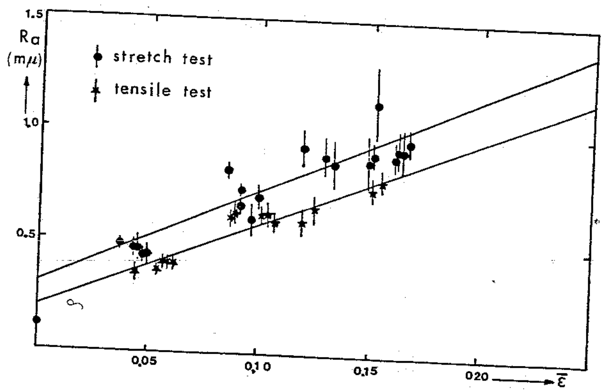

Fig. 8. The mean and variance of the roughness parameter R_a as a function of the additional effective deformation for tensile and stretch tests. The workpiece material had a prestrain $\bar{\varepsilon}_o \approx 0.1$.

DISCUSSION and CONCLUSIONS

- The experimental results obviously support the theory rather well. Nevertheless more experimental results are necessary, especially for additional metals.
- In agreement with plasticity theory it was assumed that the deformation takes place by shear in the planes of maximum shear stress. From a metallurgical point of view this means that the nearest closed packed planes provide for shear by means of dislocation glide. With the Taylor theory [9,10] it has already been proven that, for grains inside the material, these planes contribute for more than 80% to the deformation. The remaining 20% takes place in other planes. In the Taylor theory these planes are chosen on the basis of an energy criterion. Inside the material this is necessary in order to maintain the continuity of the material. This condition is absent for the surface grains. Thus according to expectations more than 80% takes place in the planes or neighbouring planes of maximum shear stress. These deviations together with those in the roughness measurements are responsible for experimental difference with the theoretical values as derived from Fig. 2. However, the agreement is quite satisfactory for the time being.
- Calculation of Δx on the base of initial and final dimensions only of the stretch test is not correct. The correct but time consuming way would be to follow the infinitesimal steps. However the difference between both methods is limited and doesn't influence the final results substantially.

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