Fracture 1977, Volume 3, ICF4, Waterloo, Canada, June 19 - 24, 1977

FRACTURE MECHANICAL ASPECTS OF ABRASIVE FRICTION, WEAR, AND CHIP FORMATION OF A γ-Fe-Ni-Al STEEL

K-H. Zum Gahr*

INTRODUCTION

The removal of matter by the formation of chips can be intended (cutting) or unintended (wear). Abrasion occurs if a material A is scratched by a much harder material B. Depending on the acute angle of the hard particle the material A is ploughed or chips are removed. If A slides across B a friction force originates that is composed of an adhesive term and a term caused by plastic deformation of A. If the energy absorbed by plastic deformation is large the adhesive term can be neglected. This is to be expected if a very tough material is scratched by hard ceramic particles. It is generally accepted, that hardness is a very important material property that affects friction and wear because it controls the actual surface area of contact [1-3]. However, additional mechanical or microstructural properties such as the nature of precipitation particles can have an effect of friction and wear as it was shown for an Al-4 wt % Cu alloy [2]. It is known from recent investigations [4,5] that localized slip in cystallites and the ductility of the environment of grain boundaries affect the fracture toughness of rather ductile alloys. As initiation and growth of cracks limit the energy absorbed in friction and determine the rate of wear it is likely that a correlation exists between these properties and fracture toughness. In this work a precipitation hardening stainless steel was used for which a larger number of microstructures can be produced. The mechanical properties including fracture toughness are already known [5]. The friction coefficient, cutting force, and wear rate were investigated in order to find out whether and under which conditions there is evidence for a correlation with fracture toughness.

EXPERIMENTAL METHODS

An experimental austenitic steel of Fe-36 At.-% Ni- 12 At.-% Al alloy (analysis in wt %: 0.005 C, 38.61 Ni, 5.80 Al, rest Fe) with an initial grain size of 165 µm was exposed to various thermal and thermomechanical treatments. These produce several microstructures which have been described in detail already [5,6] (Table 1). Friction was measured on electropolished surfaces with an angular diamond (α = 120°, load P = 1,5 N) and on ground surfaces of 22 x 17 mm^2 (load 8 N) as well as with SiC grinding paper (particle size 52 µm). The specific cutting forces with turning could be determined by strain gauges at the sintered hard metal tool. This tool was cooled by cutting lubricant during the experiment to avoid local heating. The wear rate was measured with cylindrical specimens (6 mm diameter, P = 8 N) on SiC-paper as it is used for the friction experiments. All experiments were conducted in labor-

---

*Ruhr-Universität, Bochum, Institut fur Werkstoffe, D-4630 Bochum, West Germany.

atory air at 26 - 35 % rel. humidity and 23 - 35°C. Figure 1 shows schematically the experimental methods.

RESULTS AND DISCUSSION

In Table 1 the heat treatments, microstructural characteristics and mechanical properties are summarized. SEM- and TEM-investigations indicated that in alloys with coherent particles that are cut by dislocations, ploughing by the diamond produces high slip steps in the deformed zone. Incoherent particles are cut by the diamond and no slip steps are visible in this homogeneously deforming condition. Figure 2 shows the chip formation by the scratch diamond. The coefficient of friction of two different microstructures ground with SiC-paper at 8 N is shown in Figure 3 as a function of sliding distance. Depending on the microstructure the alloy shows a different work hardening behaviour, however, about the same hardness. In microstructure G dislocations are forced by-pass precipitate particles while in C coherent particles are sheared. This leads to the formation of dislocation pile-ups and to a higher work hardening coefficient at large strains in microstructure C. Consequently the friction coefficient shows its steady state value for microstructure G while it is still increasing for C. In any case a different friction behaviour is found for the two microstructures in spite of equal hardness. It is likely that the friction coefficient is affected depending on whether deformation alone or deformation and fracture takes place during rubbing. Therefore an attempt will be made to correlate the abrasive friction force P_f with the crack extension force G if adhesion can be neglected:

$$G = \frac{P_f}{B} \tag{1}$$

B is the width of cut (Figure 1), which is related to the hardness H of the cut material and the normal force P and a dimensionless constant C_1:

$$B^2 = C_1 \cdot \frac{P}{H} \tag{2}$$

Equation (2) substituted into (1) leads to a relation between frictional force and crack extension force:

$$P_f = C_2 \cdot \sqrt{\frac{P}{H}} \cdot G \tag{3}$$

which in turn can be expressed as relation between friction coefficient $\mu = P_f/P$ and fracture toughness $K_c = \sqrt{GE}$:

$$\mu = C_2 \cdot K_c^2 \cdot E^{-1} (P.H)^{-1/2} \tag{4}$$

Equation (4) describes the friction caused by one diamond or by a number of abrasive particles that is independent of the external force P and hardness of the worn material. This is not to be expected for grinding paper. If the number of cutting particles is proportional to P and H^{-1} the following relation is to be expected:

$$\mu = C_3 \cdot K_c^2 \cdot E^{-1} . H^{-1} \tag{5}$$

In Figures 4a and 4b friction coefficients for different microstructures are shown which were obtained with a diamond and with grinding paper. In spite of some scatter there is reasonable agreement with the predictions made in equation (4) and (5) if it is remembered that the effect of adhesion is neglected.

For processing of work pieces by cutting the micromechanical process of separation is similar to abrasive friction. The cutting force P_s or the specific cutting force k_s is obtained from equation (1):

$$P_s = C_4 . G . s \tag{6}$$

where s is the feed and a the depth of cut.

$$k_s = P_s (a.s)^{-1} = C_4 . G . a^{-1} = C_4 . K_c^2 (a.E)^{-1} \tag{7}$$

The coefficient of abrasive friction and the specific cutting force should be proportional according to this model:

$$\mu = C_5 . a . k_s . (P.H)^{-1/2} \tag{8}$$

$$\mu = C_6 . a . k_s . H^{-1} \tag{9}$$

This correlation is made in Figure Measurements of friction coefficients are compared with cutting forces obtained for turning with different chip cross sections. The agreement is satisfactory. It is well known that k_s is a function of feed s. This implies that the constants C_5 and C_6 must be functions of the tool feed, tool geometry, and cutting velocity.

It can be expected that the friction coefficient μ and the wear rate $\dot{w}$ of the different microstructures are proportional. Deviations will occur if a change of the microstructure gives rise to a higher or lower ratio of fracture toughness to hardness. Higher fracture toughness leads at the same hardness to a higher friction coefficient and lower wear rate. At present the investigation of the wear behaviour of the different microstructures is in progress.

SUMMARY

The mechanism of chip formation under abrasive conditions has been discussed with its relevance to friction, wear, and cutting. A model is proposed which involves fracture toughness of the worked material. It implies that the energy required to introduce crack growth has to be considered in addition to the area of contact. On this basis the role of microstructure for these phenomenons can be better understood.

ACKNOWLEDGEMENT

I would like to thank Professor Dr. E. Hornbogen for the critical reading of the manuscript.

REFERENCES

1. GODDARD, J. and WILMAN, H., Wear, 5, 1962, 114.
2. LIN, D. S. and WILMAN, H., Wear, 14, 1969, 323.
3. HORNBOGEN, E., Fortschr.-Ber. VDI-Z., 5, 1976, Nr. 24.
4. HAHN, G. T. and ROSENFIELD, A. R., Met. Trans., 6A, 1975, 653.
5. ZUM GAHR, K.H., Arch. Eisenhw., 47, 1976, 507.
6. HORNBOGEN, E., and ZUM GAHR, K. H., Z.Metallkde., 67, 1976, 16.
7. ARCHARD, J. F., J. Appl. Phys., 24, 1953, 981.

Table 1

sample	ageing treatment[1]	precipitation phase and particle size [nm]	HV 30	σ_y MPa	σ_{max} MPa	ε_f %	K_c MPa·m$^{1/2}$
A	--	--	127	239	703	30,0	385
B	80 h at 500°C	spherical, coherent, ordered $\gamma'(Ni_3Al)$; $\gamma' \approx 2,4$	186	360	871	40,0	421
C	7,5 h at 720°C	spherical, coherent, ordered $\gamma'(Ni_3Al)$; $\gamma' \approx 13$	227	422	998	27,6	391
D	75 h at 640°C	spherical, coherent, ordered $\gamma'(Ni_3Al)$; $\gamma' \approx 13,5$	264	580	1072	17,9	269
E	17% cold rolling 192 h at 640°C	spherical, coherent $\gamma' \approx 15,4$ disc-shaped non-coherent $\varepsilon' \approx 30 \times 80$	379	890	1120	4,9	181
F	144 h at 500°C + 48 h at 800°C	rhombical, rod-shaped, non-coherent $\alpha''(FeAl) \approx 770 \times 2400$	188	299	992	29,6	352
G	75 h at 720°C	spherical, coherent $\gamma' \approx 27$; non-coherent, rhombical $\alpha'' \approx 200 \times 750$	241	415	1090	20,0	353
H	17% cold rolling 30 h at 720°C	rhombical, rod-shaped, non-coherent $\alpha''(FeAl) \approx 75 \times 250$	275	506	1147	13,4	341

[1] homogenization before ageing: 10 min at 1300°C, water quenched; HV 30 = Vickers hardness σ_y = yield stress; σ_{max} = true fracture stress; ε_f = true fracture strain; K_c = fracture-toughness (COD, δ_m-measurement)

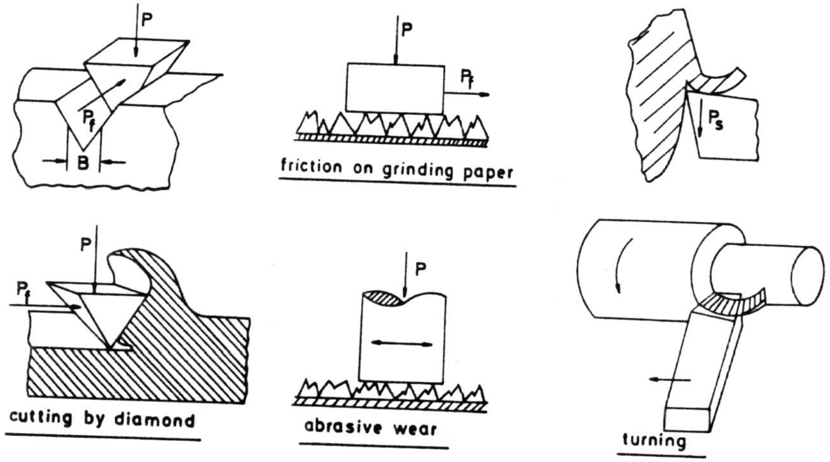


Figure 1 Schematic representation of the experimental methods

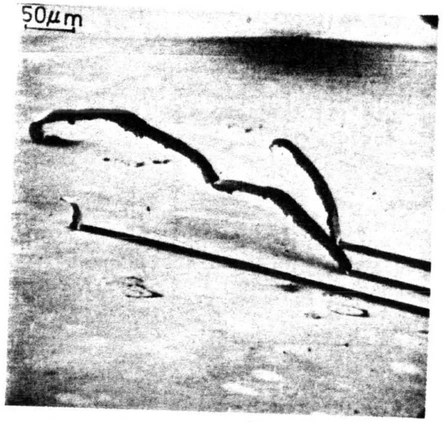


Figure 2 SEM-micrograph of chip formation by a scratch diamond

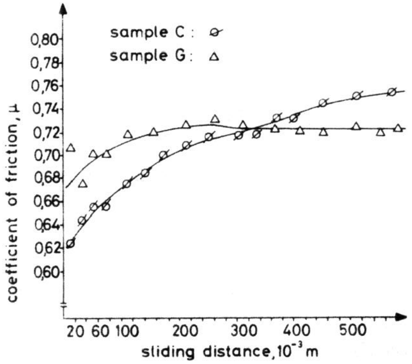
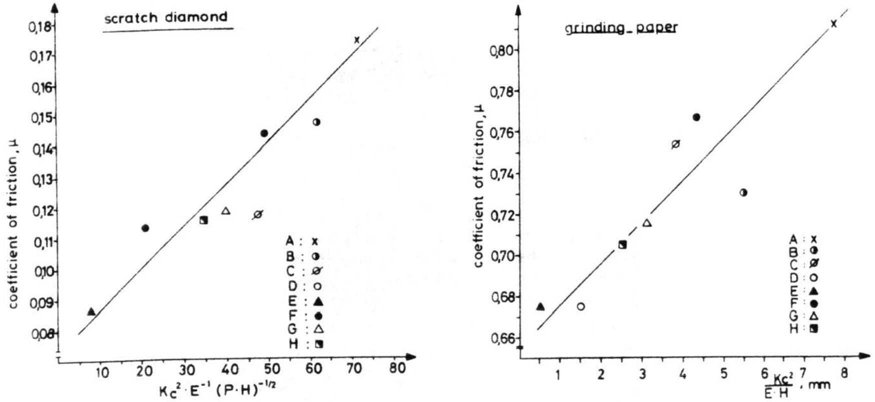


Figure 3 Coefficient of friction as a function of sliding distance of electropolished specimens on grinding paper



a) friction measurements with scratch diamond

b) friction measurements with sliding on SiC-grinding paper

Figure 4 Effect of fracture toughness on the coefficients of friction of different microstructures.

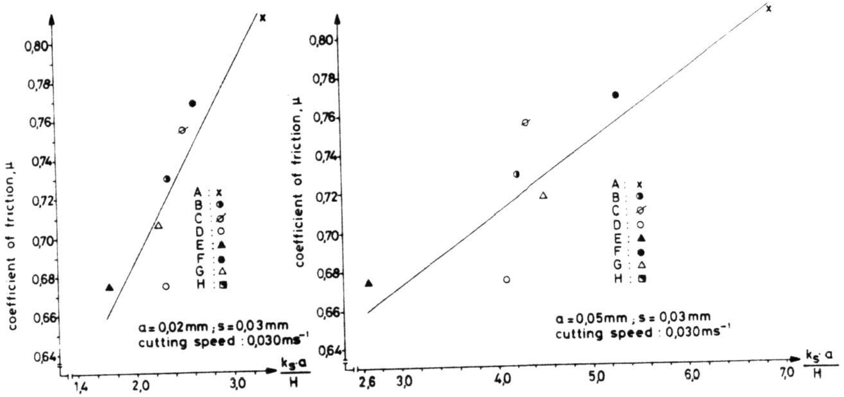


Figure 5 Relation between the coefficient of friction of different microstructures on grinding paper and the specific cutting force k_s measured for turning at two different chip cross-sections