VI. - NEW TECHNOLOGIES AND RELATED TOPICSSCRATCHING AND GRINDING PARAMETERS OF VARIOUS FERRITES

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SCRATCHING AND GRINDING PARAMETERS OF VARIOUS FERRITES

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Résumé. — On décrit des expériences effectuées sur un grand nombre de ferrites cubiques et hexagonaux : rayage par une seule pointe (4-400 μm/s), meulage à vitesse modérée (5 m/s) et meulage à grande vitesse (60-100 m/s).

Les rayures par une seule pointe sont des rainures bien définies à faible charge, s'accompagnant de craquelures et d'écaillures aux charges plus fortes. L'énergie spécifique pour le rainurage est reliée à la dureté Vickers. Dans le cas des expériences de meulage, l'énergie spécifique pour un ferrite hexagonal est en accord avec les résultats du rayage, tandis que le meulage d'un ferrite de nickel à gros grains exige moins d'énergie. Cet effet est relié au phénomène d'écaillage et à l'interaction avec les craquelures des rayures voisines. La vitesse de rotation de la meule n'a pas d'effet prononcé sur l'énergie spécifique.

Abstract. — Experiments on a number of cubic and hexagonal ferrites are described, using single-point scratching (4-400 μm/s), moderate-speed grinding (5 m/s) and high-speed grinding (60-100 m/s). The single-point scratches are well-defined grooves at low loads, with cracking and chipping occurring at higher loads. The specific energy for the groove is related to the Vickers hardness. For the grinding experiments the specific energy for an hexagonal ferrite agrees with the scratching data, whereas for a coarse-grained nickel zinc ferrite grinding needs lower energy. This effect is related to chipping and to interaction with cracks from neighbouring scratches. The wheel speed has no pronounced effect on the specific energy.

1. **Introduction.** — Shaping and surface finishing of ceramic products is a complicated and costly process. Through the use of hard abrasive particles, material is removed at a rate that depends a. o. on the properties of the abrasive and its binder, the speed of the grinding wheel and the hardness of the workpiece [1]. Because many types of machines, binders and abrasive grains are used in grinding, lapping and polishing, a description is needed that can be applied to all practical situations. The various abrasive processes have in common that material is removed (at a rate that can be measured easily) under the action of a mechanical force (measurable in principle). The force acts on both the workpiece and the abrasive grains. Here we are interested in the quantitative relations between removal rate and force on the abrasive particle, leaving aside for the present the problems of sub-surface damage in the workpiece and the wear of the abrasive itself.

A macroscopic description of an abrasive process uses the volume rate of material removal, Z, the speed of the wheel surface, v_s, the normal and tangential components of the force, F_n and F_t and the power W given by $W = F_t\, v_s$. With b_w the width of the contact zone between grinding wheel and the workpiece, one frequently normalises some of the above quantities, e. g. by defining $F_t' = F_t/b_w$. From these quantities, measured for example in a grinding experiment, one obtaines f, the force ratio, given by $f = F_t/F_n$, and e, the specific energy for removal of material, defined by $e = W/Z$. In this paper experimental results of f and e are given, obtained under a variety of circumstances on a number of ferrites ; a wide range of wheel speeds and force levels was investigated using two grinding experiments. A useful quantity for the comparison of different abrasive operations on the same material can be introduced by substituting $F_t\, v_s$ for W in the definition of the specific energy : $e = W/Z = F_t\, v_s/Z \equiv F_t'/h_{eq}$, where $h_{eq} = Z/b_w\, v_s$. This so-called continuum chip thickness [2], h_{eq}, depends only on the machine settings. From h_{eq} one derives d_{av}, the average depth of cut of the abrasive points on a grinding wheel. These quantities are related [3] by

$$d_{av} = h_{eq}^{1/2}(\cot \theta / C\, l_c)^{1/2} . \qquad (1)$$

In this expression scratching points are assumed of pyramidal shape with apex angle $2\,\theta$ and surface concentration C_b ; is the length of the contact zone between wheel and workpiece.

The specific energy, once it has been determined, and the continuum chip thickness, known from the machine settings, give the force value by $F_t' = h_{eq} . e$. This is the resultant of the forces exerted by the abra-

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sive points that are in contact with the workpiece. From the appearance of ground surfaces of brittle materials it is known [4] that both ductile deformation and brittle cracking and chipping occur. These phenomena can be related to the value of the applied force in a detailed study of single-point scratches. This type of experiment allows a controlled environment, a well-defined particle geometry and a given load ; the results can be compared with those of multipoint experiments as grinding by considering again the force ratio and the specific energy, here defined by $e = F_t/A_t$, were A_t is the cross section of the *ductile* groove. By this definition the specific scratching energy is expected to be related to the indentation hardness, e. g. the Vickers hardness measured with a $2\,\theta = 136^o$ pyramid. The groove formation is the most important phenomenon at low loads, but at higher loads first brittle cracking occurs, later also chipping takes place. In grinding the specific energy is expected to be lower because the cracked and thus partly loose zone adjacent to one groove can be removed by a second scratching point at practically no expense of energy. A complete grinding theory therefore considers not only the hardness but also the material parameters that describe fracture [5], e. g. the fracture toughness or the stress intensity factor K.

Experimental data are needed to find the quantitative relation between such material parameters and the macroscopic description of an abrasive process. Especially interesting is the question whether the material behaves differently at the high speeds used in grinding. For this purpose a number of experiments have been done on various cubic and hexagonal ferrites : firstly, low-speed single-point scratching has been studied as a basis for grinding models [6] ; secondly, various materials have been ground [7] at a speed of 5 m/s and thirdly, high-speed grinding experiments at $v_s = 60$ to 100 m/s have been carried out. In all cases the force components F_t and F_n have been measured. In view of the better reproducibility only fixed abrasive particles have been used.

2. **Single-particle scratching.** — Using diamond pyramids (apex angle $2\,\theta = 100^o, 120^o, 136^o$) and a diamond sphere horizontal scratches under a constant load, F_n, have been made on polished samples at a speed of 4 μm/s. The apparatus has been described elsewhere [6]. Typical scratches on a NiZn ferrite are shown in figure 1. For a variety of materials, it has been found that the force ratio f is independent of hardness, load, or microstructure. In good approximation f is determined by the geometry of the diamond used, i. e. $f = \cot\theta$. This f-θ relation implies that the total force on the contact plane between the pyramid and the workpiece is normal to this plane. The small deviations from the above relation are then attributed to the friction at the interface between diamond and workpiece. With a sphere the Coulomb friction was found to be of the order of 0.1, again for a variety

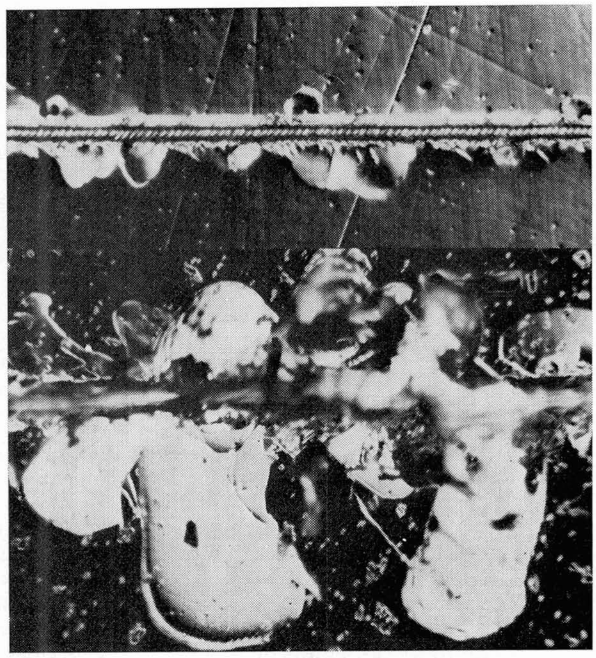

FIG. 1. — Photograph of a $Ni_{0.36}Zn_{0.64}Fe_2O_4$ sample scratched under a load of 10 g and 100 g (width of picture 200 μm).

of materials. From the dimensions of the groove and the tangential force the specific scratching energy is found. For two ferrites figure 2*a* shows that e depends on the depth of penetration of the diamond. Comparison of a number of materials shows a good correlation of e with the Vickers hardness, H_v [6].

Apart from a rather well-defined groove the scratched surface shows cracks and chips (Fig. 1). For a coarse-grained NiZn ferrite c, the extent of cracking varies with load (Fig. 3), approximately as $F_n^{2/3}$, in agreement with Lawn's penny-crack expression [8, 9], $c = F_n^{2/3}/K_e^{2/3}$; the effective stress intensity factor, K_e is estimated at 1×10^6 N/m$^{3/2}$. The $F^{2/3}$ dependence, however, it not always found [6]. Apart from the extent of cracking a scratching experiments gives also the site of cracking, thereby giving information on the weak spots, thus on the strength of the material on a microscopic scale and on the homogeneity.

3. **Measurements of grindability.** — 3.1 $v_s = 5$ m/s. — Cylindrical samples (5-10 mm diameter) with a flat surface were pressed against the flat horizontal surface of a rotating grinding wheel [7]. Two wheels were used, one with electroplated diamonds (100 μm diamonds, volume concentration 37 %) and one with a sintered binder (100 μm diamonds, 10 % concentration). The sample was loaded by placing a weight on top of it (loads between 2 and 4 N were used). The number of active diamonds was found to be about 0.1 per mm^2 sample area, the force per diamond ranges from 0.25 to 2 N for both wheels. The rate of material removal, Z, was measured as well as F_t, the tangential force on the sample. Water cooling was

a

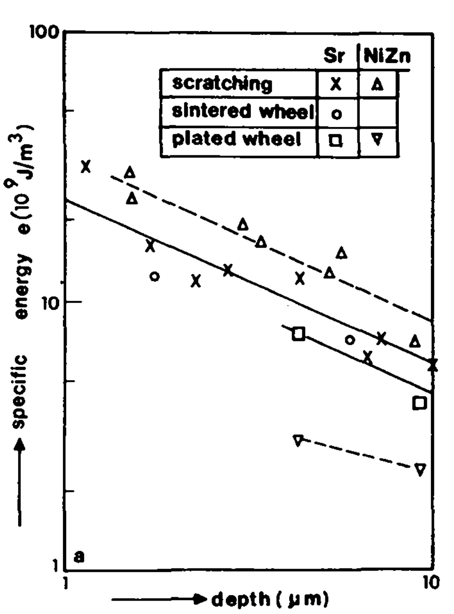

FIG. 2. *a* — Specific energy, e, as a function of scratch depth for $SrFe_{12}O_{19}$ (×) and $Ni_{0.36}Zn_{0.64}Fe_2O_4$ (△). Grinding data from figure 2*b* have been added.

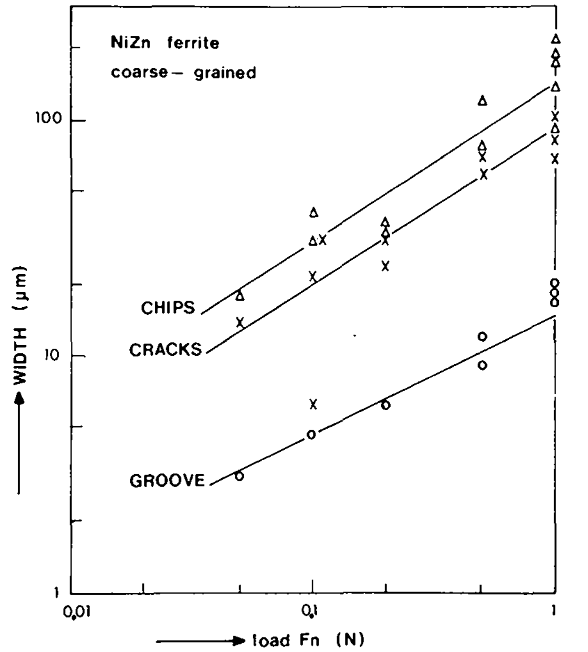

FIG. 3. — Width of groove and the extent of cracking and chipping for a coarse-grained $Ni_{0.36}Zn_{0.64}Fe_2O_4$ (cf. Fig. 1) as a function of load.

b

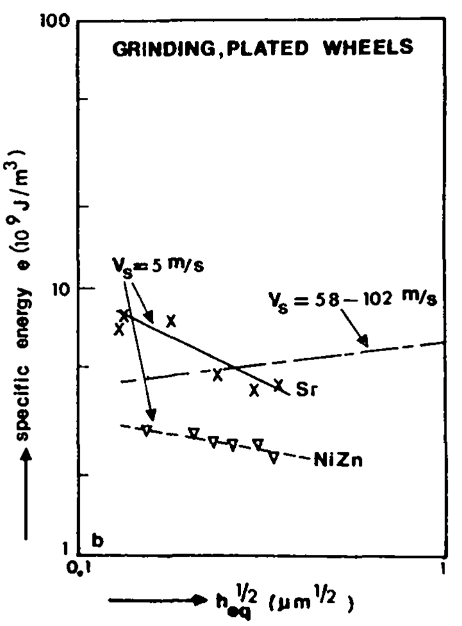

FIG. 2*b*. — Specific energy, *e*, and grinding hardness, H_g, from grinding experiments at 5 m/s and at 60-100 m/s for $SrFe_{12}O_{19}$ and $Ni_{0.36}Zn_{0.64}Fe_2O_4$. Along the abscissa $h_{eq}^{1/2}$ is plotted, which is proportional to the average depth of cut of the diamonds (eq. (1)).

used. The reproducibility improved from ± 200 % to ± 20 % when before each experiment the sintered wheel was dressed with sintered, porous alumina, and when the electroplated wheel was cleaned ultrasonically. Some typical results for F_n vs Z are shown in figure 4 for the sintered wheel for a number of ferrites. The tangential force, F_t, is a linear function of F_n; for both wheels the force ratio is $f = F_t/F_n = 0.3$. The specific energy, $e = Z/F_t\, v_s$, is

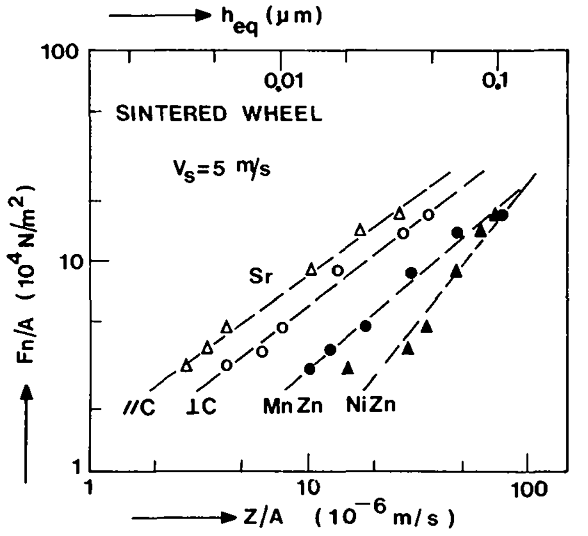

FIG. 4. — Normal force, F_n, versus rate of volume removal, Z. Both quantities are dived by A, the area of the specimen in contact with the grinding wheel. The aligned Sr hexaferrite (grain size 5 μm, porosity 8 %) has been measured in two directions (⊥ c and // c). The MnZn ferrite (p = 8 %) and the NiZn ferrite (p = 0.2 %) have both a grain size of 20 μm.

shown in figure 5 for a number of ferrites as a function of load F_n divided by specimen area, A. For $SrFe_{12}O_{19}$ and $Ni_{0.36}Zn_{0.64}Fe_2O_4$ the specific energy is also

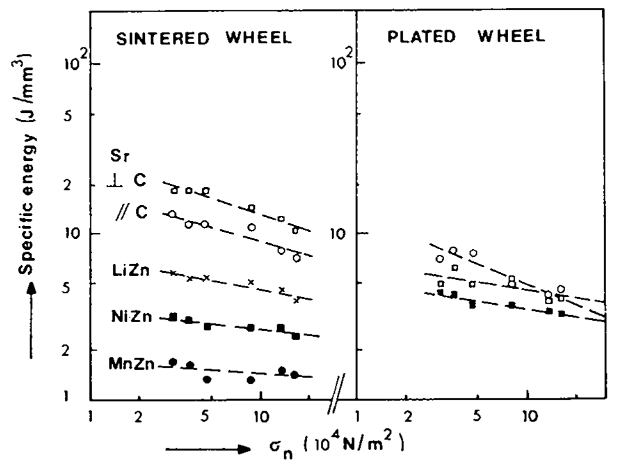

FIG. 5. — Specific energy, e, derived from $e = F_t v_s / Z$, for a number of cubic ferrites (MnZn, NiZn, LiZn) and for an aligned sample of $SrFe_{12}O_{19}$ (both ⊥ c and // c). The data obtained at $v_s = 5$ m/s with the sintered and the plated wheel are shown separately.

given in figure 2*b* where the data is plotted against $h_{eq}^{1/2}$, which, as shown in the introduction, is proportional to the average depth of cut of the diamonds on the grinding wheel.

These results show that, firstly, the two wheels give different results, and, secondly, the specific energy decreases with increase of load, or, which is equivalent, depth of cut. Although the two wheels contain diamonds of the same size, they differ by the material that holds the diamonds, the diamond concentration and the extent of protrusion of the particles. The penetration of the diamonds into the workpiece, d_{av}, can be estimated from eq. (1), using the diamond concentration, the contact length and an estimate of cot θ, for which the experimental value of the force ratio can be taken in view of the scratching results in section 2. The d_{av} values lie in the range between 2 and 18 μm. For the plated wheels this is much less than the protrusion of the diamonds (about 50 % of the size), for the sintered wheels d_{av} comes close to the expected 20 % of the particle size (100 μm). This means that the binder might contact the workpiece and give different results. The e-d_{av} data have been added to figure 2*a* for later comparison with the scratching data. The different e values found at the same load for the two wheels in figure 5 coincide when plotted versus d_{av} for $SrFe_{12}O_{19}$ (Fig. 2*a*). For other ceramic materials [7] the sintered wheel needs more energy at the same d_{av}, which also might be related to the contact between binder and workpiece.

3.2 v_s = 60-100 m/s. — The experiments were carried out on a horizontal axis grinding machine. A workpiece table moves on hydrostatic oil bearings at a speed v_w in the range of 0.1 to 60 mm/s. A nickel plated diamond wheel (diamond size 220 μm) was used between 20 000 and 36 000 r. p. m. at a depth of cut, a, between 0.05 and 1 mm. Cooling and cleaning was by means of a mist cooler. The vertical force, F_n, and the tangential force F_t, were measured by a Kistler dynamometer plus amplifiers and a tape recorder. The force was found to be pulsed, about 1/3 of the time a force was measured. This was caused by interrupted contact between wheel and workpiece due to unroundness of the wheel. The peak values of the force component divided by the width of the wheel, b_w, are given in figure 6 for $SrFe_{12}O_{19}$ as a function

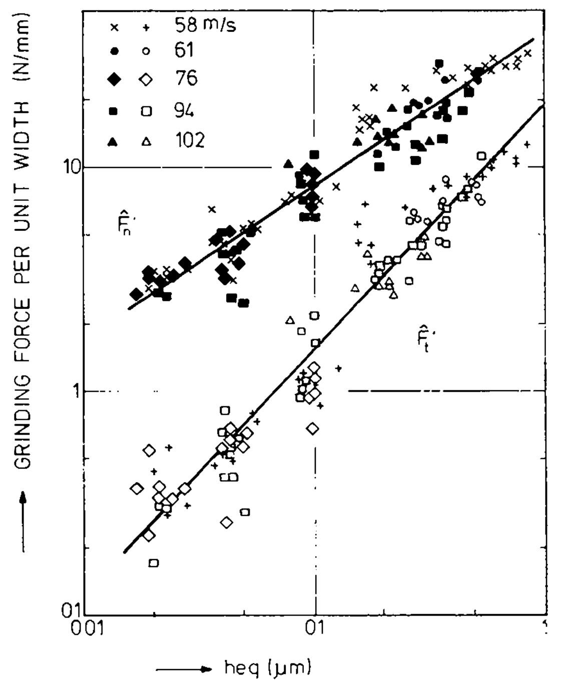

FIG. 6. — Force components, F_n and F_t, divided by the wheel width, as a function of h_{eq} (= depth of cut x workpiece speed/wheel speed) for a number of wheel speeds between 58 and 102 m/s for $SrFe_{12}O_{19}$.

of the continuum chip thickness, h_{eq}, defined by the relation $Z = b_w v_s . h_{eq}$; since $Z = ab_w v_w$, one has $h_{eq} = av_w/v_s$ for this experiment. Data for various v_s values show that, in a good approximation, the force components are unique functions of h_{eq}. For a number of materials the force ratio is in the range 0.1-0.2. The specific energy was calculated, taking the duty factor of 1/3 into account. For $SrFe_{12}O_{19}$ these quantities are given in figure 2*b* as a function of $h_{eq}^{1/2}$. Due to the unroundness of the wheel the number of active diamonds is rather low ; reliable values of the depth of cut of « the » average diamond are therefore difficult to obtain, an estimate of the order of magnitude (1-5 μm) was made from experiments on a tilted sample.

4. **Discussion.** — 4.1 FORCE RATIO. — From the single-point scratching measurements with pyramids of apex angle $2\theta f$ is given by cot θ. This result means that the force ratio, to a good approximation, is a geometrical quantity, and that scratching agrees

with ploughing theory [6]. It also follows that for rounded-off particles f does depend on load and material hardness, because of the changing *apex angle* on increasing the depth of penetration. In the grinding of ferrites f is about constant : for the $v_s = 5$ m/s apparatus f equals 0.3 which corresponds to $2\,\theta = 145^o$, the lower value of 0.15 found for the high-speed apparatus gives $2\,\theta = 163^o$; these average values point to the presence of blunt particles on the grinding wheel. For harder materials [7] f is smaller than for ferrites and depends on load, presumably also due to the smallness of the depth of cut in comparison to the tipradius of the abrasive points.

4.2 SPECIFIC ENERGY. WHEEL SPEED. — The specific energy, e, for grinding $SrFe_{12}O_{19}$ both at $v_s = 60\text{-}100$ m/s and at around 5 m/s does not show a major variation with wheel speed within the scatter of the data (Figs. 6 and 2*b*). This conclusion also holds for other ferrites not reported here. For low-speed scratching (section 2 and ref. [6]) and for lapping [10] e was found to be correlated with the Vickers hardness. In high-speed experiments two effects are presumably important for such a comparison : at the high strain-rates in grinding the hardness would be expected to increase with respect to the static value by roughly a factor 3 ; the heat developed near the scratching point, however, leads to a lower H_v value. It is difficult to say beforehand which effect dominates. In view of the brittle cracking the second relevant material property is the fracture toughness, which depends weakly on temperature. Although there are speed effects these occur at cracking speeds well below 1 m/s. The main influence on the specific energy is therefore expected to be the temperature- and speed dependence of the hardness, for which more data are needed. The result that e does not depend significantly on v_s is of practical importance. From the relation $Z = F_t\, v_s/e$ one then concludes that increasing v_s at constant force leads to increased removal rates, i. e. lower cost, or at constant removal rate to reduced force levels, i. e. less deformation in the workpiece. It would thus be interesting to investigate the speed range between 5 and 60 m/s.

4.3 DEPTH OF CUT. — Two factors influence the specific energy (Fig. 2*a*) : e decreases with increasing depth of diamond penetration, and, e is different for scratching and grinding in some cases. The first effect is found for many materials, for slow scratching, steel grinding [3, 6] and hardness indentation. This *size effect* may be caused by easier plastic deformation in larger volumes, or in these brittle materials, by increased cracking and chipping which may also influence the groove formation. The second effect, the different values for NiZn ferrite, may be due to the influence of cracking and chipping on the volume removed by grinding, whereas in scratching only the groove volume has been considered. The extent of cracking, shown in figure 3, depends on the toughness of the material. Experimental values of K_{IC} have been obtained for these materials [7] ; the higher K_{IC} value for $SrFe_{12}O_{19}$ suggests that the cracking is less extensive than for NiZn ferrite with a low K_{IC} with the result that *multipoint scratching* is more effective for the latter material.

5. **Conclusion.** — From the results shown it appears that single-point scratching provides a good model for understanding grinding. The force ratio informs about the sharpness of the abrasive particles. The specific energy for groove formation agrees with the grinding values in a hightoughness material ; for a hight or-toug more brittle material the energy is determined by the number of cracks and their extent.

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