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Power spectra of roughness caused by grinding of metals

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The roughness of metallic surfaces generated by machining depends on the intended intervention by the tool and the inadvertent consequences determined by the response of metals. The roughness generated in four different metals by grinding is studied using the power spectrum method. It was found that the level of power is determined by the intended intervention such as the depth of cut and, to some extent, by hardness because of its possible influence on micropileup geometry. The power gradient is, however, influenced by inadvertent damage which may be related to material properties such as thermal conductivity and adhesion.

Roughness of surface is a nonstationary random process[1]; variance of height distribution is related to the length of the sample. There has been much attention given to establish scale independent fractal parameters of the following engineering surfaces: fractured,[2] deposited,[3,6] processed,[4] as well as machined.[5] The interest is clearly propelled by a need to understand the evolution of surface topography as well as to use, if possible, these scale independent parameters as prognostic tools for evaluating surface damage. Reviewing work on processed surfaces, one finds that while the fractal dimension of some exceptional surfaces like magnetic thin film rigid disk[6] show scale independence, for most engineered surfaces the fractal dimension is scale dependent, at best bifractal. It has been suggested[5] that the fractal dimension is related to the mechanism of material removal.

In the evolution of machined surface topography, there are principally two superposed aspects: (i) the intended intervention such as the depth of cut, tool geometry, and feed rate; and (ii) inadvertent consequences such as fracture, plastic flow, cracking, and other damage mechanisms. The second aspect or phenomena is determined by the response of material to the intended intervention. For development of prognostic tools, the processed (power spectrum,[6] variation,[7] or structure function[5,8] method) topographical data should distinguish between the intended and inadvertent damages and finally comment on the efficacy of the process parameters in machining a given material. In this work we use the profilometer data of a grinding wheel surface as a bench mark to view the power spectra of ground surfaces. For the material to be ground, we choose aluminum which is markedly prone to wear by adhesion, copper, and hard steel (EN24) to provide a range of hardness and titanium to provide a variation in thermal conductivity and observe the changes in power spectra with changing material and depth of cut.

Resin-bonded alumina (60 μm grit) wheels (K5 V8, Carborundum Universal, India) of diameter 180 mm and width 13 mm were used to grind the test material at 1560 rpm wheel speed and 7.42 m/min table speed. The grinding was done using coolant, kerosene for grinding aluminum, and copper and machine oil for grinding steel (EN24) and titanium. The surfaces were scanned using a Taylor-Hobson profilometer (the diamond tip has a flat of 2.5 μm) in the direction of the tool travel (along) and transverse (across) to the tool travel. The surfaces were viewed in a scanning electron microscope (SEM). The hardness of the test materials is given in Table I. The profilometric data were processed using the power spectrum method.[9] The power spectra shown are averages of five power spectra corresponding to five profiles measured parallel to each other using a 10 mm scan length. The profiles were recorded 2 mm apart when the trace was in the direction of tool travel and 4 mm apart when the trace was transverse to the direction of tool travel.

Figure 1 shows the "along" spectra of the ground test materials. These spectra unencumbered by the "profile" of the grinding wheel reflect primarily the inadvertent damage caused by grinding. EN24 is the least damaged and aluminum the most damaged material. Viewing the ground surfaces in the SEM show large elliptical wear craters and back-transferred deposits on the aluminum surface; the extent of both increases with depth of cut. The titanium surface was also found to be highly disturbed with plastic flow and shallow craters.

Figure 2 shows the spectrum of the grinding wheel profile along its width. In a frequency range of 2 to 100 mm^{-1} it is linear with a slope of 3.47. At frequencies more than 100 mm^{-1} it flattens out. The spectra in this region reflect the faceted roughness of the individual grains (grinding wheel) and are determined by the way in which the grinding wheel is preprocessed by diamond

TABLE I. Hardness of the test materials.

Material	Composition (%)	Hardness H (GPa)	Young's modulus E (GPa)	H/E	Power at 10 mm^{-1} frequency (mm^3)
Hardened steel EN24	0.39C, 0.22Si 1.43Ni, 1.02Cr 0.22Mo, 0.62Mn Heat-treated	7.46	210	0.035	0.01
Titanium	Commercial purity	2.34	116	0.02	0.04
Copper	Commercial purity	1.03	124	0.008	0.02
Aluminum	Commercial purity	0.3	70	0.004	0.12

A least square fit was obtained for power, between 10 and 100 mm^{-1} frequency for 25 μm depth of cut ground surfaces. The power intercept of the straight line at 10 mm^{-1} frequency is reported in the last column.

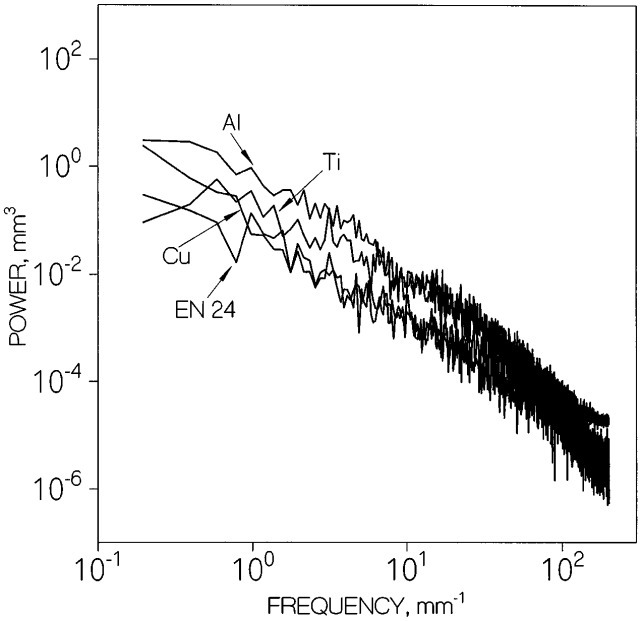

FIG. 1. Power spectrum of the test materials along the direction of grinding, 25 μm depth of cut.

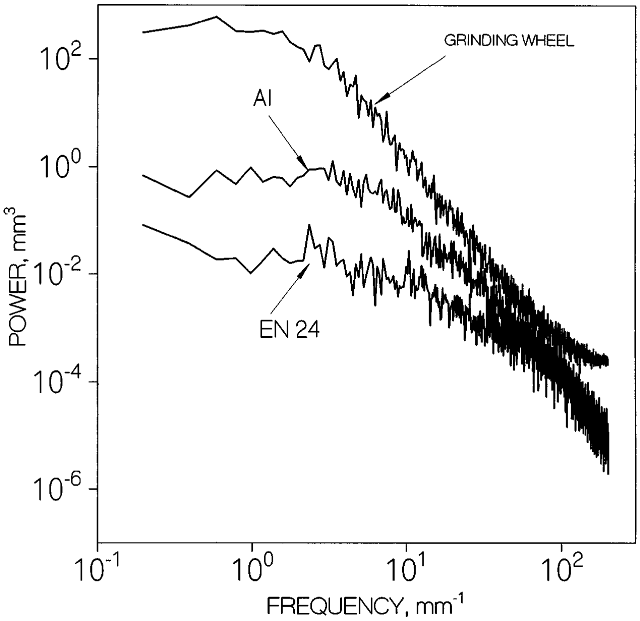

FIG. 2. Power spectrum of grinding wheel across its width and of aluminum and EN24 surfaces ground with 25 μm depth of cut, normal to the grinding direction.

dressing. In the high frequency region the EN24 "across" spectra shows a divergence away from the wheel spectra. At low depth of cut (Fig. 3) the high frequency spectra, however, show flatness, suggesting that the very small length scale protrusions of the wheel (<10 μm equivalent to 10^2 mm^{-1} frequency) imprint the profile by cutting or ploughing. It is suggested that the impressions created remain intact on unloading as the maximum load reached is small. It is seen in Fig. 3 that the aluminum surface profile is truer to the grinding wheel profile than the EN24 surface profile is. This is possibly because a groove in aluminum of low H/E ratio (0.004) on unloading recovers[10] much less than a groove made in EN24 ($H/E = 0.035$). When the depth of cut is increased, the groove depth increases. During unloading substantial recovery takes place as now the maximum load is high. The recovery occurs at depths[11] relaxing the small length scale impressions. This tendency increases with depth of cut in the high frequency range giving rise to a sharply falling power with frequency.

There is a frequency band to the left of 10^2 mm^{-1} (length scale 10 μm) where (Fig. 2) the wheel and the surface spectra converge and over which the slope of the spectra change. At frequencies less than this band the surface spectrum of EN24 (minimum inadvertent damage due to wear) diverges away (Fig. 2) nonlinearly from the wheel spectrum. The power of the spectrum in this frequency range was found to be inversely proportional to the depth of cut (Fig. 3). The divergence of spectra may be attributed to the partial sinking of the wheel profile, the extent being a function of the depth of cut. Figure 4 shows that the spectrum corresponding to the profile of the wheel cut off at 40 μm from the tip of the tallest protrusion (one which is likely to make the first contact with the surface to be ground) diverges nonlinearly away from the "full" form of the wheel in

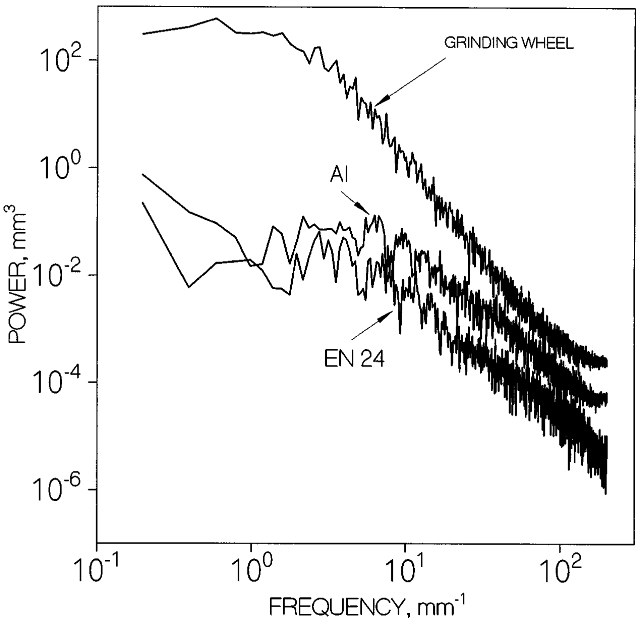

FIG. 3. Power spectrum of grinding wheel across its width and of aluminum and EN24 surfaces ground with 2 μm depth of cut, normal to the grinding direction.

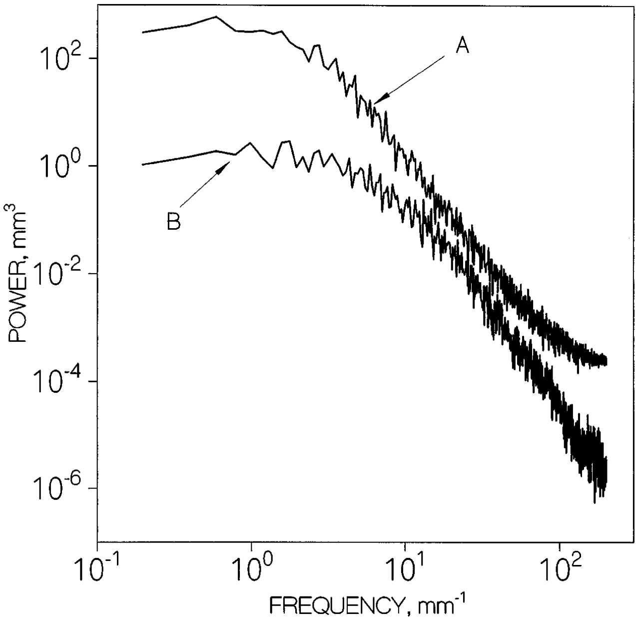

FIG. 4. (A) Power spectrum of grinding wheel as obtained using profilometric data of the wheel surface along its width, and (B) power spectrum of an ideal surface carrying the impression of the wheel sunk to a maximum depth of 40 μm (from the first contact).

this low frequency regime. It is interesting at this stage to note the effect of hardness on power. At the lowest depth of cut (2 μm) EN24 and copper samples exhibited virtually no surface damage. Table I (last column), however, shows the power of the copper surface to be about two times that of EN24. The difference in power spectra between the materials may be attributed to the large difference in hardness (the hardness of copper is seven times lower than that of EN24, Table I) between these two materials. For a given load the grinding of copper would give rise to larger grooves and transverse pileups than what would be expected in case of EN24. The corresponding roughness for copper is thus likely to be higher than in the case of EN24. The powers of titanium and aluminum are higher than that of copper (Table I), but this may be due to the surface damage observed for these materials even at lower depth of cut. The low frequency spectra of the ground surface in terms of its level and gradient of power is thus influenced by material properties and applied displacement or force. At very low frequencies (<10 mm^{-1}) the spectra reflect the overall "form" of the grinding wheel.

The wear damage increases from EN24 to copper to titanium to aluminum. Figure 5 shows the slope of the low frequency spectrum (at constant depth of cut) to increase with damage. Here the hardness and thermal properties both influence the extent of wear damage. Titanium of high hardness (compared to copper) and low thermal conductivity show extensive surface damage and a (low frequency) power spectrum which is close to that of aluminum and higher than that of copper. We have elsewhere[12] reported the low wear resistance of titanium in comparison with that of copper and suggested structural instabilities in titanium due to localized heating to be the cause for it. The high power of aluminum may be attributed to its highly damaged surface caused by adhesion. At all depths of cut the grinding wheel was found coated with aluminum.

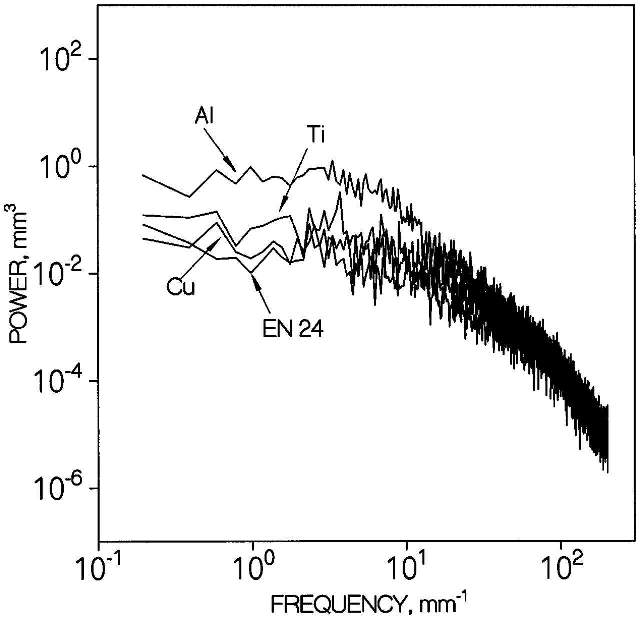

FIG. 5. Power spectrum of the test materials in a direction normal to grinding, 25 μm depth of cut.

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