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G.R. Wilms and R.L. Aghan

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ABSTRACT

A description is given of grinding studies aimed at overcoming a production problem on the dry grinding of hardened steel gears for aircraft gas turbine engines, in which grinding abuse in the form of both a softening and hardening of the steel led to high rejection rates. By using a combination of reduced grinding wheel speed and graded finishing cuts, gears could be produced without showing any signs of grinding abuse.

A feature of the grinding was the occurrence of redeposition, and the extent of the microstructural changes in relation to redeposition under different grinding conditions is discussed.

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Grinding of steel - a case study

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ABSTRACT

A description is given of grinding studies aimed at overcoming a production problem on the dry grinding of hardened steel gears for aircraft gas turbine engines, in which grinding abuse in the form of both a softening and hardening of the steel led to high rejection rates. By using a combination of reduced grinding wheel speed and graded finishing cuts, gears could be produced without showing any signs of grinding abuse.

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GRINDING OF STEEL - A CASE STUDY

1. INTRODUCTION

Grinding is an important metal removal process used in the production of components for the manufacture and maintenance of defence equipment, particularly for materials that are more difficult to shape by other machining methods. Typically, grinding is used for finish machining of hardened steel components. However, attention needs to be focussed on preventing 'grinding burn', where the temperature of the workpiece becomes high enough to change the microstructure by tempering and/or hardening.

The present investigation concerned a production problem in the grinding of gears for the gas turbine engine of a military aircraft. The gear, shown in Fig. 1, is made of a 3% nickel-chromium-molybdenum case-hardening steel, the specified case hardness being 58-63 RC (650-770 HV). The gear is driven by the engine compressor through a gear train and transmits the power required (about 150 KW (200 HP)) for the major engine accessories, such as fuel and oil pumps. Any tooth failure would therefore be catastrophic. Accordingly, the acceptance standard is very high and each gear is subjected to a nital-etch test (2% nitric acid/98% ethyl alcohol solution) after the final grinding operation to reveal any grinding abuse in the form of softening and/or hardening.

A gear showing grinding abuse revealed by the etching is exemplified in Fig. 1, where the dark-etching areas in the roots (A) and on the flanks (B) of the teeth are indicative of grind softening. In some cases there were also white to near white etching areas associated with the dark-etching areas, which are indicative of grind hardening. A taper section through a tooth (Fig. 2) shows the corresponding changes in the microstructure, consisting of an outer white-etching transformed layer, which results in hardening, together with an underlying dark-etching softened layer caused by overtempering. For comparison, the case hardness was 710 HV while the hardness of the white-etching layer was 840 HV and that of the dark-etching layer 550 HV.

Gears showing evidence of grinding abuse are rejected, and because high rejection rates were experienced in production (some 70% of gears were being rejected), the present study was initiated to overcome the problem. An account is given of the various procedures devised which were directed to preventing the occurrence of grinding abuse.

2. PRODUCTION GRINDING PROCEDURE

The problem was exacerbated by the fact that the gears had to be ground dry, as the only suitable machine available for the gear grinding was a dry grinding machine. In production 220 mm diameter aluminium oxide grinding wheels (38A60LUBE) were used, wheel speeds being 28 m/s (5500 ft/min). Two grinding wheels were used to simultaneously grind the left and right flanks of alternate teeth, with the gear oscillating during the grinding to generate the curved faces of the teeth. A total of about 0.38 mm (0.015 in) was removed in the grinding, which consisted of taking roughing cuts of 25-50 µm (0.001-0.002 in) and finishing passes of 5 µm (0.0002 in). Only the sharp edge of the wheels was utilised, the wheels being dressed with a single-point diamond before each roughing cut and before the second last finishing cut.

3. GRINDING STUDIES

3.1 Material Aspects

To first ascertain the material aspects associated with dry grinding, a tooth of a reject gear was ground on a surface grinder at MRL under similar conditions to those used in production with respect to wheel grade, wheel speed and feed. Two cuts of 25 µm (0.001 in) were made followed by one of 5 µm (0.0002 in), beginning with a freshly dressed wheel. The general appearance of the dry ground surface is shown in Fig. 3. The surface finish is poor, a particular feature being the presence of discrete pieces of metal adhering to the surface together with what appear to be smeared surface layers. This type of surface is similar to that previously found on ground 70/30 brass (1), which was attributed to a redeposition process depicted schematically in Fig. 4. It was suggested (1) that metal is picked up on some grits as they pass through the cutting zone BC and then is redeposited back onto the workpiece surface just prior to the grits re-entering the cutting zone. The region where redeposition from the wheel starts to occur is indicated by A. Progressing further towards the beginning of the cutting zone B the angle of approach between the wheel and workpiece decreases, and metal redeposited in this region is subjected to increasing amounts of plastic deformation and smearing.

A corresponding section through the ground gear tooth is shown in Fig. 5. There is a substantial white-etching hardened layer together with a deep underlying dark-etching softened layer. There is also evidence of an outermost redeposited layer which is also white-etching. Redeposition has also previously been found to occur in the grinding of mild and high strength steels (2), where it was indicated that the continual reworking of the workpiece metal, during the redeposition process, is an important additional source of heat generation which will have an important effect on the microstructural changes taking place in the surface layers. The essential difference between these previous studies and the present work is that previously the redeposited metal often appeared to be oxidised.

3.2 Lubrication

As stated earlier, being committed to dry grinding no liquid coolants/lubricants could be used in production. Hence, the possible use of solid lubricants was investigated using surface grinding under the same conditions as before (refer Sect. (a)). In this regard, previous studies on the grinding of 70/30 brass (2) and of titanium and a titanium alloy (3) showed that when the grinding wheel was packed with soap the ground surface was then virtually free of redeposited metal. In the present work, by packing the wheel with soap there was a considerable improvement in surface finish with only slight traces of redeposited metal being evident (Fig. 6 cf. Fig. 3). A corresponding section through the gear tooth workpiece showed a considerable reduction in the extent of both the white-etching layer and the underlying dark-etching layer (Fig. 7) in comparison with the dry grinding (Fig. 5). A gear ground under production conditions using the soap technique failed to pass the nital-etch test.

Next, a dry fluorocarbon lubricant was sprayed on to the workpiece surface prior to each grinding pass. The results were similar to those obtained with the soap technique, so that gears ground under production conditions again failed to pass the nital-etch test.

3.3 Wheel Speed

In previous studies on the grinding of titanium and a titanium alloy (3) it was found that the amount of redeposition became less at reduced wheel speeds. Also, for the low-stress grinding of various metals (4) for the production of damage-free, high integrity surfaces, a generalized value of 18 m/s (3500 ft/min) was recommended.

Accordingly, in the present studies wheel speed was reduced from the original of 28 m/s (5500 ft/min) to 18 m/s (3500 ft/min); speeds below 18 m/s (3500 ft/min) were not studied because this was the lowest speed that could reasonably be attained with the production grinding machine. At this speed there was less redeposited metal on the surface (Fig. 8) in comparison with the higher wheel speed (Fig. 3). Likewise, a section through the gear tooth workpiece showed a significant reduction in the extent of surface damage, where there was only a relatively shallow dark-etching layer (Fig. 9) compared with the substantial white and dark-etching layers produced at the higher wheel speed (Fig. 5). Moreover, the reduction in wheel speed had a larger effect in reducing the extent of damage than could be achieved by the application of solid lubricants (Fig. 9 cf. Fig. 7).

A gear ground under production conditions using the lower wheel speed showed considerably less evidence of grinding abuse, although it still failed to pass the nital-etch test.

3.4 Depth of Cut

The extent of damage at the lower wheel speed (Fig. 9) indicates that it emanated primarily from the roughing cuts, which would not have been removed by the few finishing passes of 5 µm (0.0002 in) used in production. The surface grinding studies revealed that, if the roughing cuts were stopped 100 µm (0.004 in) oversize and the finishing cuts were graded down to 2.5 µm (0.0001 in), there was then no evidence of any change in the workpiece microstructure, as shown in Fig. 10.

Specifically, the finishing sequence comprised the following: (i) dressing the wheel after the roughing cuts and taking four cuts of 12.5 µm (0.0005 in), (ii) taking five cuts of 5 µm (0.0002 in), and (iii) dressing the wheel and taking ten cuts of 2.5 µm (0.0001 in).

4. DISCUSSION AND CONCLUSIONS

The surface grinding studies showed that by using a combination of reduced wheel speed and graded finishing cuts extending down to 2.5 µm (0.0001 in) over a depth of 100 µm (0.004 in) no changes were apparent in the workpiece microstructure. Applying this procedure in production enabled gears to be ground which did not show any evidence of grinding abuse after the nital-etch test.

Other process parameters, such as wheel grade and table speed, were also considered. In this regard, it has been reported that softer grade wheels (H, I or J) produce less redeposition (3) and these have also been recommended for low-stress grinding (4). However, this is counter-balanced by the need to retain the form of the wheel during gear grinding, and therefore required the harder grade wheel (L) that was being used. High table speeds have been recommended for low-stress grinding (4) and it has also been reported that increased table speed reduced the extent of redeposition (3). However, following reports that increases in table speed on the production grinding machine was to the detriment of surface finish, this parameter was not studied.

The results of the present grinding studies support the view (2) that higher temperatures are generated by the redeposition process, as shown by the extensive microstructural changes introduced into the surface layers (Fig. 5) when large amounts of redeposited metal are present on the surface (Fig. 3). On the other hand, when there is virtually no redeposited metal (Fig. 6) the extent of the microstructural changes is greater (Fig. 7) than when some redeposited metal is present (Figs. 8 and 9). Hence, redeposition is not necessarily an indicator of the magnitude of the microstructural changes introduced by the grinding, i.e. on the extent of grinding abuse.

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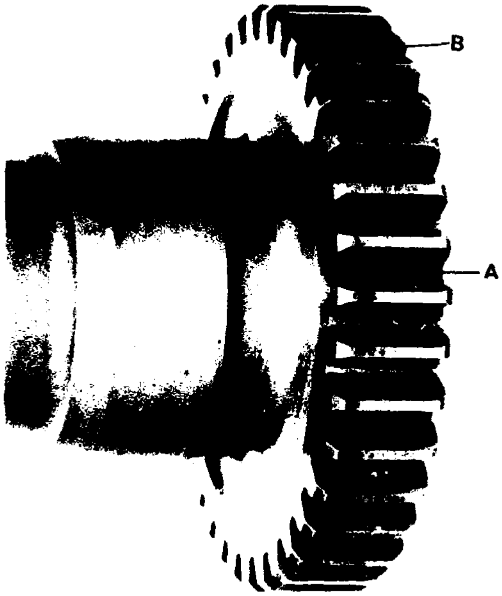

FIG. 1 Photograph of gear, showing dark-etching regions in the roots (arrow A) and on the flanks (arrow B) of the teeth which are indicative of grind softening. X 1 1/2

FIG. 2 Optical micrograph of a taper section through the surface of a gear tooth, showing the presence of an outer white-etching layer and an underlying dark-etching layer.

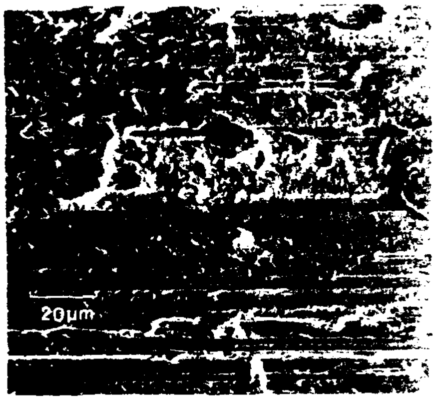

FIG. 3 Scanning electron micrograph of the surface produced when grinding dry at a wheel speed of 28 m/s. Discrete pieces of metal and smeared layers are present on the surface.

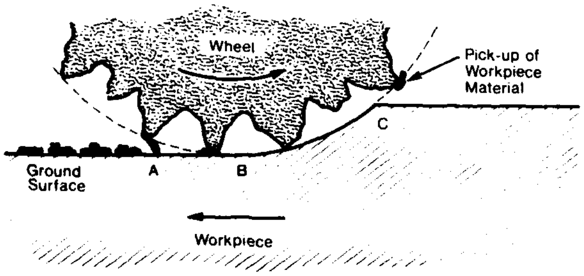

FIG. 4 Schematic illustration of the redeposition process. Redeposition starts at A, smearing of redeposited metal occurs between A and B, and B-C is the cutting zone.

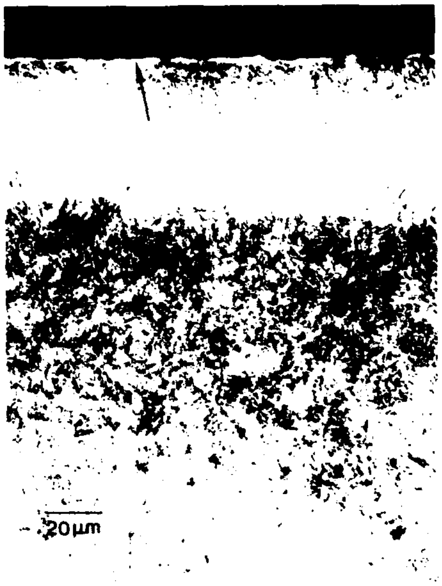

FIG. 5 Optical micrograph through surface corresponding to Fig. 3, showing a substantial white-etching layer and a deep underlying dark-etching layer. There is also evidence of an outermost redeposited white-etching layer (arrowed).

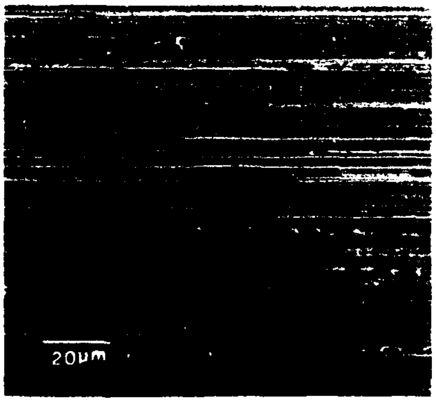

FIG. 6 Scanning electron micrograph of the surface produced when grinding at a wheel speed of 28 m/s with the wheel packed with soap. There is very little evidence of redeposited metal on the surface.

FIG. 7 Optical micrograph through surface corresponding to Fig. 6, showing a white-etching layer and an underlying dark-etching layer (cf. Fig. 5).

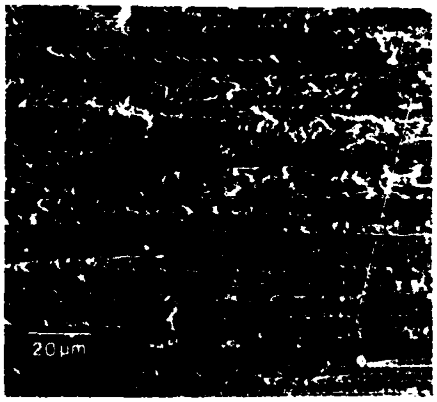

FIG. 8 Scanning electron micrograph of the surface produced when grinding dry at a wheel speed of 18 m/s. The amount of redeposition is less than that produced at 28 m/s (cf. Fig. 3).

FIG. 9 Optical micrograph through surface corresponding to Fig. 8, showing only a relatively shallow dark-etching layer which should be compared with Fig. 5.

FIG. 10 Optical micrograph through surface after grinding dry at a wheel speed of 18 m/s with graded finishing cuts. There is no detectable change in microstructure.

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