Microsecond Heat Treatment of Gears

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The performance of metal surfaces can be dramatically enhanced by the thermal process of rapid surface melting and re-solidification (RMRS). When the surface of a metal part (for instance, a gear) is melted and re-solidified in less than one thousandth of a second, the resulting changes in the material can lead to:

- Increased wear and corrosion resistance,
- Improved surface finish and appearance,
- Enhanced surface uniformity and purity, and
- Sealing of surface cracks and pores.

Even though it has long been known that these benefits can be obtained by RMRS, the process has not been used for large-scale commercial applications because of key technological barriers: the inability to produce broad area, efficient and intense energy sources capable of treating large surface areas, and the inability to deliver consistent treatments to complex and non-uniform surfaces.

Recently, these barriers to large scale RMRS have been overcome and the process has been implemented by QM Technologies in Albuquerque, NM, with its commercialization of the Ion Beam Surface Treatment (IBEST™) process that was developed and patented by Sandia National Laboratories in Albuquerque, NM. This process uses a rapidly pulsed (1–2 Hz), broad area (25–50 square cm) ion beam to melt and re-solidify the top several microns (up to .0005") of the surfaces of most materials. The process causes the surface to be molten for about a microsecond, and the surface cools by rapid thermal diffusion at approximately a billion degrees a second. Because the energy is rapidly injected into only the top few microns of the surface, the average temperature of parts does not typically exceed 100 degrees centigrade. This latter fact allows tight dimensional tolerances (less than a few ten thousandths of an inch) to be maintained.

Examples of the effects of the RMRS process on typical gears and gear materials are presented below.

Creation of a Uniform Microstructure and Removal of Defects Using RMRS

Figure 1 shows the effect of RMRS on the microstructure of a typical carburized, 8000 series gear steel. This figure shows cross sections of the near surface of the steel before and after treatment. The samples were prepared by polishing and etching to reveal the microstructure of the materials.

The treated surface region in the cross section micrograph is essentially featureless. Detailed studies of pulsed ion beam treated steel have shown that the grain size of material in the rapidly re-solidified region is typically less than 100 nm. The process creates a homogeneous, equiaxed grain structure. In addition, melting followed by rapid resolidification results in

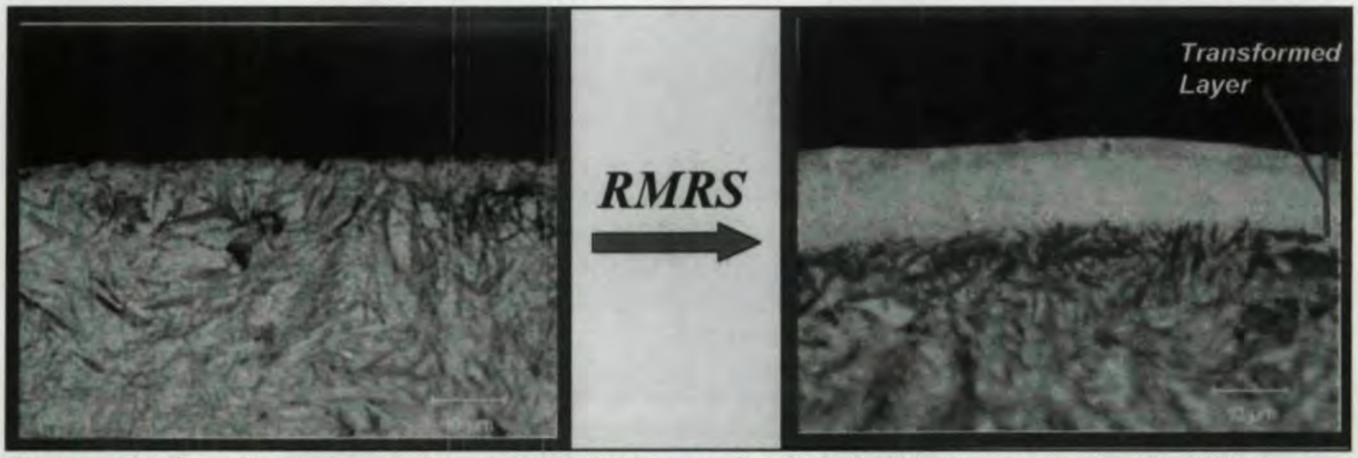


Figure 1—Metallographic cross section of untreated and RMRS processed, carburized, 8000 series gear material. The RMRS processed region is featureless, which is a result of its very small grain size and homogeneous, equiaxed structure.

a uniform redistribution of material in the region and removes localized defects like grain boundary oxidation, grain boundary carbide precipitates, and inclusions.

In carburized steels, rapid melting and re-solidification also creates a near surface region with retained austenite contents in the range of 20% to 30%. It has been reported in the literature that high levels of retained austenite can be beneficial in low cycle fatigue environments in which the enhanced strain at crack tips can cause an austenite to martensite transformation that helps to arrest further crack growth. It has also been reported that retained austenite with very small grain size can enhance high cycle fatigue life. The micrograph in Figure 1 shows that the grain size of the retained austenite in an RMRS transformed layer is very small and unresolvable by standard optical microscopy.

Further modification of the microstructure of the RMRS region has been achieved by subsequent thermal or mechanical processing. Heat treatment, cryogenic treatment, and shot peening have been shown to adjust the level of retained austenite in the transformed region. These post-RMRS processing options allow for customization of the microstructure to fit the requirements of different application environments.

In general, the RMRS process, when applied to metals, will result in the creation of a near surface region with very small, equiaxed grains and a uniform distribution of alloying elements. Defects composed of high vapor pressure constituents (for instance, inclusions) are often removed by the very rapid thermal excursion provided by RMRS.

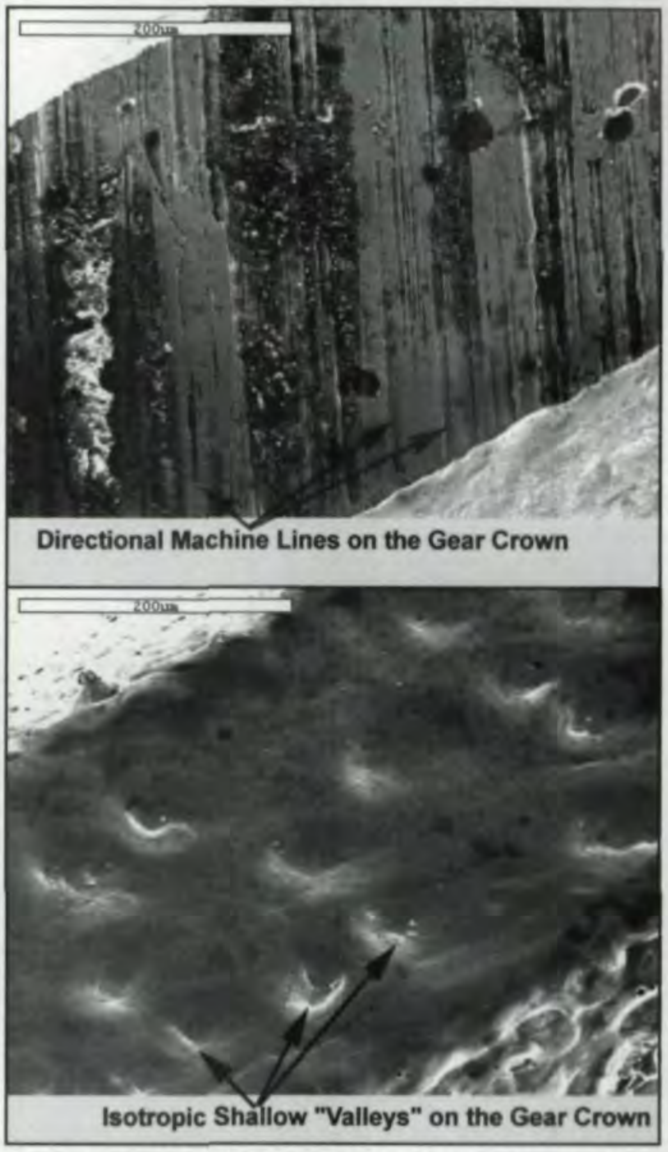
In addition, features such as cracks and pores may be sealed by the melting process. For example, it has been demonstrated that there is sufficient time during RMRS for molten material to re-flow and fill pores and cracks that are up to several micrometers in size. This capability has facilitated the use of the RMRS process for sealing near surface porosity in metal injection molded parts and higher density (density > 94%) conventional powder metal parts.

Creation of a Smoother, Isotropic Topography Using RMRS

As mentioned above, rapid melting and re-solidification results in the short range flow of material. As a result, the roughness and topography of a machined surface will be changed by RMRS.

For example, Figure 2 shows scanning electron microscope (SEM) images of the surface of the crown of a carburized steel gear tooth before and after RMRS. The untreated surface exhibits directional machine lines. In contrast, the surface of the treated gear shows that machine lines have been replaced by a longer wavelength, isotropic, shallow dimpled surface.

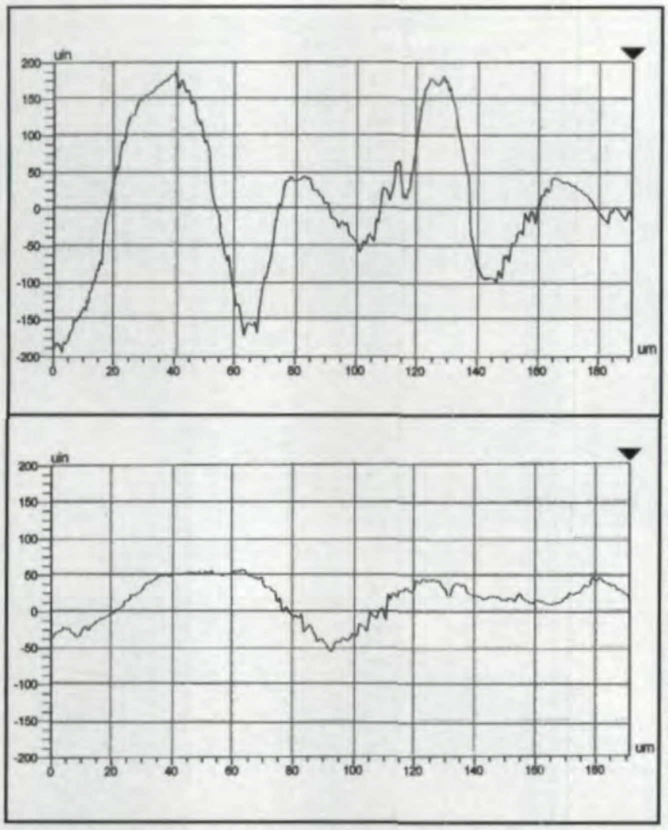
The treated gear surfaces were characterized using a Wyko NT-2000 optical profilometer. The root mean square roughness (Rq) and skewness (Rsk) of the surface features were measured. The average Rq of this gear was reduced by RMRS from an average of 90 +/- 14 micro-inches to 55 +/- 6 microinches. Other work shows that RMRS can reduce the roughness of metal surfaces by up to a factor of two to three.



Figures 2a and 2b—Scanning electron microscope images (magnification = 250 X) of untreated and RMRS treated crowns of carburized steel gear teeth. The RMRS process transformed the directional, machined topography of the untreated surface to an isotropic, longer wavelength, and slightly dimpled topography.

A line profile taken from the surface of the untreated and RMRS treated surfaces of a carburized steel gear are shown in Figures 3a and 3b. These plots show that RMRS reduces the amplitude and increases the average wavelength of the surface features.

Finally, skewness is a measurement of the asymmetry of the surface profile about the mean surface position. A positive skewness indicates that the most distant lying points on a surface profile are proportionately above the mean surface while a negative skewness indicates the most distant lying points are proportionately below the mean surface. The skewness measurements of this gear showed that the average Rsk for the machined surface was approximately 0.0 +/- 0.2 and the average Rsk of a rapidly melted and re-solidified surface was approximately –0.3 +/- 0.2. This change in skewness reflects the creation of shallow "valleys" in the surface that is observed in Figure 2. The slightly negative skewness also suggests that the treated surface has few spikes or bumps that



Figures 3a and 3b—Surface profile scans of untreated and treated crowns of carburized, steel gear teeth taken using an optical profilometer. The RMRS process reduced the root-mean-square roughness from 90 micro-inches to 55 micro-inches and increased the wavelength of the characteristic surface features.

will typically wear away quickly in sliding wear environments. The presence of shallow valleys in the surface can also help with reducing run-in time while increasing lubrication retention in sliding applications. For example, work conducted by QMT on the RMRS processing of steel piston surfaces has shown that this type of surface significantly reduces friction in sliding applications.

The changes in the surface topography caused by RMRS processing have also been shown to significantly improve the adhesion of very hard coatings. In addition to removing contamination from the surface, the RMRS process reduces the population of stress enhancing, de-cohesion points at the hard coating-substrate interface. The increase in surface cleanliness and homogeneity combined with the creation of a smoother, isotropic finish by RMRS creates a better surface for coating.

Conclusions

When applied to gears, the RMRS process has been shown to:

1. Transform the microstructure of the gea material into a very fine grained, equiaxed and homogeneous microstructure with a reduced population of cracks and pores, and
2. Create surfaces that have isotropic, shallow, long wavelength, dimpled features rather than directional machined surface features of shorter characteristic wavelength.

These changes can result in decreased wear rate and increased fatigue life of gear materials. In addition, QMT has shown that the IBEST rapid melting and re-solidification process can be used to significantly enhance the performance of surfaces in many diverse applications. For example, IBEST processing has increased the lubricity and wear resistance of metal injection molded parts, increased the lifetime of steel flexible rotary dies by up to a factor of ten, and extended the lifetime of cemented carbide tools used to machine cast iron by two to three times.

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