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A functional approach to integrating grinding temperature modeling and Barkhausen noise analysis for prediction of surface integrity in bearing steels

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ABSTRACT

The use of NDE techniques such as Barkhausen Noise Analysis (BNA) for detection of grinding induced thermal damage is often application specific due to variables in the grinding process. In this paper, Malkin's grinding energy partition model is applied in conjunction with BNA to reliably predict occurrence of thermal damage in through-hardened bearing steels independent of grinding variables. Various intensities of material transformation such as surface, sub-surface retempering and rehardening were accurately detected and validated by metallography and residual stress analysis. The results demonstrate that material-specific models independent of grinding process variables can be effectively utilized to predict thermal damage.

1. Introduction

It is well known that grinding is a finishing process characterized by high energy input and heat generation [1]. Critical power transmission devices such as gears and bearings use grinding as a finishing process on most of their load-bearing surfaces. In the case of bearing raceways, grinding is typically followed by a low material removal superfinishing process. Even though grinding is not the end state, it is critical that after grinding the raceway surface is free of thermal defects, since superfinishing is not capable of completely removing the depth of thermal damage imparted by grinding. This damage can affect bearing fatigue life.

The ever-competing priorities of productivity and surface integrity means that bearing raceways are routinely inspected for thermal damage after finish grinding, using both destructive and nondestructive techniques. Destructive techniques include surface etch, X-ray diffraction analysis and metallography, while nondestructive evaluation (NDE) techniques include Barkhausen Noise Analysis (BNA), eddy current testing, etc. BNA in particular has become a widely adopted technique for NDE in the bearing and gear industries. However, the semi-quantitative nature of BNA requires generation of multiple samples with varying levels of thermal damage to repeatably detect acceptable levels of surface integrity. Often this is very time consuming and empirical in nature.

In the case of extreme thermal damage, BNA can be misleading as the average BNA RMS, which is the widely adopted metric, may not be significantly different from that of a part with no thermal damage. To counteract this, the BNA response has been correlated to other process-related parameters such as sequence of parts ground [2,3], specific grinding energy [4] and specific grinding power [5]. While these methods are effective in high-volume or non-variable process environments, the issue of scalability of results remains when one or more grinding process variables such as material removal rates, abrasives, etc. are changed.

This work provides new insights into this issue by relating a grinding thermal partition model to BNA. The maximum grinding zone temperature [1] calculated from the grinding thermal model is used as a concise representation of all grinding process variables. It is then correlated to BNA and other material response characterizations such as X-ray residual stress analysis and metallography. The results show that the predicted maximum grinding zone temperature can be selected to meet surface integrity and residual stress requirements, and that BNA can subsequently be used to confirm that these requirements have been achieved on the ground workpiece surfaces.

2. Grinding temperature modeling

Grinding zone temperatures can be theoretically estimated by considering the grinding wheel as a moving source of heat. For external cylindrical grinding, the following aspects illustrated in Fig. 1 are considered for estimating the grinding zone temperature.

The interaction of grinding wheel diameter d_s and workpiece diameter d_w results in an equivalent diameter d_e of the grinding zone, which is given by Eq. (1) [1,6]:

$$d_e = \frac{d_w d_s}{d_w + d_s} \quad (1)$$

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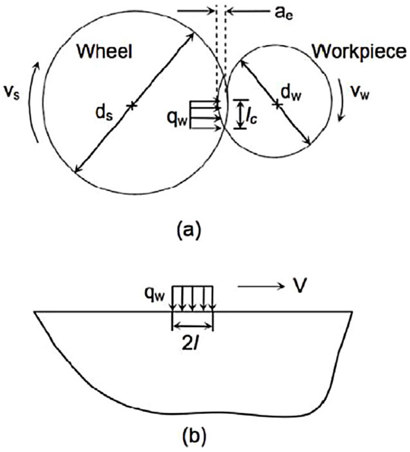

Fig. 1. External cylindrical grinding aspects [1].

The arc length of contact l_c over which the grinding energy dissipated is given by Eq. (2) [1,6]:

$$l_c = (a_e + d_e)^{1/2} \tag{2}$$

where a_e is the grinding depth of cut. The grinding energy dissipated can be represented as a heat flux q_w, which is given by Eq. (3) [1,6]:

$$q_w = \frac{\varepsilon P}{l_c b} \tag{3}$$

where ε is the energy partition (or the ratio of grinding energy that is dissipated into the workpiece as heat), P is the grinding power and b is the width of the grinding zone. The maximum rise in grinding zone temperature can then be calculated using Eq. (4) [1]:

$$\theta_m = \frac{1.13 q_w \alpha^{1/2} a_e^{1/4} d_e^{1/4}}{\mathrm{k} v_w^{1/2}} \tag{4}$$

where α is the thermal diffusivity of steel, k is the thermal conductivity of steel and v_w is the workpiece velocity.

The energy partition ratio is influenced by multiple grinding variables such as the type of abrasive, coolant application conditions, etc. Various experimental investigations have estimated the energy partition ratio to range between 60% and 85% for shallow-cut grinding of steels with aluminum oxide wheels [6–10]. In particular, the energy partition when grinding hardened bearing steels with aluminum oxide wheels has been estimated to be around 75% [9,10]. Therefore in this work the energy partition ratio is considered to be 75%.

Eq. (1) neglects the effect of elastic deformation, which would make l_c bigger [11] as it has been shown that most of the grinding energy is dissipated within the geometrical contact length [9,10]. Similarly, with a triangular heat source, instead of the uniform rectangular one considered here, the factor 1.13 in Eq. (4) has been shown to be reduced slightly to 1.06 [12]. However, since the model predicted grinding zone temperatures are relative and the material transformation is verified with BNA, the influence of variability in predicted grinding zone temperatures is likely to be minimal.

3. Experimental details

External cylindrical grinding of raceways of tapered roller bearing inner race (cones) was conducted on a shoe centerless grinder. Bearing cones of through hardened 52100 steel (58-62HRC) with specification as listed in Table 1 were ground using a commercially available aluminum oxide grinding wheel (97A100-N4) at a constant wheel speed v_s of 56 m/s. A DOE was conducted based on a matrix of grinding conditions listed in Table 2, to generate various intensities of thermal damage, i.e., undamaged, onset of retempering on surface, retempering and rehardening. A 5% water soluble coolant was used during the grinding process close to the grinding zone.

Table 1
Tapered roller bearing inner race specifications.

Race diameter—large end (mm)	74.6
Race diameter—small end (mm)	64.8
Inner diameter (mm)	59.5
Race width (mm)	17

Table 2
Range of grinding conditions.

Work speed, v_w (m/s)	3.2	1.6	0.8	0.4
Material removal rate, Q (mm^3/s)	20	50	100	200
Dressing lead, v_d (mm/s)	1.5	0.5		

Prior to grinding under each condition, the wheel was dressed with a single point diamond (with the dressing leads mentioned above) to avoid the influence of the previous grinding cycle. Grinding power was monitored using a Hall-effect power monitor with a 0–10 V response and a digital data acquisition device at 240 Hz frequency. Due to plunge cylindrical grinding of the workpiece with continuous infeed, the grinding energy increased continually until a peak point before tapering off during wheel retraction. The difference between peak grinding power and idle power was used to estimate the grinding zone temperature.

The thermal conductivity of steel plays a critical role in estimating grinding zone temperatures. The thermal conductivity for AISI 52100 steel has been established as 46.6 W/m K [13]. It has been found that this thermal conductivity value is within the range of variability up to a maximum bulk temperature increase of 400 °C [14].

Grinding tests were followed by measurement of BNA on each bearing race. BNA was measured using a commercially available AST Rollscan 350 with a general purpose sensor and flat angled pole pieces at a magnetization voltage of 13 V, a frequency of 200 Hz and filtered to 70k–200 kHz. BNA response was recorded circumferentially around the bearing race at four locations 90° apart, from which the average BNA RMS value was calculated.

Select samples were also destructively evaluated by metallography and X-ray residual stress analysis for corroboration against BNA. Microstructural analysis was performed by mounting the samples on a taper angle section of 20° to minimize the rounding errors caused during metallographic polishing. The inclined mount magnified the damage depth by 2.9 times. The residual stress analysis was conducted using Proto LXRD equipment with Chromium kα radiation of wavelength 2.28 Å. The measurements were conducted at the surface and at 6.3 μm, 12.7 μm, 25.4 μm and 50.8 μm depths using electropolishing.

4. Results and discussion

Multiple response surfaces were produced by altering the grinding parameters using a wide range of parameters within the extreme limits listed in Table 2. Based on the thermal model and the BNA, the predicted grinding zone temperature for each workpiece was plotted against the average and standard deviation of the BNA RMS value (Fig. 2). It can be seen that by altering the grinding parameters, four distinct groups of response surfaces were produced. Additionally, a very good correlation between BNA response and the predicted grinding zone temperature is evident in Fig. 2. The BNA RMS follows a polynomial curve, with the RMS reaching maximum value around 275 °C.

A distinct drop in average BNA RMS was observed under extreme grinding conditions where the predicted grinding temperature exceeded 275 °C. This is attributed to rehardening burn, which occurs very near the surface. Rehardening is the result of phase transformation due to the localized temperature exceeding the austenitizing temperature, followed by a rapid coolant quench [15].

This process produces a thin layer of untempered martensite at the surface, possessing increased hardness and ideally, compres-