Surface polishing of hardened grey cast iron with a compliant abrasive filament tool

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Abstract

Sliding guideways play a critical role in the accuracy and dynamic performance of machine tools. Discontinuous jerking motion occurs due to wringing if the guides are too smooth, but excessive wear results if the surface is too rough. The current fabrication approach uses large and expensive grinding machines that place logistical restrictions on production. A higher productivity milling process, using cubic boron nitride (CBN) tooling has been attempted, but this process does not achieve the necessary surface quality. Secondary finishing using a spindle mounted abrasive filament tool could be implemented as a post process to improve surface quality. This study determined the relationship between number of passes and Spk, Sk, and Svk areal functional parameters for three types of filament tools.

Keywords: Polishing; surface analysis; manufacturing process.

1. Introduction

Sliding guideways should have smooth uniform surfaces free of sharp peaks for optimal performance [1]. Surfaces with peaks wear more quickly during sliding contact and the abraded debris becomes trapped between the sliding guideway components. This deteriorates the soft polymer layer on the underside of the slider causing uneven contact pressure, reduced positional accuracy and shorter life for the machine tool. As a direct consequence, surface finishing methods are of key interest to machine tool builders.

Fabrication of the guideway is generally accomplished through a multistep process: the casting is milled to the desired geometric shape, heat treated to case harden the surface, and lastly ground to obtain the final roughness [2]. The last step requires very large and expensive CNC grinding centers. These machines are only installed in a select number of facilities, which increases shipping and production costs. After grinding, the casting is returned to a milling center and the ground surfaces are used as reference datums for proceeding operations that are centrally important to the performance of the machine. However, the surface finishing and subsequent milling operations could be performed by a single machine if the already required CNC milling machine could perform both the roughing and finishing operations. This would result in reduced manufacturing costs and increased productivity, since an unnecessary workpiece transfer would be avoided. This would also eliminate the high cost of the grinding machine, allow factories to be smaller, more numerous, and more closely located to their customers.

Soshi et al. proposed an alternative CBN milling strategy in the past and found that it led to more stable static and dynamic friction coefficients over a sliding distance of 600 km [1] while also being a cost effective alternative to conventional grinding operations [2]. Yet concerns regarding the quality of the milled surface limit industry-wide adoption. It has been found that graphite flakes at the surface of the workpiece promote brittle fracture ahead of the milling tool causing random peaks and cavities to form. Example profiles are shown in Fig. 1. As a result, a post processing operation capable of removing these sharp asperities is needed.
2. Abrasive filament tools

Abrasive filament tools have been used in the past for manual and automated applications including: burr removal, reduction of micro crack propagation, and polishing [3]. The compliant bristles are made of metal or synthetic materials and conform to the shape of the workpiece, exerting small normal and shearing forces on the surface. An illustration of the tool is shown in Fig. 2. Workpiece materials include metallics, superalloys, and ceramics, while common abrasive media embedded within the bristles include silicon carbide, aluminum oxide, and poly crystalline diamond [3]. It has been found that abrasive filament tools can generate surfaces that range from Ra of $13\ \mu m$ for tools made of larger diameter steel wire, to Ra of $0.40\ \mu m$ for fine grit nylon/abrasive fibers [4]. However, the exact correlation between 2D or 3D surface texture parameters and tool characteristics are complex and experimentation is often needed before obtaining the desired results [5].

3. Experimental setup and procedure

3.1. CBN Milling process

The workpiece material was FC300 (JIS) grey cast iron that was induction hardened and tempered to an average hardness of 47 HRC. A DMG Mori NV7000 three-axis vertical milling machine equipped with a Sumitomo RM3160R 125 mm diameter shell mill was used to mill the samples prior to polishing. The cutter had an axial rake angle of $-5^\circ$ and radial rake angle of $-6^\circ$. All samples were milled with a single Sumitomo BN7000 insert having 90-95% volume CBN with W-Co binder and a 20°x0.23 chamfered sharp edge. Cutting conditions for the milling operation are shown in Table 1. Each milled surface was measured five times using a Mitutoyo SJ310 contact stylus profilometer and filtered with a 0.800 mm cut-off wavelength before calculating the roughness. The average Ra value was 0.70 $\mu m \pm 11\%$. This surface is not ideal for sliding guideways, as Soshi et al. has shown that an Ra range of 0.3 - 0.5 $\mu m$ resulted in the lowest statics and dynamic friction coefficients and lower wear rates when compared to ground sliding guideway surface [1].

3.2. Abrasive polishing process

Three filament tools were tested for this study and were identified as Tool A, Tool B, and Tool C. Each tool was made from nylon filaments embedded with silicon carbide particles having a hardness of 2200 - 2600 HV that accounted for 10%-40% of the filament by weight [3]. The tools all had different abrasive particle sizes, bristle thickness, and bristle packing density. In general, these tool characteristics are not independent from each other but are instead coupled based on the tool manufacturing process. An increase in abrasive particle size required that a thicker filament be used to ensure proper bonding around the abrasive media, while thinner bristles allowed for greater bristle count per unit area resulting in a higher number of cutting edges making contact with the surface. The tool characteristics are shown in Table 2 and a comparison of the different filaments are shown in Fig. 3. For the polishing tests, spindle speed and feed rate were held constant, using the tool manufacturer’s recommended settings [3]. No lubrication or coolant was used. Unlike milling tools that have high axial stiffness, the compliant bristles elastically bend as they contact the surface of the workpiece. The magnitude of bristle deflection is primarily controlled by the effective depth of cut of the tool and is a function of the stiffness of all the bristles making contact with the surface [4,5]. To ensure consistent contact pressure between the cutting tool and the surface, the bristles must be able to deflect at the correct depth of cut to maintain the desired contact pressure.
between the compliant tool and workpiece, axial forces were monitored using a spindle mounted Kistler 9123C force dynamometer when setting tool length offsets as well as during the polishing trials. This resulted in an average dynamic axial force of 28 N ± 11 N over all runs. A multiple linear regression analysis was employed to determine if this variability had a significant effect on the results, but was found to be insignificant at the 95% confidence interval. The polishing settings are shown in Table 3.

| Spindle speed (min⁻¹) | Feed rate (mm/min) | Dynamic axial load (N) | Number of strokes |
|-----------------------|--------------------|------------------------|-------------------|
| 2000                  | 2000               | 28                     | 10, 20, 30... 100 |

3.3. Areal surface texture measurements

The 3D surface texture of each workpiece was measured at three different regions using a Zeiss Axio CSM 700 white light confocal microscope with a 20X objective lens. Individual scans had a focal range of 30 μm with a vertical scan step resolution of 0.5 μm, and a total scan area of 2.0 mm x 2.1 mm. The 3D surface data was levelled before applying a normal Gaussian filter with 0.800 mm nesting index to separate the roughness from the waviness. Five samples prepared on a grinding center used to manufacture guideways of the desired quality were also scanned.

4. Results and discussion

Areal stratified functional parameters Sk, Spk, Svk, are defined in ISO 25178-2 and derived from the bearing area curve [6]. They are used to subdivide the surface into three distinct regions and are correlated with the sliding and lubrication performance of plateau surfaces similar to those found after polishing with filament tools [7]. The Spk parameter measures the range of peak heights and characterizes the region of the surface that will wear away first during sliding contact [8]. The core roughness depth, Sk, corresponds to the region of the surface that will support the sliding load once the peaks wear away [8]. Svk measures the range of the reduced valley depths and represents the region below the core roughness that is related to lubricant retention and debris entrainment for the surface [8].

4.1. Reduction of peak heights

Polishing was found to reduce the Spk values, as shown in Fig. 4. Using a two-way ANOVA controlling for tool type and number of strokes, tool type was not a significant factor for altering the mean Sk values since each tool improved the milled surface in a similar manner. However there was evidence at the 95% confidence level that the number of strokes contributed to the measured Spk reduction. After 20 strokes, Tool B was shown to have reduced Spk by 73% while the Tool A and Tool C reduced the Spk by 60%. This change reached a saturation limit after 20-30 strokes, with additional strokes resulting in marginal changes. The ground surface had peaks that were 44% smaller than the average polished surface after 30 strokes.

4.2. Reduction of core roughness

Fig. 5 plots the core roughness depth, Sk, for each tool. Both factors were significant at the 95% confidence interval. From 10 – 60 strokes, an increase in the number of strokes was correlated with a reduction in core roughness. After 60 strokes, the core roughness began to gradually increase as repeated motion of the tool passing over the workpiece resulted in grooves being ploughed into the surface. Tool type had an effect on core roughness, with tools A and B being the more effective than Tool C. Tool C had little impact on reducing the core roughness, and it is expected that the thinner more compliant bristles did not produce a large enough shearing force to abrade the hardened cast iron. Tool B had a maximum Sk reduction of 30% after 60 strokes and was 35% larger than the ground surface.

4.3. Variation of reduced valley depths

Neither tool type nor number of strokes was found to be a significant factor for changing the reduced valley depths. The ground surfaces had significantly lower Svk value of 0.69 μm, while the average Svk for each tool was at least 30% deeper. The random variability of the Svk values are explained by that fact that CBN milling in the grey cast iron has been found to generate surface cavities up to 30 μm deep. It is believed that this is caused by the fracturing of graphite flakes at the surface of the workpiece during milling, and is therefore not a direct consequence of polishing. Work regarding the cavities...
is ongoing, but they are expected to increase lubrication retention in the surface and therefore are not seen as a detriment for linear sliding components. The $S_{vk}$ parameter may prove to be more helpful in the future for friction studies where lubrication capacity could be correlated to dynamic friction coefficients.

4.4. Surface modification after polishing

Areal surface maps in Fig. 6 demonstrate the progressive change in surface texture after polishing with Tool B for 10, 50, and 100 strokes. A comparison of milled and polished profiles is shown in Fig. 7 after polishing with Tool B for 50 strokes. The sharp peaks become shorter and their slopes flatten while the high frequency variations are removed. Valleys created during the milling process are still present, indicating that the condition of the surface prior to polishing is an important factor that influences the final surface texture. The small material removal rates of the filament tools are most effective at reducing peaks heights and less effective at altering the core roughness. If modification of the core roughness is needed, Tool B should be used as it was found to perform the best under the conditions tested. The bristle diameter for Tool B is only 10% smaller than that of Tool A, however the abrasive particles in Tool B are 65% smaller. As a result Tool B has a much higher density of cutting edges exposed along the exterior of each bristle while the relative bristle stiffness is only marginally decreased. Based on these results, it is expected that an optimal tool for this application would have filaments 1.0 mm in diameter with abrasive particles approximately 69 $\mu$m in size. The slightly thicker bristles would lead to increased stiffness while the medium sized grit would provide a sufficient number of uniformly distributed cutting edges.

5. Conclusions

This study investigated the interaction between three abrasive filament tools and the number of strokes applied to the surface during the polishing of hardened grey cast iron. Polishing reduced peak heights by 73% after 20-30 strokes, after which additional strokes had marginal improvements. Therefore, polishing can be implemented as a follow up process to CBN milling using the same milling machines currently in use, to remove the majority of the surface peaks as a preventative measure against premature wear of the guides. To accomplish this, tools with nylon bristles should be 1.0 - 0.9 mm in diameter to obtain the desirable stiffness, and be embedded with silicon carbide grains that are approximately 69 $\mu$m in diameter. While the ground surfaces had smaller peaks, less variation in the core roughness, and shallower valleys, past research indicated that this is not the optimal sliding guideway texture. Therefore, friction testing will be conducted in the future to quantify the sliding performance improvements made to the milled surface.

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