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Influence of laser beam fluence on surface quality, microstructure, mechanical properties, and tribological results for laser polishing of SKD61 tool steel

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ABSTRACT

In the present study, the surface polishing of SKD61 tool steel specimens was carried out using a microsecond fiber laser system. The operating conditions of laser controlling factors and fluence for the minimization of the areal average surface roughness (Sa), wear rate and friction coefficient are determined through the planned arrangements of three stages including the experimental design method. The Sa value of the polished surface obtained from the measurements in the *x* direction perpendicular to the laser scanning direction was effectively reduced. However, that from the measurements parallel to the scanning direction strongly depends on the overflow probability of the melt flow. In the *x* direction, the highest peak after polishing was shifted to have a frequency different to that of the as-received specimen. The ripple frequency associated with the highest peak is affected by the laser beam scanning velocity and pulse frequency only. In the *y* direction, the amplitude of the highest peak after polishing is possibly greater than that of the as-received specimen if the melt overflowing the grinding mark stems left behind after polishing was solidified locally. However, its frequency is kept the same as that of the residual stems. A small Sa value can be obtained if the polished surface has small residual stems and lacks significant melt overflow. The thicknesses of the melt zone (MZ) and the heat-affected zone (HAZ) are strongly dependent on both the applied fluence and single-style controlling factor. Increases in laser power and pulse duration increase the MZ thickness, whereas increases in scanning velocity and pulse frequency decrease the MZ thickness. The formations of MZ and HAZ have the hardness (H) and the reduced modulus (Er) lower than those of the as-received specimen. This characteristic is proved to be consistent with the iron phases and their volume fraction formed in these two zones. The wear rate of a specimen depends on the total thickness and the microstructures of these two zones. An increase in laser power and decrease in scanning velocity can decrease the wear rate. The friction coefficient decreases with decreasing Sa of a polished surface.

1. Introduction

Pulsed laser micro-polishing (PLμP) is a non-contact surface smoothing process suitable for metallic parts on the micro/meso scales. Laser polishing (LP) of metals is based on the melting of a thin surface layer, which is similar to a conventional polishing multi-step process (Willenberg, 2005; Willenberg et al., 2003). The smoothing of macrostructures is achieved using continuous wave laser radiation. A melt pool is created by the incident laser beam. The laser beam then moves over the surface with a certain scanning velocity, and the material becomes molten on one side of the melt pool and resolidifies on the other.

In Temmler et al. (2011, 2012) a thin surface layer was made molten and the surface tension led to material flow from peaks to valleys. No material was removed, but instead became reallocated while molten. A two-gloss effect can be created by selective variation of process parameters, such as laser power and process

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velocity. Thermocapillary flows are generated in PLμP when large melting durations are used. They can reduce surface roughness significantly at the expense of creating residual high-spatial-frequency process features. In Pfeffkorn et al. (2013) a two-pass polishing process was adopted, in which the first pass takes advantage of thermocapillary flows to significantly reduce surface roughness, and the second pass removes the residual process features. Experimental results indicated a 72% improvement in the average surface roughness of a Ti_6Al_4V surface. Three independent investigation methods were developed (Martan et al., 2006) for laser-induced thermal process investigation, in which the melting threshold and melting duration were determined. A surface finish method for parts built-up using selective laser sintering (SLS) has also been presented (Lamikiz et al., 2006, 2007). In this, the laser beam melted a microscopic layer on the surface, which resolidified under shielding gas protective conditions, resulting in a smoother surface. The PLμP of nickel was examined numerically and experimentally (Perry et al., 2009). The critical frequency for these experimental conditions was predicted and compared with the reduction in the average surface roughness measured for samples with two different spatial frequency components. Four regimes of PLμP were identified as a function of laser fluence for a given pulse width. A pulse Nd:YAG laser was used to polish DF2 cold-worked steel (Guo, 2009). The influence of the laser feed rate was dominant for the topography of a laser-polished surface. At constant pulse duration and pulse frequency, the polishing temperature increased with increasing the laser input energy and decreasing the pulse feed rate. Ukar et al. (2010a) applied the laser polishing process to a milled and electrical-discharge-machined surface of DIN 1.2379 tool steel. The polishing was based on the tightly controlled melting of a micro-layer of surface material, which flowed into and filled topographic valleys, creating a smoothed surface topography. The main process parameters were identified and optimized using two types of industrial laser. The properties of the laser radiation greatly influence the results. The influence of the type of intensity distribution on a steel surface was investigated in Nüsser et al. (2011), and the influence of pulse duration on the maximum polishable spatial wavelength was examined. The overlap between two successive laser beam tracks is an important laser polishing parameter, and the influence of the overlap between the laser beam tracks on surface quality was experimentally investigated for the laser polishing of AISI H13 tool steel (Hafiz et al., 2012). The surface quality was improved by 86.7% when the optimal set of process parameters was used. In Ma et al. (2013) a two-dimensional axisymmetric transient model that couples heat transfer and the fluid element method was used. The results showed that longer pulses produced more significant fluid flows, and the cut-off pulse duration between the capillary and thermocapillary regimes was estimated to be 0.66 μs for Ti_6Al_4V.

The ordinary consequences of laser irradiation are represented by the significant changes in microstructure that take place in the metallic material exposed to laser thermal energy. Therefore, the microstructure of the workpiece prior to laser polishing will influence the post-polishing structural transformation and the hardening pattern. In the study of Bordatchev et al. (2014), the thickness and hardness of the yielded layers were strongly affected by the overall settings of the LP process. The morphological changes of the polished surface were attributed to the rapid transformation of martensite, which caused volume expansion (Hua et al., 2007, 2004). In Amine et al. (2014), the X-ray diffraction (XRD) analyses showed that an increase in laser irradiation resulted in an increase in the volume fraction of the austenite phase and a decrease in the volume fraction of the carbides. Ukar et al. (2010b) supported the view that structural changes in the polished workpiece can be traced back to the constituents of the equilibrium phase diagram.

In the present study, 49 pieces of SKD61 tool steel were polished using a microsecond fiber laser system. A polished area of 7.5 mm × 7.5 mm was obtained for every workpiece. Six controlling factors were varied. The laser operating conditions were carried out for all the specimens divided into three groups in order to find the workable realm and minimize the areal average surface roughness (Sa). Laser fluence was adopted in this study as one of the representative factors. Spatial Fourier analyses of the code-C specimens were made for the *x* and *y* directions to obtain the amplitude–frequency spectra of the specimens. The results are used to compare the differences in amplitude and spatial frequency between the highest peaks of the unpolished and polished specimens. The minimization demands in Sa and the amplitudes in the two directions are regarded simultaneously to determine the qualified operating conditions. The critical spatial frequency (f_{cr}) is evaluated for all specimens, and its effect on Sa is investigated. The average thickness values of MZ and HAZ were evaluated as a function of laser fluence. The effects of laser fluence on the strain formed in these two zones are evaluated, and the relation between the strain and the iron (1 1 0) intensity in X-ray diffraction (XRD) pattern is established. The reduced modulus (E_r) and hardness (H) of specimen are presented as a function of fluence. Tribological tests were carried out to establish the wear rate as a function of the total thickness of these two zones and the friction coefficient as a function of Sa.

2. Experimental materials and procedures

2.1. Specimen details, laser system and controlling factors

The dimensions of the prepared SKD61 tool steel (4Cr5MoSiV1/AISI H13/DIN 1.2344 tool steel) specimens were 15 mm (length) × 15 mm (width) × 2 mm (thickness). Each specimen was polished in an area of 7.5 mm × 7.5 mm. The Sa value of the as-received specimen was 0.2853 ± 0.0305 μm in the direction perpendicular to the grinding marks. The chemical composition of the steel was: 0.32–0.45% C, 0.8–1.2% Si, 0.2–0.5% Mn, 4.75–5.5% Cr, 1.1–1.75% Mo, 0.3% Ni, 0.25% Cu, 0.8–1.2% V, 0.03% P, 0.03% S, and balanced by Fe. These specimens were prepared without prior heat treatment. The hardness (H) and reduced modulus (E_r) obtained from nanoindentation tests were 5.203 and 383.091 GPa, respectively. In the experiments, a commercial microsecond ytterbium-doped single-mode (TEM_{00}) fiber laser system (IPG YLR-500-AC, USA) was used to polish the samples. A schematic diagram and photograph of the LP system are shown in Fig. 1(a) and (b), respectively. The LP system is equipped with a laser source, galvanometric scanners, lenses, machined chamber and computer that controlled the laser power, sample stage elevation in the *Z* direction, and the position of the scanner moving in the *X*–*Y* plane. The intrinsic laser beam that radiates from IPG YLR-500-AC is a style of continuous wave. The laser system is equipped with an internal pulse generator and activated by "LOCAL" and "REMOTE" control regimes. In these two control regimes, there exist "Internal control", "Modulation", "External Control", and "Gate" as the modes of operation. Emission activation is performed by means of modulation signal applied to the two pins. The value of pump LD current was set using control buttons. The command for emission had to be sent via "Emission" button on front panel. Pulses were generated internally with parameters set by using Pulse Settings sub-menu on the front panel. Start or stop of the pulse train was controlled by the gate signal applied to the two pins. The scanner system is composed of a hurrySCAN *II* 14 scan head (SCANLAB, Germany) with an objective (ID no. 116913). It is designed for positioning laser beam. The emission of the *X*- and *Y*- direction incident upon the specimen was controlled precisely by the two