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Surface quality, microstructure, mechanical properties and tribological results of the SKD 61 tool steel with prior heat treatment affected by the deposited energy of continuous wave laser micro-polishing

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ABSTRACT

SKD 61 tool steel specimens hardened by heat treatment are subjected to continuous wave laser micro-polishing (CWLμP). A total of 46 specimens are classified into three groups in order to find the operating conditions to minimize the areal average surface roughness (Sa) via a three-stage process. Deposited energy per area (DE, unit: J/mm^2) is defined as a composite parameter of laser power (P), laser beam scanning velocity (V), and focused spot diameter (SS). The parameters of Sa and the sum of the thickness sum of the melt zone (MZ) and heat-affected zone (HAZ), as well as the mechanical properties of hardness (H) and reduced modulus (E_r), are then expressed as a function of DE. Appropriate choices of laser operating conditions allow the Sa corresponding to the DE value at about 70 J/mm^2 to be the smallest for these specimens. Due to the complex behavior involved in the thermocapillary flow, the only controlling parameter that Sa increases monotonically with is the hatch distance. Decreases in focal offset (FO) and laser power (P) cause a decrease in the highest amplitude of the polished surface in the spatial frequency analyses. The highest amplitude cannot decrease if the scanning velocity is excessively high or low. The core roughness depth (S_k) and the reduced peak height (S_{pk}) and valley depth (S_{vk}) are found to be linearly proportional to Sa. The H and E_r values of the specimens are lowered by increasing the applied deposited energy, although DE is not the sole governing parameter. The mean values of H and Er in the MZ, HAZ, and base material are found to increase by increasing the depth beneath the top surface of a specimen. The smaller wear rate in the specimens of CWLμP compared to that of the as-received specimen can be attributed to the lubrication effect arising in the tribo-contacts of specimens with a grain size greater than the critical value. The differences in several properties between the as-received specimens with and without heat treatment are compared and discussed.

1. Introduction

Laser micro-polishing (LμP) 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). In order to obtain uniform surfaces, Willenberg et al. (2003) also developed a combined process. It was remelting in the first step, then evaporating plus remelting in the second step after Electro Discharge Machining (EDM) or milled surfaces. The smoothing of macrostructures is achieved using continuous wave laser radiation. A melt pool is first 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 the process of polishing with pulsed laser radiation, the procedural parameters of laser power and scanning velocity have a significant influence on the roughness of the treated surface. For micro laser polishing both the pulse energy and laser beam diameter affects the geometry of the melt pool, while pulse duration governs the interaction time between the laser radiation and material. The interaction time between the laser beam and the material

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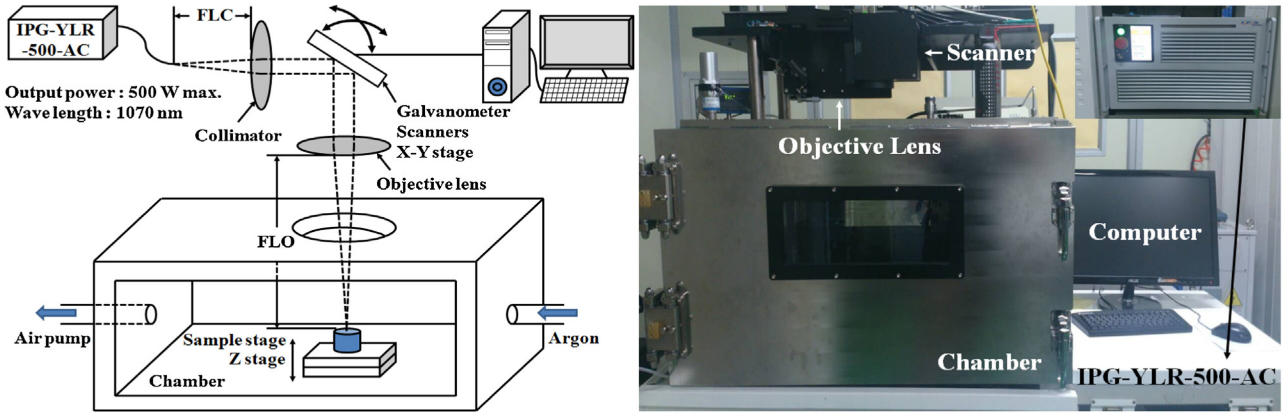

Fig. 1. (a) Schematic diagram of the PLμP setup and (b) photograph of the system.

surface of the specimen is the same order of magnitude as the lifetime of the melt pool. The molten material may thus have already resolidified before a consecutive laser pulse remelts the surface again, but in a slightly different place. In contrast, with micro polishing with continuous wave (CW) laser radiation the geometry of the melt pool is affected significantly not only by the laser beam diameter and laser power, but also directly by the scanning velocity. The laser radiation in the CW laser radiation is factored by the molten material, and the lifetime of the melt pool is governed by the scanning velocity. This inspires us to define the deposited energy in terms of these three parameters in the present study. Continuous-wave laser polishing has been investigated with regard to macro-scale metal parts (Lamikiz et al., 2006), with positive results. The measurements of topography and roughness parameters show that the laser polishing can achieve surface improvements up to three times with no macro-geometric deviations. Ramos and Bourell (2002) indicated that moving laser beam just provides enough heat energy to melt the surface peaks. The molten material flows down into the surface valleys by surface tension, gravity and laser pressure, thus reducing the roughness. However, this process resulted in melt zone (MZ) depths and heat affected zone (HAZ) depths of hundreds of micrometers (Willenberg et al., 2003).

Laser polishing is generally a multistep process (Temmler et al., 2009), moving from the smoothing of milling grooves at the macro level up to the gloss-level (i.e., micro polishing level). The laser heat energy just caused melting on an extremely thin surface layer by laser radiation (Kiedrowski et al., 2005). The smoothing of material microstructures is achieved by the use of CW laser radiation. Using CW laser radiation the macro laser polishing process can create a continuous remelted surface layer which is between 10 μm and 80 μm in depth (Temmler et al., 2012). The initial surface roughness and its spatial wavelength are of importance to the choice of whether macro or micro polishing will be used. With macro laser polishing the roughness within the interval of spatial wavelength from 80 μm to 1280 μm can be smoothed effectively. The effectiveness of this approach is limited with regard to roughness with spatial wavelengths lower than 80 μm, due to the formation of martensitic structures during cooling of the solidified material. However, this issue can be reduced by micro laser polishing.

A cylinder-bore surface treatment was carried out using a CW Nd: YAG laser in order to form oil reserve holes but still keep the initial plateaued texture (Duffet et al., 2003). The goal of this earlier work was to obtain an amelioration of the ring and liner surface friction. A CO_2 CW laser was used to polish the spot surface of silica rods (Wang et al., 2003), and the same study assessed the effect of the laser-surface inclination angle on the related power requirement was assessed both experimental and theoretically.

In Temmler et al. (2011, 2012) a thin surface layer was made molten and the surface tension led to the material flowing from peaks to valleys. No material was removed, but instead became reallocated while molten. A two-gloss effect can be created by selective variations of the process parameters, such as laser power and process velocity. Thermocapillary flows are generated in PLμP when large melting durations are used, and these can reduce surface roughness significantly at the expense of creating residual high-spatial-frequency process features. How the tool path may affect the removal of material during laser polishing was investigated in Tam and Cheng (2010), which presented an analysis of the removal due to polishing along adjacent path lines. Four tool paths were covered, and the results showed that changes in the direction of the tool path should be well distributed in order to have more uniform removal of material. Pfeffkorn et al. (2013) adopted a two-pass polishing process, in which the first pass takes advantage of thermocapillary flows to significantly reduce surface roughness, and the second removes the residual process features. The experimental results indicated a 72% improvement in the average surface roughness of a Ti_6Al_4V surface. Three independent investigation methods were developed in Martan et al. (2006) to investigate laser-induced thermal processes, in which the melting threshold and melting duration were determined. A surface finishing method for parts built-up using selective laser sintering (SLS) has also been presented (Lamikiz et al., 2006, 2007). In this earlier study 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), and the critical frequency for the 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 Nd:YAG CW laser was used to polish DF2 cold-worked steel (Guo, 2009). The laser feed rate was the dominant influence for the topography of the resulting laser-polished surface. At a constant pulse duration and pulse frequency, the polishing temperature rose as the laser input energy increased and the pulse feed rate decreased. Ukar et al. (2010a,b) 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 the surface material, which flowed into and filled topographic valleys, creating a smoothed surface topography, and the properties of the laser radiation greatly influenced the results. The influence of the type of intensity distribution on a steel surface was investigated in Nüsser et al. (2011), and the effect of pulse duration on the maximum polishable spatial wavelength was examined. The overlap between two successive