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Prediction of roughness after ball burnishing of thermally coated surfaces

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ABSTRACT

An analytical model for a ball burnishing process is developed, which allows a prediction of the roughness of a thermally sprayed coating after a post treatment. Based on the observation of a roughness peak, a correlation between the leveling during rolling and the surface pressure under the rolling ball as well as a material parameter is derived and made mathematically describable. The model is verified by experimental studies with various rolling parameters and materials. The agreement between the experimental data and the calculated values is satisfactory.

1. Introduction

In the field of forming technology, coatings are used to increase the wear resistance of forming tools, as described by Doege and Behrens (2007). This is especially necessary in deep drawing of high-strength sheet materials due to the high loads on the forming tools. Conventional coating methods to increase the wear resistance of forming tools are vapor deposition (CVD) and physical vapor deposition (PVD) processes (Sresomroeng et al., 2011). In addition, thermally sprayed coatings can be used to increase the wear resistance. In this connection, filler materials are melted by means of a spray gun. The melt material is projected against the surface to be coated. After cooling down, the filler materials have turned into a hard, wear resistant coating. Tekkaya et al. (2012) demonstrated that the service life of deep drawing tools can be increased by a multiple by applying thermally sprayed coatings. However, the disadvantage of thermally sprayed coatings is the high surface roughness after spraying. Poor surface qualities of the produced components and low draw ratios are the results if coated forming tools are used without a post treatment of the surface. Ball burnishing is a promising approach to reduce the roughness of thermally sprayed coatings. Tekkaya et al. (2013) showed that the friction coefficient between coating and sheet metal can be reduced significantly by ball burnishing. This leads to an increase of the limiting drawing ratio. In addition to the smoothing of the surface, ball burnishing offers further advantages. By the rolling process, compressive residual stresses are generated. This is advantageous for wear since cracking in the surfaces can be reduced. Finally, the surface hardness increases due to cold work hardening, as described by Broszeit and Steindorf (1989). The principle of the burnishing process of a coated surface is depicted in Fig. 1. A rolling ball is pressed against the surface by a hydraulic pressure. Moving the burnishing tool results in a rolling of the burnishing ball on the surface and this results in a leveling of the surface irregularities.

Ball burnishing tools are commonly used in a lathe to smooth rotationally symmetrical components like shafts. As shown by Loípez de Lacalle et al. (2005), complex free form surfaces can be ball burnished by mounting the burnishing tool in a CNC milling machine. If a specific surface quality shall be achieved, a selected control of the rolling parameters is required. Luca et al. (2005) demonstrated that surface conditions after rolling depend on the materials to be machined, the initial roughness, and the rolling parameters (rolling force, feed). In order to adapt the surface roughness to specific requirements, there are different approaches to set the rolling parameters.

The identification of the influence of rolling parameters on the rolling results can be conducted experimentally. Neema and Pandey (1980) identified the rolling force and the number of passes as the main factors affecting the surface quality after burnishing. The works were carried out on mild steel, which was pre-processed by turning. The relationship of the depth of impression of the roller body to the surface and the leveling was examined in the studies of Moore (1948). It is shown that a complete flattening of the asperities is not possible due to the cold work hardening. Furthermore, experimental studies about smoothing the surface of the rotationally symmetric parts of Al–Cu alloys were carried out by Hassan

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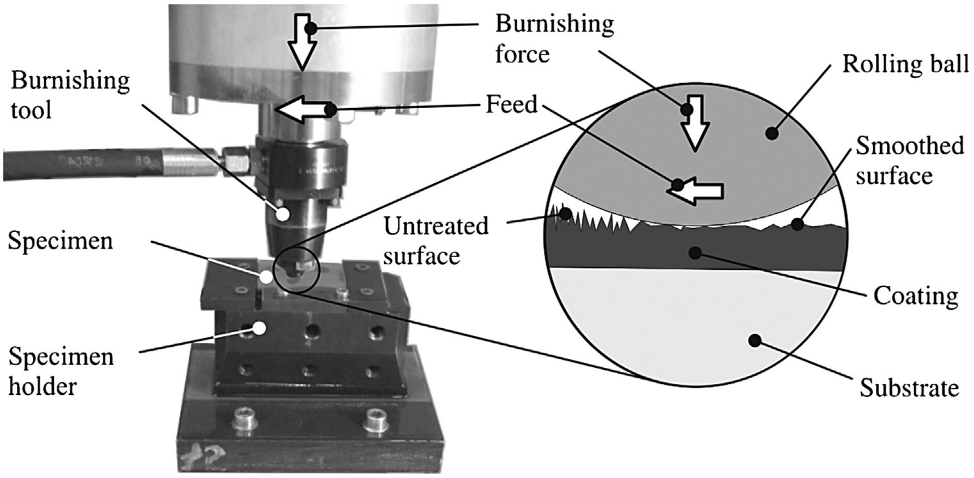

Fig. 1. Ball burnishing of a thermally coated surface.

(1997). The modified rolling parameters were the feed, velocity, force, number of passes, ball diameter, hardness of the material, and the initial roughness. It turned out that an increasing rolling force results in an improved surface roughness. However, if the force is increased excessively, the surface is damaged and, thus the surface quality decreases. A strong influence of the rolling force and the material hardness on the leveling is described in the work of Röttger (1982), in which the influence of burnishing is examined for hard-turned surfaces. An increase in the rolling force results in an improvement in the surface quality after rolling. Furthermore, the roughness after burnishing had an almost linear relationship to the initial roughness.

A further possibility to design the rolling process is the use of numerical modeling. Due to the complex boundary conditions as well as the fine mesh density, only limited portions, and not the entire rolling process, can be considered in a finite element simulation. But the numerical analysis of the rolling process has the advantage (compared to experimental investigations) that the material flow at the roughness peaks can be investigated. Balland et al. (2013) demonstrated the formation of a ridge on each side of the created groove as a result of the rolling process with high forces.

The burnishing process can be investigated also analytically. In the work of Li et al. (2012), a method for designing the burnishing process of turned surfaces with longitudinal grooves is presented. The smoothing of the surface depends only on the yield stress of the work piece and the geometrical conditions of the surface asperities. It is assumed that the flattening is in direct dependence on the angle of the roughness peaks, which is in contradiction to the approach that is part of this article.

The works described previously deal with the influence of the rolling parameters on the smoothing of roughness peaks by rolling of uncoated components. The investigations were conducted experimentally, by simulation, or analytically on rotationally symmetric components. A direct transfer of this knowledge to the rolling process of thermal spray coated surfaces with the specific surface caused by the spraying process as well as the multi-layer system is not possible. A closed-form, analytical model for the configuration of the rolling process of thermally coated surfaces and, in particular, for the use of rolling tools in a CNC milling does not exist. Therefore, the aim of this article is the development of an analytical model to predict the surface roughness in dependence on the rolling parameters for a ball burnishing process of thermally sprayed coatings. This model will allow the design of the rolling process in dependence on the required surfaces.

2. Analytical approach

In order to identify the relationships between the smoothing of the surface and the rolling parameters, a microscopic examination of the roughness peaks is carried out.

2.1. Approximation of the thermally coated surface by means of pyramids

The surface of a thermally sprayed coating has a rough, hilly topography, which is caused by the coating process (Fig. 2a). The coating surface is approximated with pyramids for mathematical description. During the ball burnishing process, the roughness peaks are forged and thereby the surface is smoothed (Fig. 2b). This, in turn, results in a block-shaped section at the top of the pyramid. The material flow and, thus, the shape of the pyramids after the application of a force was validated by simulations using the simulation software Abaqus.

2.2. True strain

A roughness peak before deformation is represented as a pyramid. After smoothing of the roughness peak by the rolling process, the form of the peak can be depicted as a combination of a truncated pyramid and cuboid (Fig. 3). Assuming uniform deformation of all pyramids, the average roughness ($Rz_{\mathrm{untreated}}$) of the coated surface can be defined as the pyramid height. After forming, the average roughness (Rz_{rolled}) can be obtained as the average height of the deformed pyramids (Fig. 3).

During the ball burnishing process, there is a strong compression at the top of the roughness peaks as result of the pyramid shape. The lower part of the pyramid is not deformed. However, the change in the total height is used to define an average true strain over the complete height of the roughness peak ($\varphi_{\mathrm{rolling}}$):

$$\varphi_{\mathrm{rolling}} = \ln\left(\frac{Rz_{\mathrm{rolled}}}{Rz_{\mathrm{untreated}}}\right) \tag{1}$$

Since the volume of the roughness peaks before and after deformation remains unchanged, the volume of the upper part of the pyramid before forming V_1 can be equated to the cuboid after forming V_2 (Fig. 3).

$$V_1 = V_2 \tag{2}$$