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Thermo-Physical Modelling of Track Width During Laser Polishing of H13 Tool Steel

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Abstract

A three-dimensional CFD model has been developed to predict track width during laser polishing (LP) of H13 tool steel. The developed model incorporates several different mechanisms for heat transfer such as conduction, convection, and radiation as well as temperature dependencies for relevant material properties. Experimental calibration was carried out to obtain adequate absorptivity value. After performing the mesh-sensitivity assessment, simulation results have been validated against experimental data. The relatively low errors obtained suggest that the developed model is capable to accurately describe the effect of process parameters on molten pool dimensions and/or geometry.

Keywords: : Laser polishing; thermo-physical model; numerical simulation; experimental calibration

1. Introduction

The majority of the manufacturing processes cannot be used as primary means to generate acceptable surface quality. For instance, while the roughness of the forged parts varies between 3.2 μm and 12.5 μm, milling will typically yield surfaces with R_a between 0.8 μm and 6.3 μm [1]. However, for many applications, these values are

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well above the acceptable levels of quality such that secondary polishing processes are required to further improve the roughness of the surface.

Among them, laser polishing (LP) represents a contactless manufacturing option that continue to receive a constant attention during the past decade, particularly since it was shown that it can produce surface quality improvements of up to 90-95% [2]. Moreover, LP enables the possibility of selective polishing for small areas (< 0.1 mm^2) that can be used to prevent problems like edge rounding [3]. By accounting for workpiece material, initial roughness and laser parameters, it was determined that LP process can be run with speeds of up to 3 s/cm^2 and that is 600 times faster than the conventional manual polishing techniques that is still widely used by the mold and die industry [4].

The surveyed literature suggests that LP can be successfully used to enhance the surface quality of a wide range of metallic [2] and nonmetallic materials [4, 5]. However, uncontrollable/unknown mechanisms occurring during melting and solidification phases of LP can introduce a broad variety of defects such as undercuts, ripples, bulges, martensite needles and step structures which in turn will decrease the overall surface quality of the polished surface [6]. Evidently, a deeper understanding of the interactions between various LP parameters might be able to prevent the formation of such unwanted structures but so far, LP process was primarily investigated by means of costly and time consuming trial-and-error experiments.

The traditional complement of the experimental work is constituted by the theoretical analysis that – when adequately performed – could provide important insightful information regarding the thermo-physical mechanisms underlying the LP process. However, with the exception of several analytical or semi-analytical studies [7-9], the vast majority of non-experimental works reported so far have relied on numerical methods, most likely due to the high complexity and/or nonlinearity of the phenomena involved. For instance, the one-dimensional unsteady model proposed in [10] was capable to determine the energy density required for melting of the silicon carbide during LP. Along the same lines, a 1D unsteady model was also devised in [11] in order to determine the melting depth. The inherent simplifying assumptions of the model were related to a uniform laser distribution energy as well as a dominant conduction mode for heat transfer. By contrast, a 2D modified fixed domain method in conjunction with Stephan boundary equation has been used in [12] to trace the liquid-solid boundary in a molten pool during polishing of 304 stainless steel and melt depth has been predicted by an enthalpy-based model solved through the CFD technique in [13, 14].

Pre- and post-polished surface geometry was also one of the points of interest for some of the past simulation works. In this context, the decomposition of the initial surface geometry into different spatial frequency components was used in [15] to predict the post-polished surface topography and a number of later studies [16-19] have reinforced the idea that critical frequency represents to date, one of the most important theoretical advancements in the field of LP. All previously-reported simulations imply that the accuracy of the heat transfer simulation can significantly influence the accuracy of the modeling result.

However, to the best of our knowledge, no prior attempts were made to analyze the width of the polished track along a LP line as a measurable process outcome. As such, the aim of the present work was to develop a numerical model capable to predict the width of the polished line by reducing the number of simplifying assumptions that would inevitably lead to less accurate predictions. In the current implementation, material absorptivity (*i.e.*, the capacity of the workpiece material to partially absorb the incident laser energy) will be specified throughout experimental calibration as it plays a prominent role on the overall thermodynamic balance of the process. It is also important to note here that the width of the laser polished track has important implications on both the quality of the polished surface as well as the overall tool path planning strategy to be adopted.

2. Thermo-physical processes underlying laser polishing

Undoubtedly, a good understanding of the thermo-physical processes and laser/material properties/interactions constitute some of the key ingredients of reliable and accurate LP simulations. In this context, it can be stated that when laser irradiates the surface a certain fraction of its energy will be absorbed into the workpiece while the rest will be reflected and thereby affect the surrounding environment. The fraction of absorbed energy, defined by absorptivity, depends on the surface properties of the workpiece as well as the electromagnetic wave properties of laser beam [20].

Following this logic, it can be inferred that the laser energy that is absorbed by the workpiece will be converted