Surface & Coatings Technology 273 (2015) 60–76

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

A computer simulation study of the effects of temperature change rate on austenite kinetics in laser hardening

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ARTICLE INFO

Article history:
Received 18 September 2014
Accepted in revised form 31 January 2015
Available online 19 March 2015

Keywords:
Laser hardening
Austenitisation kinetics
Computer simulation
Phase transformation
Martensitic transformation
Hardness measurement

ABSTRACT

The paper presents a modelling of the laser hardening process by a high-power diode laser (HPDL). Through numerical implementation into the finite element method (FEM) code ABAQUS, the model is used in the computer simulation of two case studies of laser hardening selected for experimental validation. In the experiment, 100 × 100 × 15 mm cuboid samples made of 50CrV4 steel were subjected to laser hardening with significantly different sets of applied technological parameters (laser beam power, laser beam velocity) but still aiming at attaining a comparable maximum temperature on the sample surface. The simulation considers two alternative approaches to microstructure evolution and subsequent material hardness determination: one relying on the heating rate dependent austenitisation temperatures (Ac_1 and Ac_3) governing microstructure transformation kinetics and the other neglecting heating rate dependence. Physical objectivity of the computed results is verified based on the corresponding temperature field measurements on the sample surface during heat treatment process and hardness measurements through the thickness of the laser-hardened sample. The experimental validation clearly proves that considering austenite kinetics at a high temperature change rate in computer simulation is definitely more physically congruent. In the study of the applied process parameters impact, the effect of a higher temperature change rate on austenite kinetics is shown by the temperature shift of austenite and ferrite to austenite start formations. From the investigation of the effect of different heat inputs providing the same maximum temperature on the sample surface it results that deeper area of increased hardness is established when less laser beam power and velocity are applied.

1. Introduction

Laser hardening is a heat treatment process that is used to increase hardness of a workpiece surface domain by means of laser beam energy. Aimed at increasing the surface wear resistance, it is mainly used as the final heat treatment that normally transforms microstructure of the heat-affected surface domain while maintaining the microstructure of the interior of the workpiece. Considering the energy field distribution is rather concentrated around the laser beam source, laser hardening is mainly used for local heat treatment of specified workpiece surfaces of various geometrical shapes, such as the surfaces of manufacturing tools that are exposed to sliding, cutting, and/or forming.

The advantages of laser hardening over conventional methods of hardening (e.g., induction hardening, flame hardening, or furnace hardening) are its flexibility and ability to automate the hardening process and its precise, contactless local heat treatment with no need for additional cooling media such as oil or water. Because the energy of the laser beam heats up the workpiece surface rapidly, a high temperature difference between the heated surface domain and the interior of the workpiece is established. The interior of the workpiece acts as a heat sink because of its significantly larger volume, thus allowing the surface domain to cool quickly after heating and the interior temperature not to increase significantly. This results in a smaller heat-affected zone, less temperature-dependent deformation, and rapid hardening.

Laser hardening enables treatment of different types of steel because there is a wide range of technological parameters available [1]. Directly related to the given laser source are the laser type and its wavelength, nominal power and the power density distribution of the laser beam. The velocity of the laser beam with regard to the workpiece is an additional and significant process parameter [2,3]. For a determination of optimal hardening process parameters, the chemical composition and microstructure of the steel from which the workpiece is made should be known. The microstructure, being dependent on previous mechanical and/or heat treatment performed on the workpiece [4], and the specified heat treatment parameters determine the kinetics of phase

Abbreviations: HPDL, High-power diode laser; FEM, Finite element method; FE, Finite element; TTA, Time–Temperature–Austenitisation diagram; TTT, Time–Temperature–Transformation diagram; CCT, Continuous–cooling–transformation diagram

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http://dx.doi.org/10.1016/j.surfcoat.2015.01.075
0257-8972/

transformations during the heat treatment process. The amount and type of phase transformation have a key impact on the mechanical state of the workpiece after heat treatment [5].

In order to obtain increased hardness after heat treatment on the surface domain of the workpiece, this domain should be heated above the temperature of austenitisation. In the cooling phase, austenite normally transforms into a mixture of martensite, bainite, pearlite, or ferrite microstructure, depending on the cooling rate of the steel. As the heating rates in laser heat treatment are normally in the order of 10^2 to 10^4 °C/s, a greater driving force is required to transform the base material to austenite microstructure, which results in a higher austenitisation temperature in comparison to conventional slow heating (e.g., heating in a furnace) [1,2]. The influence of a constant heating rate on the austenitisation temperatures Ac_1 and Ac_3, the temperature at which austenite begins to form (Ac_1) and the temperature at which ferrite completes its transformation into austenite (Ac_3), has been experimentally analysed for heating rates up to 2400 °C/s in [6]. It is shown that with an increase in the heating rate, the austenitisation temperatures Ac_1 and Ac_3 increase as well. The dependence of the austenitisation temperatures Ac_1 and Ac_3 at a constant heating rate is well known as the time–temperature–austenitisation (TTA) diagram.

A proper determination of the Ac_1 and Ac_3 temperatures during computer simulation of laser heating is important because of the impact these temperatures have on material properties, kinetics of phase transformation, volume dilatation and latent heat release, amount of transformed microstructure, and a determination of hardness profile. In the literature there are essentially two approaches to the Ac_1 and Ac_3 temperatures determination.

In the first approach, the Ac_1 and Ac_3 temperatures are assumed as heating rate independent. Accordingly, they are constant and equivalent to the Ac_1 and Ac_3 temperatures for conventional slow heating while the phase transformation kinetics during heating is not explicitly defined. The latter is rather simplified and determined by linear interpolation between the austenitisation temperatures [7] or simply defined as on/off function with respect to temperature [8,9]. In [7], the author used linear interpolation of volume dilatation during phase transformation of initial microstructure into austenite, which is in direct correlation to the linear interpolation of microstructural kinetics of considered C15 and C45 steel. The respective austenitisation temperatures were determined in accordance with empirical equations based on chemical composition of the considered steels. Following the on/off approach, the value of the Ac_3 temperature of stainless steel with unspecified composition was determined in [8] to be 780 °C, whereas in [9] the value of 770 °C was presented as the Ac_3 temperature of C60 steel, wherein material has to be heated with a mean temperature of 833 °C for 2 s for complete austenitisation.

Within the second approach, where the austenitisation temperatures are considered as heating rate dependent, there are also different methods for the austenitisation temperatures determination. Among the first to give a comprehensive phenomenology description of the transformation hardening of steel surface by laser beam were Ashby and Easterling [2,3], who developed also corresponding thermal and kinetic model for laser hardening. In their opinion, the pearlite colonies on rapid heating first transform to austenite, then depending on the value of temperature relative to the Ac_3 temperature, a part or all the ferrite may transform too. The pearlite becomes austenite containing 0.8% carbon while the ferrite becomes austenite with negligible carbon content. Thereafter the carbon diffuses from the high to the low concentration regions, to an extent which depends on temperature and time. Considering the above assumptions they presented a pearlite to austenite kinetics law which is governed by interlamellar spacing of the pearlite and thermal history, while the homogenisation of austenite was modelled with carbon diffusion evolution [2]. Based on the developed simple models for pearlite dissolution, austenite homogenization and martensite formation, and considering the resulting temperature variation $T(z, t)$, Ashby and Easterling presented in [2] structural changes caused in hypoeutectoid steels under applied heat cycle. The extent of respective structural change is determined by considering whether the structural change is diffusive or non-diffusive. While the extent of diffusive structural changes depends on the total number of diffusive jumps which take place during the cycle and is measured by the kinetic strength I of the heat cycle, the extent of non-diffusional structural change, i.e. austenite to martensite transformation, depends on quenching rate d T/d t, rather than on kinetic strength I.

After giving a review on the development of kinetics and thermal coupling models that were based on Ashby and Easterling's approach and their further numerical implementation, Skvarenina and Shin presented in [10] a more sophisticated model where coupling of a 2D diffusion model with a 3D transient thermal model was applied in the analysis of laser hardening of a crankshaft made of AISI 1536 steel. By assuming the homogenization of austenite is governed by solute diffusion, Fick's 2nd law of diffusion was used to describe the kinetics. Furthermore, still remaining within Ashby and Easterling's approach, Bailey et al. presented in [11] a full 3D thermal and kinetics model which was then sequentially coupled to a 3D stress model in order to predict residual stresses. They solved the kinetics model by applying explicit finite volume scheme while the homogenisation of austenite was solved with Fick's 2nd law using finite volume method. From [10] it is also evident that the characteristic of all so-called Ashby and Easterling's approach based models is the inconvenience regarding required material properties determination. For proper calculation of microstructural kinetics detailed information of initial microstructure, incorporated diffusion and activation energy has to be either provided experimentally or assumed.

Another heating rate dependent approach for the calculation of austenite kinetics and determination of austenitisation temperatures was proposed by several research groups through a series of publications in [12,13], where the approach was comprehensively introduced and applied to steel XC42. The phase transformation calculation model by heating is based on the additivity rule, where the isothermal transformation kinetics is modelled according to the law developed by Johnson–Mehl [14] and Avrami [15]. The authors in [12] presented the formation of austenite through two steps– first the pearlite dissolution which is followed by the transformation of ferrite. The growth of austenite is modelled by two-phase Johnson–Mehl–Avrami law, one for dissolution of pearlite and the other for the transformation of ferrite, with the beginning of ferrite to austenite transformation being possible after the completed transformation of pearlite to austenite. The authors in [12] used isothermal heating diagram to determine the Avrami exponents used in the calculation of phase transformation during austenitisation. Their first guess of the isothermal heating diagram was estimated from experimental data of continuous heating tests and used to calculate the evolution of transformation during continuous heating, which was then compared to the experimental results. Based on this comparison a new guess of isothermal heating diagram was obtained. By applying the described procedure iteratively the optimal isothermal heating diagram was determined which was then used for further predictions. The authors pointed that the beginning and the end of corresponding transformation kinetics during heating are well predicted and congruent with experimental results most likely because of iterative correction procedure, while especially the calculated amount of pearlite to austenite is subjected to great discrepancy. The disadvantage of this approach is the lack of clarity regarding iterative adapting of isothermal heating diagram and also sensitivity of the calculated thermal field accuracy, which can impact the estimation of isothermal heating diagram.

In [16], still using Avrami approach, Mioković et al. also summed up their research on the effect of heating rate on the formation of austenite microstructure and the effect of cooling rate on the formation of martensite microstructure in case of a short time hardening process. In their first experiment, hollow cylindrical specimens with an outer