Optics and Laser Technology 107 (2018) 491–499

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

A model for the estimation of hardness of laser bent strips

Vikash Kumar, Uday S. Dixit *

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India

ARTICLE INFO

Article history:
Received 15 March 2018
Received in revised form 10 June 2018
Accepted 14 June 2018
Available online 28 June 2018

Keywords:
Laser bending
Finite element method
Phase transformation
Microstructure
Hardness

ABSTRACT

In this work, a model is developed for the estimation of hardness of the laser bent parts. The model incorporates the effects of phase fraction, cooling rate as well as strain hardening. This is accomplished by using microstructure integrated finite element method simulation of laser bending of steel strips. The methodology is illustrated with an example of laser bending of AH36 steel strips. The Johnson-Mehl-Avrami-Kolmogorov law and Scheil's additivity rule are employed to simulate the kinetics of diffusional phase transformation, while Koistinen-Marburger equation is employed for non-diffusional phase transformation. Effects of latent heat release during phase transformations, temperature and phase fractions on the variation of thermo-physical properties are considered. The proposed model is validated through experiments. The model is able to simulate the kinetics of phase transformation in laser bending that leads to reasonably accurate estimation of phase fractions and hardness of laser bent strips.

1. Introduction

Laser forming is a flexible forming process that does not require the application of force by a tool; instead it relies on the thermal stresses introduced by a laser beam. Due to its flexibility, the process is suitable for batch production and rapid prototyping. In the past, numerical and experimental investigations of laser bending process were carried out to understand the process mechanisms [1–4] and the effects of important process parameters on mechanical properties of the bent part [5–8].

Researchers have shown experimentally and numerically that the application of lasers in metal forming process induces microstructural changes that affect the geometry change and the mechanical properties of the material. Cheng and Yao [9] carried out microstructure integrated modeling of multi-scan laser bending process. They adapted the numerical model of hot rolling for laser bending of AISI 1012 steel. The bend angle and yield stress of the material was modeled considering strain hardening, dynamic recovery, recrystallization, superheating and phase transformation. The numerical and experimental results were in good agreement with each other. Fan et al. [10] developed a thermal-microstructural-mechanical model to understand the laser forming process. They investigated the effect of phase transformation on flow behavior of Ti-6Al-4V during laser forming. The phase transformation during heating and cooling was modeled using John-Mehl-Avrami-Kolmogorov (JMAK) law. The phase transformation of AISI 1010 steel during laser bending was examined by Fan et al. [11]. During heating, the phase transformation was modeled by the modified JMAK law, while during cooling Bhadeshia's phase transformation model [12] was applied to predict the phase transformation. The hardness in the heat affected zone was influenced by both phase constituents and work hardening. Many researchers conducted experiments to study the microstructural changes occurring after laser scanning and measured the hardness of the laser formed product. For example, Chan and Liang [13] studied the microstructural change of hardened high carbon alloy steel after laser bending. The hardness of the laser scanned zone increased due to formation of martensite with fine carbide particles on the top surface and with small amount of bainite near the bottom surface. Yilbas et al. [14] observed that the ferrite-pearlite microstructure of AISI 304 steel sheet transformed to martensite at the surface region of the laser irradiated layer due to high cooling rate.

A review of literature reveals that some models have been developed to predict the phase fractions in laser forming, but there is hardly any model on the estimation of hardness of laser formed products. On the other hand some research groups have developed numerical models for predicting the phase fraction [15–17] and hardness [18,19] of the workpiece after hot working processes. For example, Wang et al. [20] developed a finite element method (FEM) model for quenching of 1080 carbon steel cylinders. The hardness of the quenched sample was estimated by accounting the hardness of different phases viz., pearlite, martensite and retained austenite. The hardness distribution predicted from the FEM simulation of the quenching model was found to be in good

---

* Corresponding author.
E-mail address: uday@iitg.ac.in (U.S. Dixit).

https://doi.org/10.1016/j.optlastec.2018.06.029
0030-3992/

agreement with the experimental results. Kakhki et al. [21] developed a numerical model to simulate the kinetics of phase transformation; they predicted the microstructure and hardness during water and oil quenching of a gear made of AISI 4140 low alloy steel. For estimating the distribution of hardness, the effect of cooling rate was also considered along with phase fractions.

The aforesaid models predict the hardness accurately but these are not directly applicable to laser bending process. Laser bending is a fast heating and cooling process unlike hot working processes. In laser bending the cooling process is similar to quenching in a typical hardening heat treatment except for significant plastic deformation in the former. Literature contains phase transformation models for cooling after hot rolling [16] and quenching [17], which can be suitably combined to model laser forming. This work proposes a novel finite element method based model to predict the hardness distribution of the laser bent strip. The model incorporates effects of phase fraction, cooling rate as well as strain hardening of the material. Strain hardening effect plays a significant role in laser bending, where most of the plastic deformation occurs during cooling stage. The accuracy of the proposed model is validated through experiments on laser bending of AH36 steel.

This article is organized as follows. Section 2 describes the kinetics of phase transformation incorporating diffusional and non-diffusional transformations. The JMAK law [22,23] incorporating Scheil's additivity rule [24] is employed to model the kinetics of diffusional phase transformations. The Koinstinen-Marburger equation [25] was used to compute the evolution of martensite during cooling of steel. In Section 3, an FEM model is developed to simulate the microstructure integrated laser bending process. Here, metallurgical and thermal behaviors of material are incorporated to predict the volume fraction of different phases of the laser scanned strip. A model for the estimation of hardness is developed to predict the Vickers hardness of the laser bent strips. In Section 4, the experimental conditions and corresponding FEM simulation are elaborated. The validation of developed FEM model and discussion is presented in Section 5. Concluding remarks are presented in Section 6.

2. Governing equation of phase transformation

Phase transformation occurs during continuous cooling of the laser irradiated steel sheet forming various phases such as ferrite, pearlite, bainite, cementite and martensite. The volume fraction of these phases depends on the cooling rate and the composition of the workpiece material. In order to deal with all these phases, the volume fraction of each of the phase is represented by X_f, where the subscript f ranges from 1 to 6 and indicates different phases— 1: austenite, 2: ferrite, 3: bainite, 4: pearlite, 5: cementite and 6: martensite. The phase transformation is an isochoric process; therefore, the sum of volume fractions must be unity i.e., $\sum_{f=1}^{f=6} X_f = 1$, where X_f lies in between 0 and 1. The phase transformation of the steel sheet during heating from room temperature to austenitizing temperature depends on heating rate, temperature and the austenitization time. Luo et al. [26] obtained a Time-Temperature Austenitization (TTA) diagram of low carbon steel (SA508 Gr.3). As per it, time required for austenitization decreases with increase in temperature and it reduces to zero above 925 °C. TTA diagram of Luo et al. [26] were digitized and used in this work.

There are two types of transformations— diffusional and non-diffusional. In case of hypoeutectoid steels, the formation of proeutectoid ferrite, pearlite and bainite occurs due to diffusional transformation. Diffusional transformation is a time-dependent phenomenon. It strongly depends on temperature and proceeds by nucleation and grain growth. The evolution of these phase transformation can be predicted through an approximate solution using data from time-temperature-transformation (TTT) diagrams. The phase transformation analysis using this diagram is done by assuming that the cooling process may be represented by a curve divided in a sequence of isothermal steps, with a duration Δt as shown in Fig. 1. For each isothermal step, the kinetics of diffusional transformation is described by the JMAK law. The JMAK law can be expressed as [23,27,28]

$$X_f(T) = \hat{X}_f^{\max}\left[1 - \exp\{-\mathrm{b_f}(\mathrm{t})^{\mathrm{n_f}}\}\right], \quad f = 2, \ldots, 5 \tag{1}$$

where $X_f(T)$ is the volume fraction of f phase during the time t at a constant temperature T, $\hat{X}_f^{\max}$ is the maximum volume fraction of an f phase, b_f the diffusion coefficient and n_f is the Avrami exponent of transformation; b_f and n_f are the functions of temperature, and represent the condition of nucleation and growth rates [23,28]. The diffusion coefficient b_f (T) and Avrami exponent $n_f(T)$ can be determined by substituting the volume fraction of the phase at two different times in Eq. (1). Usually these two times are chosen as the start time t_f^s and finish time t_f^f. This provides the following expressions:

$$b_f(T) = -\frac{1}{\left(t_f^s\right)^{n_f}} \ln\left(1 - \frac{\mathrm{X_f^s}}{\hat{\mathrm{X}}_\mathrm{f}^{\max}}\right), \tag{2}$$

$$n_f(T) = \frac{\ln\left\{\dfrac{\ln\left(1 - \frac{\mathrm{X_f^s}}{\hat{\mathrm{X}}_\mathrm{f}^{\max}}\right)}{\ln\left(1 - \frac{\mathrm{X_f^f}}{\hat{\mathrm{X}}_\mathrm{f}^{\max}}\right)}\right\}}{\ln\left(\frac{\mathrm{t_f^s}}{\mathrm{t_f^f}}\right)}, \tag{3}$$

where $X_f^s$and X_f^f are the transformed volume fraction at the start and finish of the f phase transformation, respectively. It is very difficult to know the exact starting and finishing of the phase transformation. Moreover, the JMAK law may not be accurate at the very beginning and the end of the transformation. Hence, it is usual to take X_f^s and X_f^f as 0.01 and 0.99, respectively. The parameter $\hat{X}_f^{\max}$ is represented by

$$\hat{X}_f^{\max} = X_f^{\max}\left(1 - \sum_{i=2;\, i \neq f}^{6} X_i\right), \tag{4}$$

where $X_f^{\max}$ is the maximum possible amount of volume fraction for an f-phase. The $X_f^{\max}$ for proeutectoid ferrite can be determined using lever rule in iron-iron carbide phase carbon diagram. Consider an alloy of C_0 wt% carbon (C), between 0.022 and 0.76 wt% C. Cooling an alloy of this composition is represented by moving down the vertical line yy'. At point a, the microstructure will consist entirely of grains of the austenite (γ) phase, as shown in Fig. 2.

Boundary line PQ represents the phase transformation line from austenite (γ) to proeutectoid ferrite $(\alpha) + \gamma$. Cooling from point b to c, just above the eutectoid but still in the $(\alpha + \gamma)$ region, will produce an increased fraction of the α phase. At point c, the compositions of the α and γ can be determined by constructing a tie line at the eutectoid temperature (T_e); the α phase contains 0.022 wt% C, whereas γ phase contains 0.76 wt% C. The lever rule can be used to compute the maximum fraction of proeutectoid ferrite $(X_2^{\max})$ as follows:

$$X_2^{\max} = \frac{U}{U + V} = \frac{0.76 - C_0}{0.76 - 0.022} = \frac{0.76 - C_0}{0.738}. \tag{5}$$

As the temperature is lowered, all the γ phase that remained at temperature T_e will transform to pearlite, bainite and martensite depending on cooling rate. In case of other phases viz., bainite, pearlite, cementite and martensite, the maximum volume fraction i.e.,$X_3^{\max}$, $X_4^{\max}$, $X_5^{\max}$ and $X_6^{\max}$, respectively, is equal to 1.