International Journal of Heat and Mass Transfer 79 (2014) 189–200

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Variable beam intensity profile shaping for layer uniformity control in laser hardening applications

Dan Wellburn *, S. Shang, S.Y. Wang, Y.Z. Sun, J. Cheng, J. Liang, C.S. Liu

Key Laboratory for Anisotropy and Texture of Materials, North Eastern University, Shenyang, Liaoning Province, China

ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form 5 August 2014
Accepted 6 August 2014
Available online 23 August 2014

Keywords:
Laser transformation hardening
Temperature field
Beam shaping
Layer uniformity
Transformation kinetics

ABSTRACT

A circular laser beam with a variable intensity profile is used to manipulate the time dependent temperature field within the surface of a hypo-eutectoid steel with the aim of controlling the uniformity of the resultant hardened layer. A 3D thermal model with a moving surface heat source is coupled with a simple rate equation containing a temperature dependent time constant calculated using the initial grain size and carbon content of the steel. The transformation kinetics of the pearlite/ferrite → austenite conversion are modelled and used to calculate the resultant martensite fraction in the material surface and the martensite field is plotted to reveal the shape and extent of the hardened layer. The beam profiles used in the model are recreated in an experiment using a variable laser beam profile shaper. The beam shaper is capable of transforming the raw top-hat beam output of a laser into a thin annular shaped beam with a uniform central intensity feature; the power ratio of the central to annular intensity features can be varied. Microscopy and microhardness tests are used to characterise the shape and hardness of a cross-section of the hardened layer created by a single pass of the laser beam. Both the experiment and the model show that the uniformity of the hardened layer can be controlled by selection of the appropriate power ratio of central to annular intensities. It is found that there are optimal power ratios for maximum uniformity that increase with increasing processing speed.

1. Introduction

Laser transformation hardening is one of a range of heat treatments available to produce hard martensitic surface layers in carbon steels. The advantage of laser hardening over other heat treatment techniques is the controllable delivery of the energy directly to the required area. This gives the benefits of controllable case depth, greatly reduced possibility of damage to nearby materials or components, and a smaller heat affected zone outside of the hardened region. Control of the case depth of the hardened layer is usually accomplished by choosing a suitable combination of laser power, beam diameter and processing speed. When using conventional laser beams – those with circular cross-sections and either Gaussian or top-hat (uniform) intensity profiles – the hardened layer under the path of the moving beam takes on a bowl-like or meniscus shape. This effect is due to the reduced beam interaction time experienced by surface elements furthest from the centre of the beam in the case of a top-hat or Gaussian beam and is compounded by the reduced intensity in those areas in the case of a Gaussian beam. Variations in the depth of the hardened layer are usually undesirable, especially where wide area coverage is required or where the case depth is critical. Solutions to this problem can be roughly split into three categories: engineering the path of the moving beam; engineering the cross-sectional shape of the beam; and engineering the intensity profile within the beam shape. The aim of this research is to achieve control of the temperature field and therefore the uniformity of the hardened layer by engineering of the intensity profile within a circular shaped beam. The beam profile is circular to allow use of the beam in any processing direction, and variable so that it may be adapted to suit different processing speeds.

2. State of the art

The most commonly used method of compensating for the reduction in case depth at the edge of the treated area is by overlapping of the adjacent tracks. With the correct overlap ratio, a uniform hardened depth over a wide area can be achieved; however the effect of excessive overlapping on previously hardened tracks is deleterious. Van Ingelgem et al. [1] and Kim et al. [2] report the periodic reduction in surface hardness due to back tempering

* Corresponding author. Address: Room 627 Zhi Xing (ATM) Building, North Eastern University, 3-11 Wen Hua Road, Shenyang, Liaoning Province, China. Tel.: +86 (1) 86 40462104.

E-mail address: dan@atm.neu.edu.cn (D. Wellburn).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.020
0017-9310/

Nomenclature

A^*	specific area of hardened layer
A	area of hardened layer
A_0	absorption coefficient
c_c	critical carbon content
c	carbon content of steel
c_e	carbon content of pearlite
c_p	specific heat
d	depth of hardened layer
D	diffusion coefficient
D_0	diffusion coefficient at infinite temperature
f	fraction of transformed austenite
f_{eq}	equilibrium austenite fraction
f_i	pearlite fraction
g	initial average grain size
h	convection coefficient (air)
I_1/I_2	intensity of central/annular feature
k	thermal conductivity
$\mathbf{n}$	normal vector
P_1/P_2	power of central, annular feature
P_{12}	power ratio of central to annular features
P_{tot}	total laser power
Q_a	activation energy per mol
Q_{laser}	laser heat source
ρ	density
R	molar gas constant
R_1/R_2	outer radius of central, annular feature
T	material temperature
T_{amb}	ambient Temperature
v	laser processing speed
w	width of hardened layer

Greek symbols

ε	surface emissivity
σ	Stefan–Boltzmann constant
τ	transformation time constant

caused by overlapping of laser hardened tracks in stainless and carbon steels. If back tempering is to be minimized, then overlapping ratios must be reduced and/or the extent of the tempering region must be minimized when completing successive passes. For this to be possible, a single pass of the laser beam must *itself* create a uniform hardened layer. This can be achieved to some extent by shaping the outline of the moving beam in order to compensate for the reduced interaction times at the edges of the circular-shaped top-hat beam. Leung et al. [3] reported improved uniformity in hardness across a 15 mm wide area treated with a 15 mm by 2 mm strip shaped beam with a uniform intensity profile. Square-shaped and long rectangle[1] beams are less effective than strip or line shaped beams due to conduction losses at the outer edges leading to lower temperatures in those regions. Safdar et al. [4] report the effects of using long and short rectangle, square, circle, and triangle shaped beams on the hardened layer in a single laser pass on EN43A steel. Forward facing triangle shaped beams were shown to be most effective due to a reduction in heating rates and hence a decrease in the AC_1 temperature compared with other geometries.

Uniformities in hardened layer depth can be further improved by shaping the intensity profile within the beam outline. This can overcome the effects of reduced beam interaction times *and* conduction losses at edges of the treated area. Li et al. [5] report the use of a square 5×5 beam array created using a Quasi-Dammann grating to achieve a hardened layer with a uniform depth in Q235 steel. The optimum intensities of the beams in the array varied in the ratio 1:2:3 from the middle to the outer edges in the direction orthogonal to the axis of motion. Hagino et al. [6] report the use of a computer generated hologram to transform a top-hat beam into a line beam with an M-shaped beam profile in order to improve the uniformity of the hardened layer in 0.45% carbon steel. Bonss et al. [7] report the use of line scanning functions using rapid scanning mirror optics in order to create idealised temperature distributions for hardened layer uniformity across an area much wider than the beam diameter.

Primartomo [8] investigated the surface hardening effects of using a Diffractive Optical Kinoform in order to produce the 'armchair' shaped beam profile previously conceived by Burger et al. [9], which is optimised to create a uniform square shaped temperature distribution on the surface of the material. The beam profile is characterised by a very high intensity leading edge with an initially sharp, then gradual fall in intensity towards the trailing edge of the beam. Across its width, the beam has a shallow U-shaped intensity profile to compensate for lateral conduction losses. Burger designed this intensity profile for a specific material at a particular processing speed, and therefore the intensity profile reported is only optimised for use over a relatively short range of Péclet numbers. If the Péclet number is varied, the temperature field created by the moving beam also varies [10–14]. Wellburn [14] concluded that in laser surface heating applications, for any beam to remain fit for purpose, the intensity profile itself must be varied along with the Péclet number.

In this research, the objective is the creation of a uniform hardened layer in a single pass of a circular-shaped laser beam on the surface of an AISI 1045 carbon steel plate. To achieve the objective, the intensity profile within the circular beam shape is varied at different processing speeds. Specifically, a thin annular ring intensity profile is created with a uniform intensity fill in its centre. The relative intensities of the annular ring and central fill are varied to control the temperature field and therefore the transformation of microstructural phases in the material. A 3D finite element model is used to investigate the temperature field and resultant transformation kinetics within a block of hypo-eutectoid steel. Experiments are carried out to validate the main findings of the model. A refractive laser beam shaper is used to transform the output intensity profile of a fibre delivered laser beam to create uniform hardened layers in steel plates. Micro-hardness tests, optical microscopy and SEM are used to assess the hardness, shape and microstructure of the hardened layer.

Wellburn [14] and Shang et al. [15] have already reported this type of variable beam profile for laser surface heating in general and for laser curing of conductive inks respectively. Wellburn [14] first reported the use of these types of beam profiles to control the temperature distribution in the surface layer of the material. It was found that by careful choice of the relative intensities of the annular ring and central intensity features, the maximum

[1] Long and short rectangles refer to the orientation of the rectangle with respect to the direction of movement, which is parallel to the longest and shortest sides respectively.