Journal of Materials Processing Technology 239 (2017) 326–335

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Spatially resolved temporal stress evolution during laser surface spot hardening of steel

V. Kostov, J. Gibmeier*, A. Wanner

Institute of Applied Materials (IAM-WK), Karlsruhe Institute of Technology, Karlsruhe, 76131, Germany

ARTICLE INFO

Article history:
Received 10 February 2016
Received in revised form 10 August 2016
Accepted 30 August 2016
Available online 30 August 2016

Keywords:
Time resolved synchrotron X-ray diffraction
In-situ stress analysis
Residual stress
Laser surface hardening

ABSTRACT

The time-dependent stress evolution, the resulting residual stresses as well as the microstructure of the heat treatable low alloyed steel AISI 4140 induced by laser surface spot hardening was investigated systematically by means of synchrotron X-ray diffraction. In-situ stress analyses with a time resolution up to 100 ms were carried out at the synchrotron beamlines P05@PETRAIII(*), DESY, Hamburg and PDIFF@ANKA, Karlsruhe, by the application of the measurement and evaluation approach for very fast X-ray diffraction stress analyses. During the laser surface spot hardening using a homogenization working optic with a spot size of approx. $8 \times 8\,mm^2$ at a maximum temperature $T_{A,max}$ of 1150 °C and heating/cooling rates $v_{heat/cool}$ of 1000 K/s time-resolved diffraction data were collected for various measurement positions inside and outside of the processed zone aiming to analyze the different origins for residual stress build-up. The in-situ tests were supplemented by X-ray residual stress analyses and microscopical investigations of the microstructure subsequent to the laser hardening process (ex-situ analyses).

The results show that inside of the martensitic transformed region (process zone) in radial and in tangential direction homogeneous compressive residual stresses are generated. The data of the in-situ diffraction experiments reveal that these compressive residual stresses develop due to (i) local compressive elasto-plastic deformations and (ii) local phase specific transformation strains. Outside the process zone, the compressive residual stresses are balanced by rather high inhomogeneous tensile residual stresses. By means of the in-situ determined diffraction data it is proven that these tensile residual stresses have their origin in the superposition of (i) quenching effects outside the process zone, (ii) local elasto-plastic deformations and (iii) the effect of phase transformations in the nearby process zone.

1. Introduction

Surface optimization procedures in order to improve the wear resistance and fatigue limit of near surface material states is of great technical importance with regard to the improvement of the behavior and the endurance of engineering components since degradation like, e.g. corrosion or fatigue crack initiation usually starts at the surface. In this respect mechanical, thermal or thermo-chemical surface optimization processes have a huge practical relevance in industrial manufacturing.

Laser surface hardening is based on the local phase transformations through the heat input by means of a focused laser beam. The laser beam heats the steel work piece top surface very fast above the austenitization temperature A_{C3} such that due to the conduction of the heat a local, near-surface region transforms into austenite. Subsequently, the heat-affected material is subjected to a controlled quenching process, which is also called self-quenching, since during reduction of the laser power the heat flows rapidly from the process zone into the cold surrounding material. Martensite transformation occurs inside the prior austenitized surface-near region, which is accompanied by a strong increase in hardness. The bulk material remains unaffected and thus remains ductile. As consequence of this localized phase transformation strongly inhomogeneous residual stress distribution inside and outside the process zone are generated, as e.g. shown by Kostov et al. (2011). In comparison with other surface hardening techniques such as flame or induction hardening, the distortion after laser surface hardening is only minimal, as demonstrated e.g. by Müller (1999). Furthermore, modern laser beam systems are operated using optical fiber-coupled working optics, which offers a high degree of flexibility and makes this treatment technology attractive for the integration in various production processes. The fiber

* Corresponding author.
E-mail address: jens.gibmeier@kit.edu (J. Gibmeier).

http://dx.doi.org/10.1016/j.jmatprotec.2016.08.035
0924-0136/

coupling allows for processing of steel components and mechanical tools with large dimensions and complex shapes, as reviewed by J.C. Ion (2002). However, the industrial acceptance of the laser hardening technology is still limited, which is due to the high process complexity along with the incomplete process comprehension regarding the residual stress generation. Prediction of the laser hardening process is still unreliable and the control of the process is largely based on experience and observation of the final state.

2. State of the art

Process comprehension and state of the art of laser surface hardening of steels is essentially based on ex-situ case studies for particular materials and components subsequent to laser hardening. E.g. in Obergfell et al. (2003) the laser hardened surface layers of three different lower carbon steels were characterized by means of microhardness readings, the dislocation density, type, size and distribution of carbides as well as the grain size of the former austenite grains using SEM (scanning electron microscopy), TEM (transmission electron microscopy) and XRD (X-ray diffraction). Furthermore, in Miokovic (2006) the effects of the heating and cooling rates on microhardness, microstructure and the dissolution of the iron carbides are shown for laser hardened AISI 4140. In Domes (1995) and in Müller (1999) results of X-ray stress analyses at the surface as well as in depth of different laser hardened steels are presented for different process parameters, e.g., maximum process temperature, laser irradiation time and laser beam movement speed (see Domes, 1995) or sample geometry and sample material (see Müller, 1999). Schädlich et al. (1992) showed for instance that the compressive residual stresses in laser hardened notched samples improve the fatigue properties. Furthermore, the effects of the process atmosphere (air, vacuum, helium) as well as of the repeated austenite-martensite-transformation on the residual stress distribution after laser surface hardening are studied in Kostov et al. (2011, 2014a,b) by means of X-ray stress analyses carried out ex-situ after the laser treatment. It is shown that the lateral residual stress field is strongly non-uniform and complex. The two surface parallel mean residual stress components exhibit an inhomogeneous distribution, in particular outside the process zone. However, in all these ex-situ studies the explanations for the origins of the residual stress generation are generally only based on assumptions for the superposition of various effects regarding the thermal and elastic stains evolution. However, these effects could not be separated by means of the analysis results.

A large step towards obtaining direct information on the residual stress generation processes was reached by very fast synchrotron XRD strain-/stress analyses that provide real-time insight into the strain/stress evolution during laser surface hardening as presented in Kostov et al. (2012). By this methodical approach the temporal evolution of thermal and elastic strains can be separated.

A comparison between the temporal evolutions of the thermal and the elastic strains (and the deviatoric stresses that can be calculated from these elastic strains) obtained by using two different laser working optics (providing either a homogeneous circular beam spot with 3 mm diameter or a homogeneous rectangular beam spot with dimension $8 \times 8\,mm^2$) was carried out for a particular laser spot hardening process. The reasons for residual stress build-up in the center of the laser spot, e.g. quenching effects, phase transformation strains etc., were qualified, derived and discussed regarding the different heat flow in the sample due to the different laser spots applied. In a follow-up study (Kostov et al., 2014a,b) time-resolved diffraction data were obtained for different maximum process temperatures in the laser spot center. Based on these results the separation of the compressive and tensile elasto-plastic deformation during heating-up and quenching was realized and the residual stress build-up with respect to the maximum process temperature could be explained.

In the present work, we focus our time-resolved strain/stress analyses on the formation of residual stress in the vicinity of the laser spot. In this region inhomogeneous tensile residual stresses are induced by laser spot hardening, as presented in the ex situ study by Kostov et al., 2011. By means of the observation of the time-resolved strain/stress distributions for different measurement positions on the hardened sample surface we aim to reach a deeper comprehension of the different mechanisms for the generation of local residual stresses and to quantify their effects on the local residual stress build-up outside the laser processed zone.

3. Experimental procedures

3.1. Material and sample preparation

All investigations were carried out on low alloyed heat treatable steel AISI 4140 (German steel grade 42CrMo4) in a quenched and tempered state. Cylindrical samples with a diameter of 25 mm and a height of 10 mm were used. Prior to the laser processing the samples were mechanically ground at one circular faces in order to provide a defined surface with low roughness. Afterwards, a stress relieve heat treatment at 510 °C for 90 min followed by slow cooling was carried out in order to minimize the impact of the previous preparation steps.

3.2. Laser spot hardening

The experimental set-up is similar to previous laser experiments described in detail in Kostov et al. (2012) and (2014a,b). In the present study for all tests the control temperature (surface temperature) $T_{A,max}$ in the center of the laser spot was set to 1150 °C and a heating rate v_{heat} in the process zone of 1000 K/s was applied. Controlled cooling was carried out with a rate v_{cool} of 1000 K/s down to a surface temperature of 180 °C. The stationary laser beam in continuous wave mode was provided by a 6 kW high power diode laser (HPDL) system from Laserline Ltd. A fiber-coupled homogenizing optic with a spot size of approx. $8 \times 8\,mm^2$ was applied. The power of the laser beam was controlled via pyrometric temperature measurements by means of a monochromatic pyrometer (Mergentaler Ltd.) with a spot size of approximately ø 2 mm, which has its focus point in the center of the laser spot, providing a measuring range between 180 °C and 1500 °C. The temperature measurement of the pyrometer is based on an elaborate calibration by stepwise heating a 1 mm thin plate of AISI 4140 (with similar surface quality as the in-situ samples) using identical process parameters and conditions as for the in-situ experiments in the measuring range at a stepsize of 100 °C. The measured temperatures are used as bases for the pyrometer output. The respective calibration was consigned in the pyrometer software. The working optic and the pyrometer were mounted on a specially designed process chamber allowing providing an oxide free surface hardening (s. Fig. 1a). The absence of oxide layers is important for a reproducible temperature measurement/laser processing. A detailed description of the experimental set-up for oxide free laser material processing, i.e. the HPDL-system, the pyrometer and the process chamber, is given in Kostov et al. (2012). It must be noted that via the control loop to fulfill the predefined cooling rate of 1000 K/s a slight deviation from the input requirement occurs for temperatures below approx. 300 °C, which is due to the limited sample volume. This can be seen by the temperature course given in Fig. 4a.