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Prediction of the residual state in 304 austenitic steel after laser shock peening – Effects of plastic deformation and martensitic phase transformation

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ABSTRACT

Laser Shock Peening (LSP) can be used to improve the surface properties of metallic materials. During the LSP process, martensitic phase transformation can take place in austenitic steels under certain processing conditions in addition to plastic deformation. In this study, the plastic strains and the amount of martensite in 304 austenitic stainless steel after LSP is numerically predicted. In order to simulate the response, an existing elasto-plastic model that includes phase transformation is extended to capture the rate dependency of plastic deformation during LSP. The influence of temperature, laser pulse duration and laser intensity on the residual state is studied. It is, for example, found that martensite formation is accelerated by lowering the processing temperature, increasing the peening pressure as well as extending the laser pulse duration.

1. Introduction

Fatigue, corrosion and wear resistance of steel components are of major concern in many engineering applications. In order to improve such properties, different surface treatments can be employed. A classical method is shot peening where round non-abrasive metallic, glass or ceramic particles impact a surface at high speed. A similar method is ultrasonic peening where ultrasonic waves are applied to the surface of the material [1,2]. A third peening method – which is the topic of the present article – is Laser Shock Peening (LSP), where short pulses from a high energy laser beam are applied to a workpiece surface [3]. Common to all peening processes is that they are mechanical (not thermal) processes, where pressure is applied to the workpiece surface, causing plastic deformation and possible phase transformation in the affected region, cf. [4]. After peening, relaxation takes place and residual compressive stresses develop, which increase the fatigue, wear and corrosion resistance of the surface [5,6]. Peening processes have been studied both experimentally and by numerical models, for example in [7,8]. In [9], it has been found that LSP is the peening process that has the greatest penetration depth of the compressive residual stresses. The spatial resolution of LSP is very high and consequently it can be applied to confined regions, such as in the vicinity of holes or notches, that are inaccessible to other peening methods.

In LSP, the surface of the metal is covered with a black paint or a metallic foil which forms an ablative layer. A laser beam is focused on the target which results in the ablative layer being vaporised. The temperature of the vaporised material rises quickly to temperatures in the order of 10 000 K, resulting in ionisation and creation of a plasma [10]. Once formed, the plasma continues to absorb the energy until the end of the laser pulse duration. Increasing the temperature implies increasing pressure and hydrodynamic expansion of the plasma that creates a shock wave which propagates into the workpiece. The process is schematically illustrated in Fig. 1. To enhance the effect, the target material can be confined beneath a layer of water or glass. The confining medium impedes expansion of the plasma away from the surface which increases the pressure in the target material up to five times compared to an unconfined material [11].

LSP is usually performed with laser intensities in the range between 1 GW/cm^2 and 20 GW/cm^2 and a typical pulse duration is 3 ns to 30 ns. The laser pulse creates a pressure of up to 10 GPa in a spot with a radius in the order of a few millimeters. The pressure wave propagates into the material and plastic strains are created if the pressure exceeds the Hugoniot elastic limit. Since the plastically deformed region is constrained by the surrounding material, this results in the formation of compressive residual stresses.

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In this paper, focus will be on 304 austenitic stainless steel which cannot be hardened by heat treatment [13]. Instead LSP can be used as an alternative. Austenitic 304 steel is a widely used engineering material, not least in sheet metal forming. Plastic deformation and consequently peening treatment of the material may cause martensitic phase transformation which increases the hardness of the surface and also influences the formability of the material [14–16]. Many experimental investigations have been performed on the influence of LSP process parameters on the amount of martensite in 304 steel.

Considerable scatter in the experimental measurements of residual martensite after LSP exists in the literature. The amount of phase transformation depends strongly on the LSP process parameters and on the experimental procedure as for example the type of confining medium and ablative layer that are used. For some parameter settings, no martensite will form, cf. the review in [17]. The influence of process parameters on martensite formation further highlights the need for investigation of the LSP processing conditions on the residual state. In [18], the microstructural changes due to LSP were studied using TEM. Experiments on a non-confined material with an ablative layer of black paint and a very short laser pulse but high laser intensity were performed. Presence of martensite was observed, although it was not quantitatively examined. Using certain process parameters, embryos of martensite were observed in approximately half of the examined grains in [18]. In [17], large amounts of martensite were found after LSP when glass was used as a confinement layer. Up to 35.3% of martensite was found at room temperature and up to 45.5% martensite at 77 K. In [19], martensite was found after LSP of 304 stainless steel and different peening processes. Ref. [20], again show presence of martensite after LSP of the same type of steel. It can further be noted that other alloys may also contain martensite after LSP, such as the NiTi alloy studied in [21].

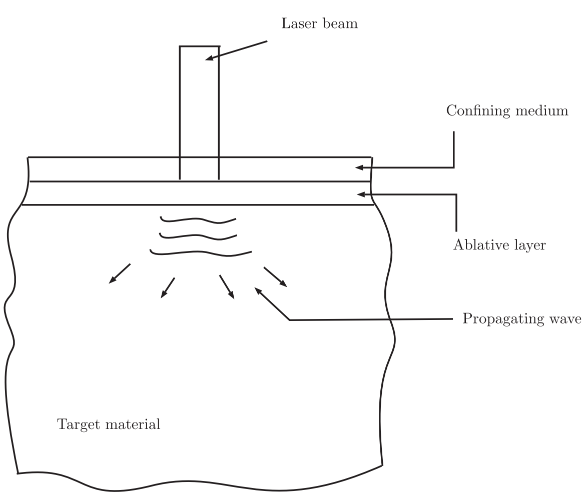

Fig. 1. Illustration of the laser shock peening process, after [12].

The conclusion from these studies is that for certain settings of the process parameters, martensite is formed at room temperature, and at lower temperatures the volume fraction of martensite will be higher. The increasing formation of martensite at lower temperature is not unique for LSP, but is a general characteristic for 304 steel, cf. [22]. An early numerical analysis of LSP using the finite element method (FEM) was presented in [12], where the residual stress distribution in 304 steel was investigated. Later, 3D models have been considered in order to capture the residual state following multiple shocks and at more complex spatial distributions of the shocks [23,24]. However, none of these numerical simulations consider phase transformation. A phenomenological model of martensitic phase transformation, previously established in [22], is further developed in the present work. The constitutive model includes austenite to martensite phase transformation as well as large strain plasticity. A yield potential and a transformation potential are used to model the interaction between plasticity and phase transformation. The constitutive model takes into consideration that the two processes, plasticity and phase transformation, may be activated independently of each other. Martensitic phase transformation is associated with volume increase which will induce yielding in the weaker austenitic phase although the external load is insufficient to induce plasticity in the material, a matter which is further discussed in [22]. LSP takes place at very high strain rates and rate dependency is taken into account by considering the yield potential as a dynamic potential, cf. [25]. The model will subsequently be used to identify the relative influence of process parameters on the formation of martensite and plastic deformation. The influence of different process parameters such as peak pressure, laser energy, laser intensity and ambient temperature on the residual state will be investigated.

2. Model of laser shock peening

An axisymmetric finite element model is used to simulate the residual state in 304 stainless steel after relaxation, when peened

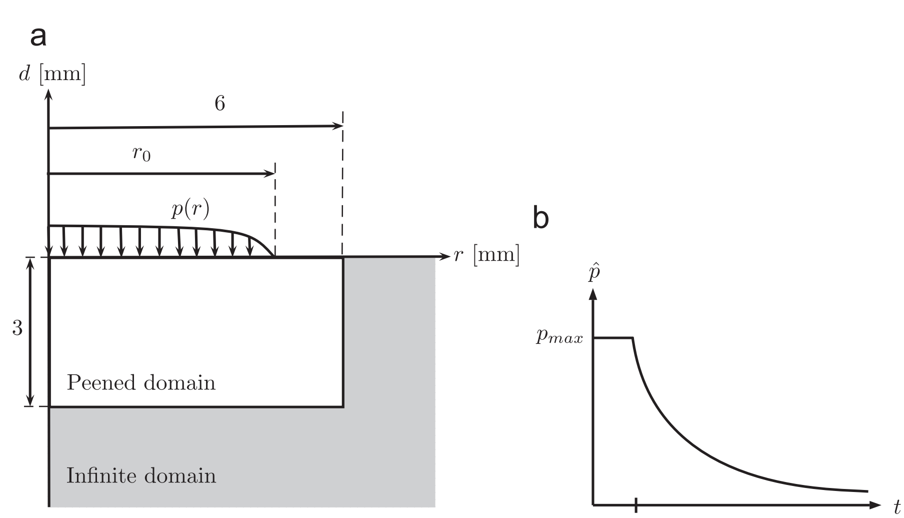

Fig. 2. (a) Model of the LSP (b) Temporal pressure distribution.