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Materials Characterization at High Strain Rates

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Abstract

The identification of material properties at high strain rates is of considerable technical interest, e.g., in applications for passenger safety-related parts which are expected to absorb energy in case of collisions. To additionally meet the requirements of a rapid and resource-efficient materials characterization, a novel high-speed hardness testing method based on laser-induced shock waves was investigated. The principal applicability of this laser-induced shockwave indentation technique for materials characterization at high strain rates is shown.

Keywords: Laser shock processing, High throughput, Measurement

1 Introduction

Besides various safety-related applications, strain rates can reach up to 10^4 s^{-1} for most metal fabrication processes like cutting, forging, stamping, or forming [1]. The deformability is affected by strain rate because of microstructural reasons combined with dislocation mechanics [2]. Amongst others, mild steel, carbon steels, austenitic steels, and maraging steels become strain rate sensitive above 10^3 s^{-1} [3]. So far, ballistic testing is a widely used and standardized process. However, several challenges arise when performing tests at cycle rates above 10 times the speed of the standard procedures [4] and at strain rates above 10^2 s^{-1}. Those challenges concern the limited dynamics of mechanical and measurement processes, which lead to inaccuracies. This gives reason to explore and identify material characteristics at high strain and cycle rates.

Suitable mechanical-based techniques rarely exist, which also consider the ongoing demand for rapid materials characterization. So far, those techniques are performed on a nanoscale as weight and stiffness are the limiting factors for mechanical-based indentation systems [1]. For this purpose, high speed nano-indentation testing has emerged as an advanced materials characterization technique to study mechanical properties at strain rates between $10^1 \ldots 10^3$ s^{-1}. Moreover, with improved electronics and novel designs, it is already possible to perform those tests faster than 1 s per indent [5]. Larger systems like ballistic testing are considerably slower.

To increase the testing speed at a larger scale, a new materials characterization approach is being studied which is based on laser-induced shock waves. This laser-based technique (Fig. 1) is hereinafter referred to as LiSE. Characteristic values are extracted from the indentation geometry, which correlate with mechanic material properties.

A TEA-CO_2 laser is used to induce shock waves above spherical indenters. So far, up to 90 indentations per minute can be created reproducibly with LiSE [6]. Reproducible indentations are theoretically possible at cycle rates of more than 20 Hz [7]. The TEA-CO_2 laser creates quasi-instantly a plasma at laser intensities $> 10^8$ W/cm², which absorbs nearly all the laser-specific wavelength of 10.6 µm [8]. The plasma absorption hinders ablation on metals and technical ceramics [9] which is why ablation layers are not necessary [10].

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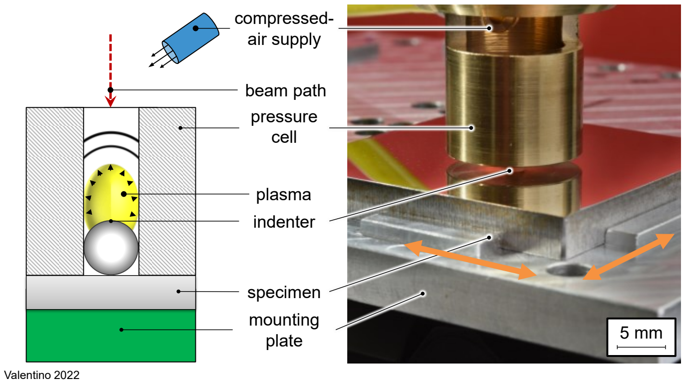

Fig. 1: Setup of the laser-induced shock wave indentation technique

The shock wave is the result of the laser-plasma-interaction, which is used to penetrate the indenter inside a specimen. The indenter is penetrated inside the specimen at more than 10^3 s^{-1} [11]. Amongst others, the strain rate is influenced by the pulse energy and pressure cell [6]. So far, it has been found that the extracted characteristic values indentation depth, pile-up height, and indentation diameter strongly correlate with the Vickers hardness [11] and tensile strength [12].

2 Methods

In this study, LiSE was used to investigate the feasibility to characterize the ballistic steel 30CrMoNb5-2. Such ballistic steel is usually tested at high strain rates with ballistic tests. Material properties were determined according to [6] and compared to conventionally measured values. The pulse energy was varied between 2.7 J and 6.6 J. The LiSE setup is described in detail in [6].

3 Results and Discussion

The resulting indentation diameter and depth as function of pulse energy are shown in Fig. 2. Both characteristic values increase with increasing pulse energy. No indentation is found for the lowest pulse energy of 2.7 J. When increasing the pulse energy to 4.6 J, artefacts are observed on the surface (Fig. 2). These artefacts lead to an increase of the deviation of the measured indentation depth and diameter. The artefacts can be explained by a phase transformation of the retained austenite present in the as-delivered state to a martensitic structure in the deformation area. Martensite causes a volume change in the microstructure [13] leading to a subsequent bulging of the surface. Such effects are also observed for harder materials and higher pulse energies but similar material compositions [6]. The Vickers hardness and the tensile strength are calculated from the measured characteristic values according to [6]. The calculated hardness (Fig. 3 a) and tensile strength (Fig. 3 b) decrease with increasing pulse energy. A higher pulse energy leads to a larger strain rate [6]. Larger strain rates are associated with increase in yield strength [3]. The contrary effect is observed here. Especially, the calculated tensile strength is considerably lower compared to the specified one determined under standard conditions. Thermal effects significant to the process are not induced by the laser [14]. However, adiabatic heating may affect the indentation process at higher strain rates. In future research, this contrary strain rate effect will be investigated for LiSE. Nevertheless, it is suggested that strain rate effects significantly affect the hardness and tensile strength for 30CrMoNb5-2. Thus, LiSE is potentially suitable for hardness and tensile characterization of materials that experience high strain rates during application and accordingly, need to be tested under these conditions.

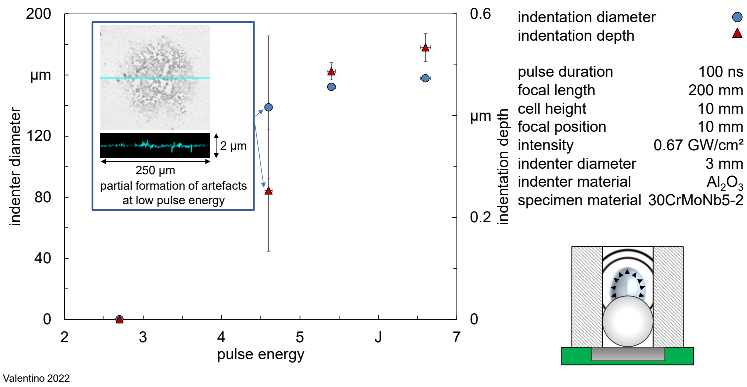

Fig. 2: Indentation diameter and depth in dependence of the pulse energy

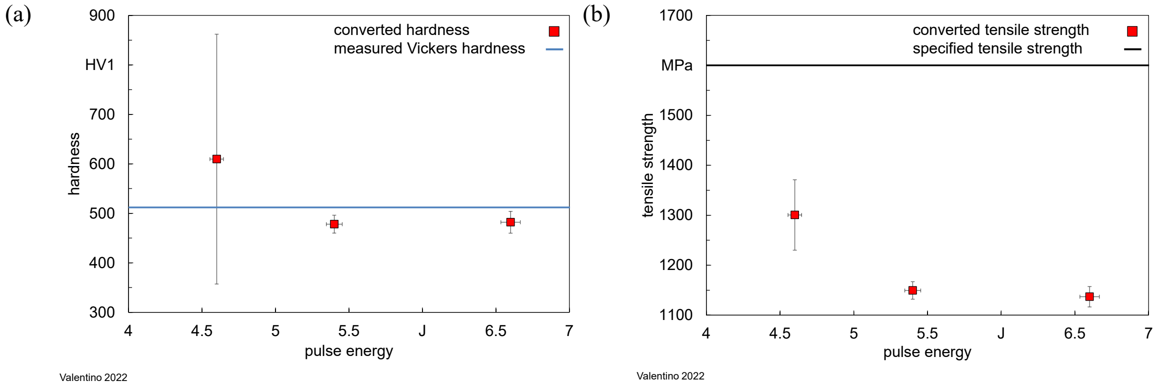

Fig. 3: (a) Converted and measured hardness and (b) converted and measured tensile strength in dependence of the pulse energy

4 Summary

The principal applicability of the laser-induced shockwave indentation technique for materials characterization at high strain rates is shown for the ballistic steel 30CrMoNb5-2.

Acknowledgements

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