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# Application of a nanosecond laser pulse to evaluate dynamic hardness under ultra-high strain rate ☆

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ABSTRACT

The paper presents results of experimental tests of plastic metals deformation generated by a shock wave induced by laser pulse. Tests were carried out on the Nd:YAG laser with a wavelength of 1064 nm and the laser pulse of 10 ns duration. The shock wave generate by the laser pulse was used to induced local plastic deformation of the material surface. The study examined the possibility of application the process to develop a new method of measuring the dynamic hardness of materials under ultra-high strain rate. It has been shown that the shock wave induced by the laser pulse with an energy of 0.35–1.22 J causes a repeatable plastic deformation of surface of commercially available metals and alloys without thermal effects on the surfaces. Based on the knowledge of an imprint geometry, it is possible to evaluate the dynamic hardness of materials at strain rate in the range of $10^7$ $s^{-1}$.

## 1. Introduction

Knowledge of the behaviour of materials and their properties under conditions of dynamic deformation is essential for proper designing of machines and equipment and for predicting their behaviour in manufacturing and operating processes. Ultra-high-speed deformations occur in the processes of friction and machining of materials, as well as, operation of components used in many fields of technology. Properties of materials under conditions of dynamic deformation significantly differ from those in static conditions. They depend on the speed of deformation, microstructure of the material and temperature. Strain rate substantially affects the strength properties of construction materials. Sensitivity to the strain rate considerably increases at strain rates above 10 $s^{-1}$ of most metals and alloys [1–3]. With the increase in the strain rate the yield stress raises. It has been shown [4] that the sensitivity to the strain rate grows linearly with the increasing strain rate for steel in the range of strain rate of 10–$10^4$ $s^{-1}$. Other material properties such as tensile strength, uniform or total elongation also dependent on the deformation rate [5]. Therefore, in order to determine properties of materials under different conditions, experimental tests are needed in the widest possible range of the strain rate.

Evaluation of the plastic properties of materials and layers deformed at the high strain rate is a serious experimental issue [1,3]. There are several methods for material testing at high speed deformation such as the Split Hopkinson Pressure Bar (SHPB) method, miniaturised direct impact test, shock methods, explosive methods, but all are complex and destructive [2].

Mechanical properties at high strain rate may be tested also by means of dynamic hardness testers. Strain rate in these devices is typically in the range of $10^3$ $s^{-1}$. Dynamic hardness measurements are based on a dynamic action of an indenter on the surface of the tested materials. These methods are not standardized and the measurement results should be treated as approximate. Recently, the reports on development of new methods for measuring the dynamic hardness using a high velocity gas gun have occurred. The strain rate in these methods is about 1500–2200 $s^{-1}$ [6,7]. The results of the dynamic hardness measurements based on the Vickers method are presented in [6]. The obtained hardness values for different materials varied from a few to several percent relative to the hardness values in static conditions. Studies of the dynamic hardness indicate the presence of analogous relationships between hardness and other mechanical properties, e.g. yield point or ultimate strength, as for the respective static characteristics [5,8]. Dynamic hardness measurements are non-destructive, fast and less complex compared to other methods of material testing in considered conditions. They allow indirectly, determining other material properties, e.g. the yield point [7,8].

The study of processes occurring in materials at very high speed rate is possible using nanosecond laser pulses [9,10]. A shock wave is generated for this purpose. As a result of the laser

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radiation on material plasma and a pressure wave are generated. Nanosecond high power pulses and specially selected absorption layer as well as constrained layers, allow obtaining a wave pressure from a few to several GPa [9]. The absorption layer should ensure a proper conduct of the development and expansion of the plasma cloud without impact of thermal effects on the tested material. The proper propagation of the pressure wave to the material is provided by the use of a constrained layer. It reduces scattering of the pressure wave. Medium with suitably selected impedance is used as the constrained layer, typically it is water or quartz glass [9,11,12]. When the constrained layer is applied, there is a growth of the amplitude of the pressure pulse, improving its shape, shortening the rise time and decay time, and improving the repeatability of these characteristics. In the case of liquids, it also increases the speed of the cooling process at the interface of phases, which reduces the thermal diffusion of the tested material [11]. The described process has been used for many years for example for surface treatment of metals and alloys, laser shot peening – LSP [13–15]. LSP is a mechanical process without thermal effect.

In the 1990s, attempts to use the pressure wave generated by a laser pulse to testing the adhesion of thin layers obtained by PVD and CVD methods were made (laser spallation technique). Tensile stresses that caused separation of the layer from the surface at the interface of the material/layer phases have been studied [2]. In these methods, adhesion of layers is calculated based on the pressure at which the shock wave acts on the tested material, its speed of propagation in the material and geometry of debonding of the layer. The accuracy of the method depends mainly on the accuracy of pressure measurements and the propagation velocity of the shock wave. Due to very short time of process, from several to tens of nanoseconds, advanced measurement techniques are required [16,17].

Up to now, there is no information about tests on evaluation of the hardness of the materials using a laser pulse. However, the imprint size after plastic deformation caused by shock wave induced by laser pulse was investigated previously for example in works [18,19]. Li et al. notice that laser peen texturing can be regarded as a new method for dynamic hardness measurement and showed that deeper imprints indicate the smaller dynamic hardness. Theoretical and experimental studies of plastic deformation of the surface of various materials induced by a single or multiple laser pulse have been conducted mainly in order to determine the hardening of the material or internal stresses after the LSP process [18,20,21]. Numerical simulations of surface deformation under a single laser pulse showed a homogeneous imprint in the place of the impact of the shock wave. The size of the zone of deformation depends on the laser pulse energy and material properties [13,20]. The strain rate during the process has been estimated from $10^7$ to $10^9\ \mathrm{s}^{-1}$ [22].

The paper presents the results of plastic deformation of the material generated by the single nanosecond laser pulse and attempts to use the results for evaluation of the hardness of the material under the ultra-high strain rate.

## 2. Material and methods

The study of plastic deformation induced by a nanosecond laser pulse was carried out for typical commercial metals and alloys: aluminium EN 1050 (99.5% Al), copper EN CW004A (99.9% Cu), stainless steel EN X5CrNi18-10 1.4301 (AISI 304) and two aluminium alloys AlSi12 ISO 3522-1984 and 6060 AlMgSi0.5 (0.35-0.6% Mg, 3–0.6% Si, 0.10–0.30% Fe plus Al). Round samples of a diameter of 25 mm were cut by WEDM method out of sheets 1 mm thick. Surface of the materials was electrolytically polished. Brinell hardness (2.5 mm ball, 613 N load) was measured before the experiment for all tested materials.

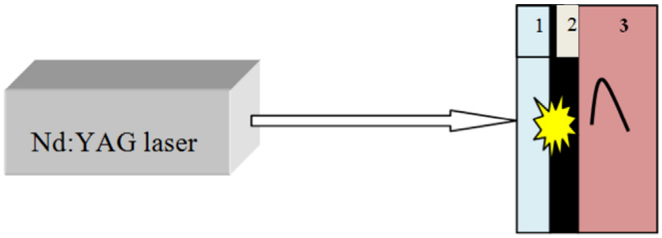

**Fig. 1.** Schematic illustration of experimental setup for materials testing using a laser pulse. 1 – Liquid, 2 – absorption layer, 3 – material, p – pressure pulse.

Nd:YAG Quantel YG 981E laser with a wavelength of 1.064 μm and pulse time of 10 ns was applied in the test. The distribution of laser energy used in study is Flat type. Four values of the pulse energy were used: 0.35, 0.7, 1, 1.22 J. The diagram of the measurement system is shown in Fig. 1. The laser pulse through a liquid layer-1 is directed to the absorption layer-2 causing its rapid evaporation and plasma generation. A pressure wave is formed as a result of rapid expansion of the plasma cloud, propagating in the material-3. Graphite was used as the absorption layer 5 μm thick, while distilled water 1 mm thick was used as the constrained layer. Graphite and black paint are commonly used in research and industry for LSP, they are easy to apply and remove. A thin layer of graphite is removed due to ablation during the process and does not affect the size of the deformation zone. At very short, nanosecond laser pulses, and a suitably selected type and thickness of the absorption layer, the thermal effects associated with the interaction of the beam with the material are negligible [13]. This allows examine such a case as pure mechanical interaction of the pressure wave with tested material.

To relate dynamic hardness to plastic properties of materials, it is essential to estimate the plastic strain rate during the process. The plastic deformation is not uniform and varies considerably within the plastic zone temporarily and spatially. Koeppel at al. [6] proposed that the average value of strain rate for the dynamic measurement of hardness could be determined as the ratio of the speed indenter to the size of indentation. In the proposed method, the shock wave operates as an indenter. The shock wave velocity changes-decreases in the outer medium, and reaches the speed of sound in the material. The diameter of the deformed zone is $2 \cdot 10^{-3}$ m for the used stage. Thus, the average strain rate of tested metals and alloys caused by the shock wave estimated based on this method is $10^6$–$10^7$ 1/s, when the diameter of imprint is considerate. For small changes of the deformation zone, it can be assumed that the strain rate is fixed for set measurement conditions, i.e. energy and time pulse, wavelength as well as identical absorption layer and constrained layer.

The precise measurement of strain rate are possible using advanced equipment, for example by measuring the speed of free surface with interferometric method (VISAR). Such tests have been conducted in measurements of the adhesion of layers by the laser spallation technique. Strain rate was estimated in the range $10^6$–$10^8$ 1/s for nano seconds laser pulse depending on applied parameters of the process [23]. Thus, the ranges of the strain rate determined by both methods are similar.

The parameters of the process, i.e. duration of the pulse, diameter of the laser spot, thickness and type of the absorption and the constrained layer were identical for all samples.

The effect of the laser pulse energy on the plastic deformation zone was studied. It was assumed that change of the laser pulse energy caused different pressure level of shock wave and rise time, decay time, strain rate are constant during the process.

In order to assess the impact of the laser pulse on the surface of