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Energy of Laser Induced Shockwaves

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Abstract. High throughput experimentation is a possibility to develop new materials in a short time in order to meet the demands of efficient characterisation of compositions. Thus, fundamentals of a new hardness measurement method are investigated based on laser-induced shockwaves. In this study, plasma is created with a nanosecond pulsed TEA CO_2 laser on top of an indenter. Further interactions of the plasma with the high intensity laser beam result in a shockwave. The pressure of the shockwave is used to push an indenter inside a material surface. So far, the energy transfer of the shockwave on indenters is not fully understood. Therefore, pendulum experiments are conducted to calculate how much energy can be transferred from the shockwave into the indenter. For these experiments, a bob, which geometry is equal to the indenter geometry, is connected to a thread pendulum and maximum deflection angles are recorded with a high-speed camera. Under standard conditions and the assumption of a spherical expansion of the shockwave, the experiments show that with a 6 J pulse energy a shockwave energy of up to 9 µJ can be used for indentation tests.

Keywords: Micro forming, Energy efficiency, Quality control

1 Introduction

Conventional material developments are based on expensive experimental investigations of different material properties. To meet the demands of efficient identification of compositions, which pursue the objective to realizing a specific performance profile of a material, high-throughput experimentation in materials science has been recognized as a new scientific approach to generate knowledge [1]. New techniques must operate at least at the same accuracy level as existing methods. One example is the hardness measurement. The conventional indentation and evaluation process usually takes several seconds. A new method was presented in [2] and is based on laser induced shockwaves to establish a new high throughput measurement method. When energy density of a CO_2 laser pulse exceeds a critical point, a plasma is induced and results in a shockwave [3]. The shockwave pressure is used to push an indenter inside a material. The induced depth and diameter in the material is measured and can be correlated with the material hardness. Previous experiments showed that a shift in focal position below the indenter increases the created indentations [2]. In addition, it was shown that although the plasma temperature increases up to 19000 K [4] above the indenter, no significant heating of the tested sheet underneath the indenter is measured during the indentation process [5].

In the context of high throughput, lasers offer high flexibility and high dynamic. Laser systems are used as measuring devices since the 1960s. At that time, Brech and Cross first introduced material emission analysis with a ruby laser [6]. Most laser-induced shockwave studies concern the analysis and understanding of surface hardening effects with wavelengths in the range of 1064 nm [7]. In the region of this wavelength and shorter, the metal is mainly directly ablated to create a high temperature plasma. Fabbro et al. showed that by using a confined and for the wavelength transmissive medium above the surface, the acting pressure on the metal surface is increased [7]. However, direct ablation leads to a change in surface conditions of the formed or indented material, which is not advantageous, also in terms of high throughput. Instead, pulsed CO_2 lasers are used for high-speed processing of thin metals, such as forming or cutting processes, because pre-treatment [8] and ablation layers are not necessary [9], because almost all the irradiation of the CO_2 laser wavelength is absorbed by the instantly formed plasma [10]. Barchukov et al. showed for pulsed CO_2 laser that the plasma initiates approximately 5 mm above the surface [11], but plasma formation can be influenced by the shift in focal position of the laser beam [2]. According to Marpaung et al., pulsed CO_2 laser-induced plasma can be described in two characteristic plasma regions [12]. One part is the primary plasma, which is found above the surface. The primary plasma is the initial energy source for the shockwave. The other part is the secondary plasma, which expands from the primary plasma. Vollertsen et al. observed that for forming operations of thin aluminium sheets with a thickness of 50 µm with 5.3 J pulse energy average pressures of

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4.5 MPa are possible [13]. Further experiments showed that the pressure decreases regressively with increasing distance [14] and that the plasma height correlates with the maximum pressure [15]. For micro forming operations, Veenaas et al. showed that CO_2-lasers are a reliable tool, where the maximum shockwave pressure was found 9 mm above the surface on Aluminium rods [8].

However, the energy transfer of the shockwave on the indenters is not fully understood and analysed so far. In addition, high pressure deviations are observed in some studies [13]. Defined laser-induced shockwaves would enable high throughput hardness measurement with a measurement time for the hardness indentation and procedure of less than one second. Therefore, pendulum experiments are conducted to calculate how much energy can be transferred from the shockwave into the indenter. If no friction occurs, the transferred energy is equal to the deflection angle. The goal of this paper is to understand the energy transfer from laser induced shockwaves on indenters.

2 Experimental set-ups

The experiments are conducted with a pulsed TEA CO_2 laser from SLCR. The laser has a pulse duration of 100 ns and a maximum pulse energy of 6 J. A focusing mirror with a focal length of 200 mm is used, resulting in a 2 mm x 2 mm laser spot. Two different pendulum experimental set-ups were applied to capture the bob movement (as shown in Fig. 1 a and Fig. 1 b). For both set-ups the same camera and camera settings are used. Additionally, the influence of focal position f_p (as shown in Fig. 1 c), of pulse energy and of the positioning of the laser on the bob was studied.

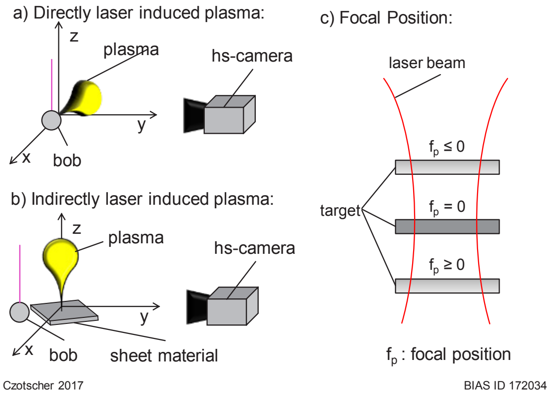

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Fig. 1. Schematic experimental setup (directly a) and indirectly b)) and the influence of focal position c).

The motion of the bob was recorded with the high-speed camera Phantom VEO 410L from Vision Control. The high-speed camera Phantom v5.1 captured the deflection angle of the bob in both experiments with an array of 1280 x 800 pixels, a framerate of 1000 fps and an exposure time of 200 µs. For the first setup, the laser beam is directly irradiated on a hardened 100Cr6 steel bob with a diameter of 4 mm. The bob possesses a through hole of 1 mm in diameter to fix the indenter with a thread pendulum. The mass of the bob is 0.241 g. The induced shockwave results in a movement of the bob, which is recorded with a high-speed camera. The schematic setup is found in Fig. 2. In the second setup, the shockwave is induced on a separate target and the expanding shockwave induces a movement on the bob (see Fig. 3). The maximum deflection angle of the bob is measured. The bob was positioned at different positions relative to the laser beam. For each position, five measurements were conducted. Moreover, the standard deviation was calculated for these measured values. After each created plasma, several seconds were waited until the next laser shot was given on another part of the sample to minimize interaction effects between the already created plasma and the new plasma.

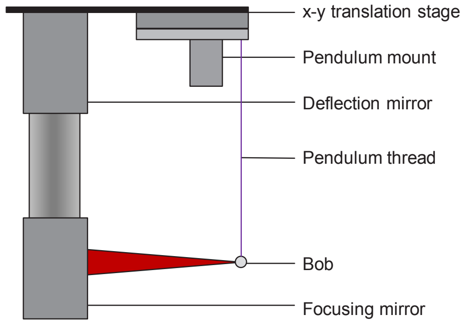

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Fig. 2. Pendulum setup with laser beam, which is directly irradiated on indenter.

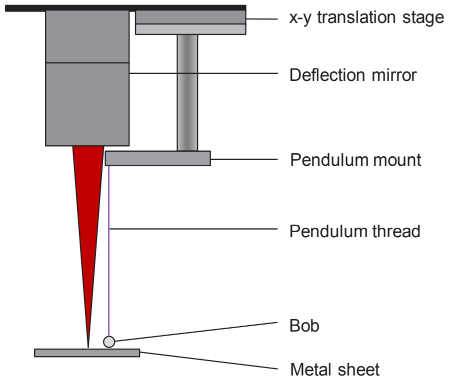

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Fig. 3. Pendulum setup with laser beam, which is irradiated on external target.

3 Method

3.1 Shockwave expansion model

Idealisations of a real pendulum are made to calculate the transferred energy from the kinetic energy of the shockwave on the bob: The pendulum consists of a point mass, which is connected to an inextensible thread.

Motion only occurs in two dimensions. The kinetic energy from the shockwave is transferred without loss into potential energy. As a result, the energy transferred into the bob E_p can be calculated by the maximum deflection angle φ:

$$E_p = m_k \cdot g \cdot l_p \cdot (1\text{-}\cos\varphi) \quad (1)$$

Where m_k is the mass of the bob, g the gravity and l_p is the length of the thread. When the expansion radius of the shockwave r_s, is known and half width of the laser spot $d_s = 1$ mm is taken as the initial point of the shockwave, the transferred energy on the bob E_p and the radius of the bob r_k can be used to determine the maximum possible shockwave energy E_s. Previous research done by Kawaguchi analysed the formation and expansion of TEA CO_2 laser-induced shockwaves [16]. They showed that the upper part of the expanding shockwave is spheroidal. The central part of the expanding plasma is cylindrical, whereas in the lower regions deviations in shape occurred. Additionally, Walter et al. showed that for larger distances from the shockwave initiation that the shockwave form is spherical [17]. The shockwave that is formed along the plasma transforms into a spheroidal shockwave, which is illustrated in Fig. 4.

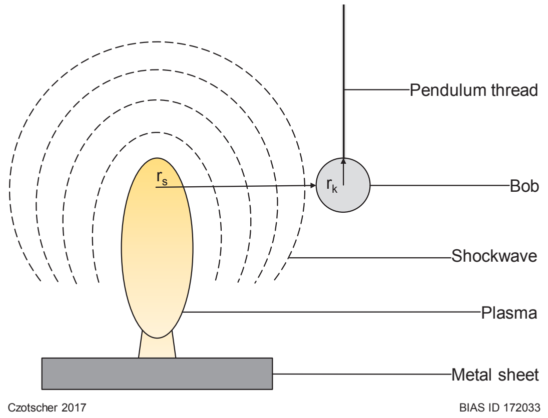

Fig. 4. Expansion of shockwave according to [15].

Accordingly, the part of shockwave energy that is transferred on the bob is relative to its area. The bob area A_b can be described as:

$$A_b = \pi \cdot r_k^2 \quad (2)$$

By considering for the upper part a spherical and for the lower part a cylindrical expansion of the shockwave, the total surface area of the shockwave A_s can be calculated as follows:

$$A_s = 2 \cdot \pi \cdot (r_s - d_s) \cdot h + 2 \cdot \pi \cdot (r_s - d_s)^2 + \pi \cdot (r_s - d_s)^2 \quad (3)$$

The height of the cylinder h is taken from Veenaas et al. experiments with TEA CO_2 laser that analysed the pressure at different heights along the expanding plasma [8]. By cross-multiplication, the shockwave energy can be calculated as follows:

$$E_s = E_p \cdot [2 \cdot (r_s - d_s) \cdot h + 3 \cdot (r_s - d_s)^2] / (\pi \cdot r_k^2) \quad (4)$$

4 Results

4.1 Direct laser irradiation

Shockwaves induced with different pulse energies directly on the bob show a positive influence of the transferred energy on the bob. However, the differences are small and between 5.6 J and 6.0 J no significant changes are observed (as shown in Fig. 5). The influence on shift in focal position is demonstrated in Fig. 6. Additional to the focus position, the focus is shifted $f_p = -10$ mm below and $f_p = +10$ mm above the target. The deviation increases if the focal position is shifted. The transferred energy increases with the shift in focal position fp = -10 mm. The transferred energy in dependence of the positioning of the laser beam on the bob is shown in Fig. 7. The laser beam is positioned $z = +1$ mm above the centre of the bob and $z = -1$ mm below the centre. The transferred energy decreases when the laser is not positioned concentrically on the bob. The transferred energy decreases more for $z = +1$ mm compared to $z = -1$ mm and the concentrically position. The deviation increases when the laser beam is below the bob ($z = -1$ mm).

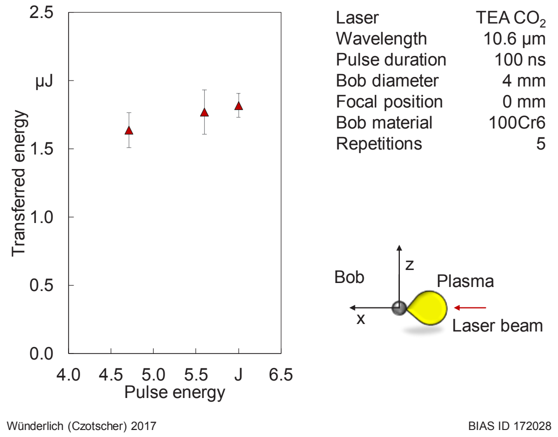

Fig. 5. Correlation between pulse energy and transferred potential energy on bob.

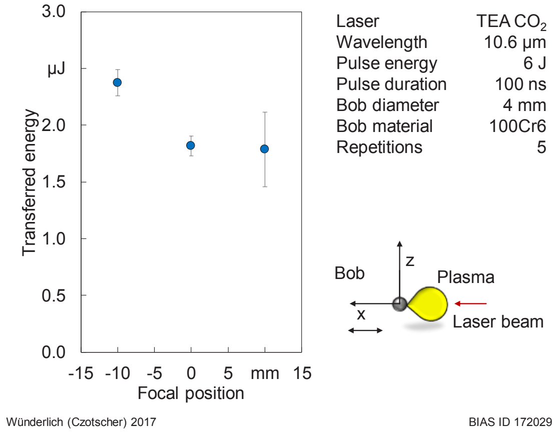

Fig. 6. Influence of focal position on transferred energy on bob.

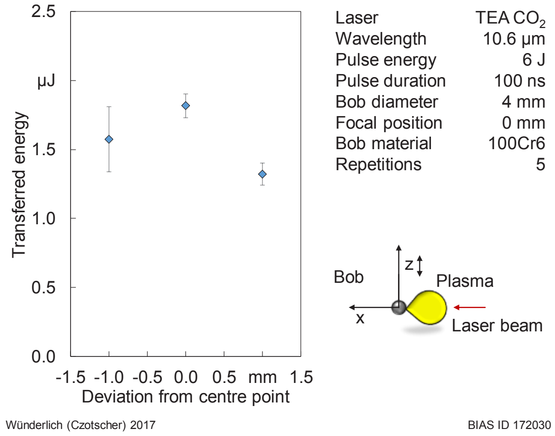

Fig. 7. Influence of positioning of the laser beam on bob.

4.2 Laser irradiation on external target

Fig. 8 shows the calculated transferred energy at different pendulum positions relative to the induced shockwave centre. The centreline shows the estimated centre of the shockwave mentioned in [2]. Values measured closer to the surface show that the transferred energy is higher compared to larger distances. In this case, the energy decreases exponentially. At the X-distance of 17.8 mm and higher, the transferred energy does not change significantly in z-direction.

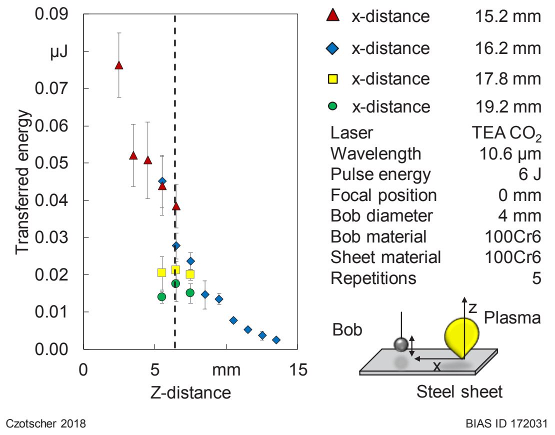

Fig. 8. Transferred energy measured at different Z-distances from induced shockwave.

With Eq. 4 and the calculated transferred energy in Fig. 8, the shockwave energy can be calculated as shown in Fig. 9. No significant changes are observed between the distance of 6.5 mm and 7.5 mm. The average values are between 5 µJ and 9 µJ. When at the distance of 6.5 mm, the bob is moved closer the shockwave, the transferred energy on the bob increases exponentially (see Fig. 10). By extrapolation and considering half of the laser beam spot width of 1 mm, a maximum transferred energy of E_p =1.8 µJ is estimated.

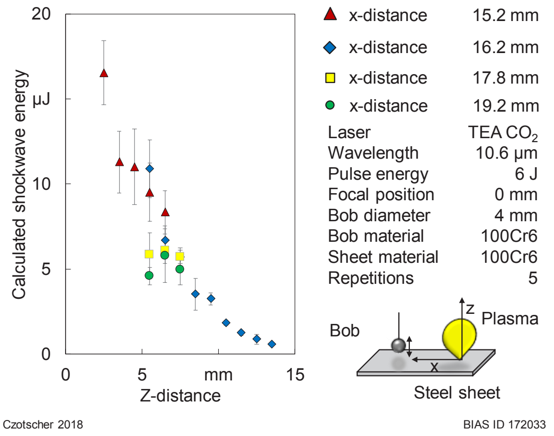

Fig. 9. Calculated shockwave energy with Eq. 4 for different Z-distances from induced shockwave.

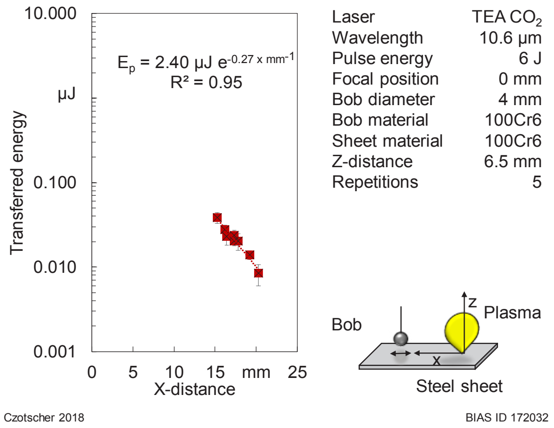

Fig. 10. Transferred energy measured at different X-distances from indirectly induced shockwave.

5 Discussion

For direct interaction of the laser beam with the bob, the deviation of transferred energy decreases when the laser beam is focused directly on the bob (see Fig. 6 and Fig. 7). However, the transferred energy increases if the focal position is shifted behind the bob (f_p = -10 mm). The increase can be explained by a larger focal area, which emits more electrons out of the bob surface. These electrons absorb further irradiation of the laser beam. Moreover, when the focal position of the laser is shifted below the workpiece, as shown in [2], the created plasma is closer to the material surface. Consequently, higher forces act on the bob. The positive effect of more emitted electrons due to a larger spot area also explains why a shift in focal position above the bob surface of f_p = 10 mm does not lead to a significant change in transferred energy compared to the position in focus (f_p = 0 mm). However, as plasma observations showed in [2], the plasma form becomes more instable the further the focal position of the laser is shifted. This also increases the deviation in transferred energy. Additionally, if the laser beam is not positioned concentrically on the probe, it negatively affects the transferred energy and increases the deviation (see

Fig. 7). In Fig. 8, it is observed for indirect induced shockwaves that the transferred kinetic energy increases when the pendulum with the bob is placed closer to the surface. This effect can be explained as following: The reflection of the shockwave on the target surfaces leads to a superposition of the induced shockwave and the reflected part. This increases the measured deflection angle of the pendulum and therefore, the transferred energy. This effect was not observed in [8], when the plasma was induced on a small surface (Aluminium rod). When the bob is moved further up a plateau is found, which is in the region of estimated expansion centre of the shockwave [15]. Again, a decrease in transferred energy can be found by moving the pendulum even further up. These results can be explained by the measurements obtained in Fig. 7. The expanding shockwave does not push the bob concentrically and thus less energy is transferred.

All in all, for direct interaction of the bob with the laser beam, 1.8 µJ transferred energy is measured for the position in focus. For indirect induced energy, also 1.8 µJ are calculated by extrapolation (see Fig. 10). By assuming a spherical expansion of the shockwave and using Eq. 4, in total 6 J pulse energy are transformed into 9 µJ kinetic shockwave energy. This shockwave energy is sufficient to create indentations in metallic materials as shown in [2]. It was shown that with a 4 mm indentation ball, indentation diameter of up to 210 µm were created on aluminium alloy materials.

6 Conclusions

- A TEA CO_2 laser pulse with an energy of 6 J induced on 100Cr6 can be transferred in a shockwave energy of up to 9 µJ. This energy is sufficient to create an indentation diameter in aluminium alloy with a 4 mm indenter of 210 µm.
- For directly and indirectly laser-induced shockwaves, the calculated initial shockwave energy is the same. However, the creation of the shockwave on large targets, such as metal sheets, leads to a superposition of the laser-induced shockwave and the reflected shockwave on the target surface. This leads to an overpressure in the surface region and to relatively higher transferred energies on the bob in this area.

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