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Process stability of laser induced plasma for hardness measurements

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Abstract

Optical plasma position measurements are performed to establish a new hardness measurement method based on laser-induced shockwaves. The process differs from conventional hardness measurements: Plasma is created with a pulsed TEA-CO_2 nanosecond laser on a material surface. Further interactions between the laser beam and plasma result in a shockwave. The pressure of the shockwave can be used to push a test specimen inside a material surface. On the one hand, plasma can be formed above the test specimen, which is then directly pushed inside the material surface. On the other hand, the plasma can be created on an external target, and the shockwave then pushes the test specimen inside the material. To increase the reproducibility of the laser-induced shockwave process, the influence of target material is analysed. Aluminium alloy (EN AW 6082), hardened steel (100Cr_2) and ceramic (Al_2O_3) are tested as target materials. The geometry of the plasma and the position of the shockwave centre above the surface are detected to gain further knowledge of the process. The experiments showed that the oxide ceramic target material shows the lowest plasma geometry and shockwave pressure deviations and accordingly, the highest reproducibility, which makes it suitable for further laser-induced hardness measurements.

Keywords: Process control; Material; Measurement

1. Introduction

The ongoing trend of miniaturization in manufacturing processes requires high through-put to realise cost efficiency, Geiger et al., 2001. With further analyses, it is possible and necessary to verify these products for

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future applications. Accordingly, new unconventional methods must be considered as measurement methods to meet the demand for high-through-put and to enable the analysis of small dimensions. One approach is the contact free testing with laser. Jaeggi et al., 2014 showed that laser systems offer in the micro range the potential for the realisation of high through-put processes. The analysis of materials with lasers has already been used since 1960s for the laser atomic emission spectro-chemical analysis. It was first introduced by Brech and Cross, 1962. The potential for microanalysis has been quickly recognized. Laser analysis gains growing acceptance in a wide range of applications. The advantage of laser analysis with CO_2-laser is the rapid analysis without the need of sample pre-treatment in many cases, e.g. Veenaas et al., 2013. No ablation layer must be applied for metal sheets because the laser-induced plasma absorbs almost completely the wavelength of CO_2-laser, e.g. Miziolek et al., 2006. Research has been conducted in the understanding of the plasma phases and characteristics induced by laser pulses mostly in very low pressure atmospheres, Kagawa et al., 1984. Marpaung et al., 2000 analysed the influence of atmosphere on the CO_2-laser induced plasma. They showed that in in higher atmospheric pressures the primary and secondary plasma stages can still be detected although these cannot be differed with the camera anymore. Barchukov et al., 1974 investigated low-threshold gas breakdown and found that the plasma initiates approximately 5 mm above the surface independently from the material such as Copper or Aluminium sheets. If the energy density of the laser pulse exceeds a critical threshold, the fast expansion of the plasma will result in a shockwave, e.g. by O'Keefe et al., 1973. Walter et al., 2007 described the shockwave expansion spherically and in forming experiments Vollertsen et al., 2009 showed pressure peaks for forming processes in the range of some MPa. Fabbro et al., 1990 established three fundamental stages of evolution process of plasma. First, during the pulse duration, the plasma is created and it induces a shockwave. During the next phase, the plasma still maintains but the pressure decreases. Finally, the plasma recombines. It is noted from Wielage and Vollertsen, 2010 that for growing distance, the pressure decreases and is too small to produce plastic deformation on the material. Within the range of high shockwave pressures, micro forming processes are possible. Especially, CO_2-lasers have shown to be an unconventional but very reliable tool in the micro range for forming operations as shown by Veenaas et al., 2013. Another advantage of CO_2-lasers is the ability to work at standard atmosphere conditions, which makes it very attractive for industrial approaches. Others like Fairand et al., 1972 introduced in the 70s laser shock peening processes as a technique to improve surface material features. They used shockwaves to influence the microstructural and mechanical properties of the surface of Aluminium 7075. In further research, Clauer and Fairand, 1979 obtained pressures of about 5.7 GPa at standard atmospheric conditions by using a pulsed laser of about 2.7×10^9 W/m^2. The described approaches of plasma analysis and utilizing the shockwave pressure for forming operations are combined to establish a new hardness measurement technique. In previous research, Czotscher et al., 2017 showed the correlation between the determined plasma centre by pressure measurements and by plasma analysis. However, also high pressure deviations on Aluminium sheets were determined for pulse energies of 5.5 J. Accordingly, a suitable material for plasma creation must be found to establish a new hardness measurement method. The goal of this research is to increase the understanding of the connection between the formation of laser-induced plasma and the material it is created on. The creation phase and the reproducibility of the plasma in dependence of the material are analysed.

2. Experimental setup and method

The experiments are conducted on a TEA-CO_2-laser with a pulse duration of 100 ns. The maximum energy per pulse of the laser is 6 J but for the experiments 3 J were used. The setup for the pressure and plasma size measurement is schematically shown in Fig 1. The laser beam was irradiated on different materials such as

Aluminium alloy AlSi1MgMn (DIN EN AW 6082), Aluminium Oxide ceramic (Al_2O_3) and hardened steel (100Cr2). The laser beam was focused on the material surface and has an area of 4 mm².

For the plasma analysis, such as the size and position, at least ten measurements were conducted. The development of the pressure was measured at five different distances from the plasma centre. At least three measurements were conducted with the pressure sensor at each distance. The high-speed camera Phantom v5.1 from Vision Control was used with an array of 128 pixels x 400 pixels and a framerate of 17956 fps to detect the plasma. The exposure time of the camera is 10 µs. Between the camera and plasma, a neutral gray filter was placed to reduce the intensity of the plasma emission. The first captured picture of the plasma was evaluated. The geometry of the plasma as shown in Fig 2 was evaluated with Matlab. The number of ignited pixels were used to calculate the geometric centre, the height and the area of the plasma. The height of the plasma is the maximum number of ignited pixels in vertical direction. All ignited pixels are counted for the plasma area. The geometric centre of the plasma is the arithmetic mean position of all ignited pixels of the plasma. The distance of the geometric centre above the surface was calculated accordingly and is called geometric centre position. The maximum pressure was recorded with a PVDF sensor from Piezotech connected to a charge amplifier from Kistler type 5015A. The sensor active area is 1 mm² and the shock calibration data specified a piezo strain constant of 24.0 pC/N.

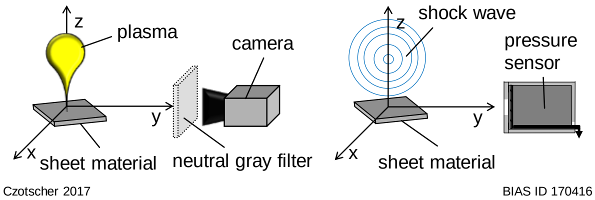

Fig. 1. Schematic setup to detect the size and pressure of the laser-induced plasma

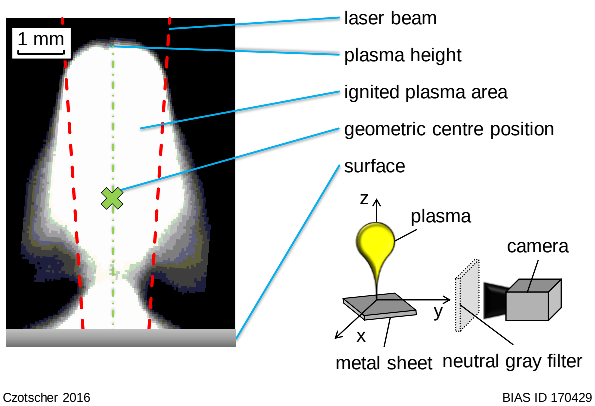

Fig. 2. Determination of the plasma position and size

3. Results

The height and the geometric centre position of the plasma are shown in Fig 3. The average height of the plasma is 6 mm for the analysed materials. The height differences between the materials are not significant. Similar results are observed with the geometric centre position of the plasma. The average geometric centre position is at 3.5 mm for all materials. The oxide ceramic material Al_2O_3 shows the lowest height deviations compared to the other two materials. Another parameter that has been observed is the characteristic ignited area (see Fig 4). The largest area and highest deviations are observed for Aluminium alloy. Smallest areas are observed for steel and lowest deviations for the ceramic material.

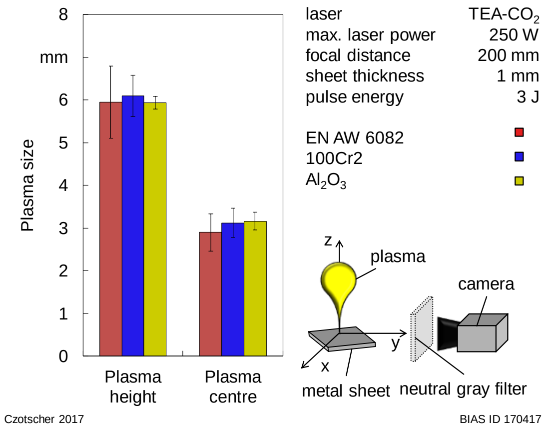

Fig. 3. Plasma height and geometric centre for the tested materials

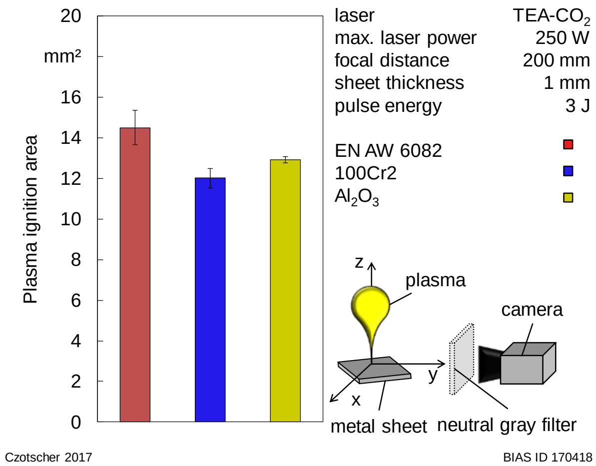

Fig. 4. Ignited plasma area for the tested materials

The variation coefficient of the plasma height and geometric plasma centre position is shown in Fig 5. The variation coefficient is determined by the deviation of all measured values of one material divided by the average value of the same material. Lower values describe a higher reproducibility of the plasma. It is found that ceramic shows the lowest variation coefficient for the height, geometric centre position and area.

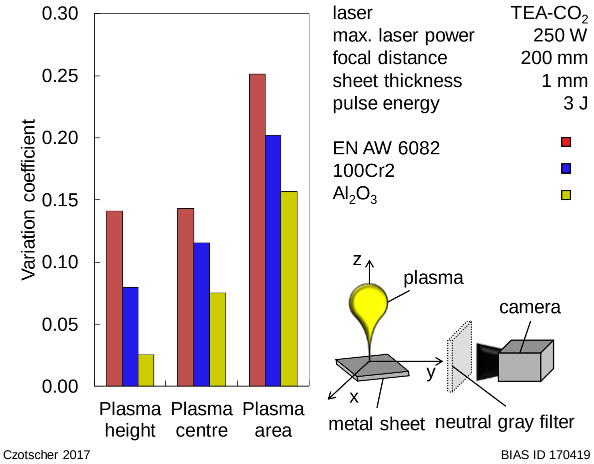

Fig. 5. Variation coefficients of plasma height, geometric centre position and area of tested materials

The results of the pressure measurements are shown in Fig 6. Closer to the plasma, the deviation is at its highest for all materials. The shockwave pressure deviation decreases for larger distances from the plasma. From the development of the pressure p(x) with increasing distance x, a power function can be derived as shown in equation Eq. (1). The characteristic constants a and b of the power functions and the coefficient of determination R^2 are shown in Table 1 for the tested materials. The constant b, which describes the expansion of the shockwave is close to b = -1 for all materials. Highest pressures and highest constant a are observed for the Aluminium alloy (a = 54.3). The highest coefficient of determination R^2 is shown for the oxide ceramic (R^2 = 0.92).

$$\rho(x) = a \cdot x^b \tag{1}$$

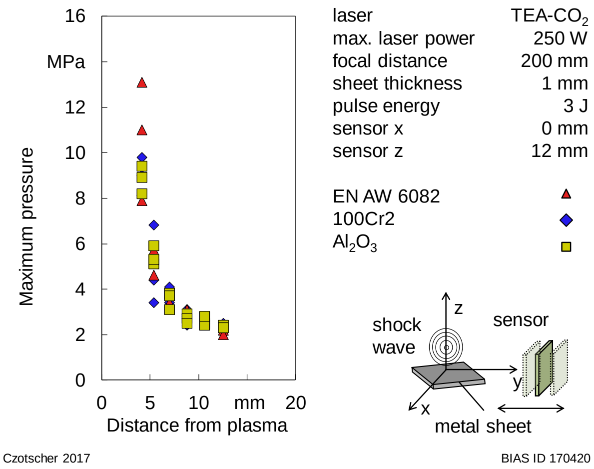

Fig. 6. Development of shockwave pressure depending on distance from plasma centre

Table 1. Constants and coefficient of determinations of the material power functions

	DIN EN AW 6082	100Cr2	Al_2O_3
Constant a	54.3	36.7	41.9
Constant b	-1.3	-1.1	-1.2
Coefficient of determination	0.90	0.83	0.92

4. Discussion

No significant influences on the plasma geometry has been observed (as shown in Fig 3 and Fig 4), similar to the results shown by Barchukov et.al., 1974. However, it is found that the material influences the reproducibility of the laser-induced plasma and shockwave pressure. The oxide ceramic Al_2O_3 shows lowest plasma geometry deviations (Fig 5) as well as lowest pressure deviations as shown in Table 1. Two aspects can be considered to describe the higher reproducibility of Al_2O_3. On the one hand, these observations may correlate with the work needed to extract electrons from a material surface, the so-called work function. Aluminium oxide has a higher work function compared to steel or Aluminium. On the other hand, the oxide ceramic only consists of two elements, whereas in Aluminium alloy and steel more elements and different metallic phases can be found. Moreover, Aluminium and steel tend to create an oxide layer whereas Aluminium oxide is already a chemical compound of Aluminium and oxygen. It can be concluded that metallic oxide layers and different phases within a material may have a negative effect on the reproducibility of the laser-induced plasma and shockwave pressure. In this context, the oxide ceramic shows a higher homogeneity compared to the other tested materials, which decreases the scatter of the analysed parameters. On this account, the experiments have shown that the laser-induced plasma and the resulting shockwave can be influenced by the material it is created on. The reproducibility of the laser-induced shockwave process can be further enhanced to establish a new hardness measurement method.

5. Conclusion

The conducted laser-induced plasma experiments showed that:

- The oxide ceramic Al_2O_3 has a positive effect on the reproducibility of the plasma geometry and shockwave pressure, which makes it suitable for laser-induced hardness measurements.

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