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Indentation technique based on laser-induced shockwaves for material testing with moving specimen

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Abstract

A method for determining material hardness of metals is based on laser-induced shockwaves generated with a pulsed TEA-CO_2 nanosecond laser. The laser creates a plasma, which interacts further with the laser beam and subsequently generates a shockwave. The shockwave is ignited above a spherical indenter, made of Al_2O_3, which is pushed thereby into the metal surface. The indentation geometry can be analyzed to draw conclusions about material properties. The process duration depends mainly on two factors: Generating and analyzing the indentations. To speed up the indentation process an approach with a constant movement of the specimen during indentation was tested. The results show a constant reduction of indentation diameter and depth with moving specimen compared to non-moving specimen until 900 mm/min. At higher speeds the deviation increases. Therefore, positioning times with acceleration and deceleration can be avoided and thus up to 900 indentations per minute with 1 mm distance between each indentation could be realized.

Keywords: indentation; hardness; laser-induced shockwave; constant movement; material testing

1. Introduction

The need for sustainability and resource efficiency leads to an ongoing development of construction materials. The development is a cost-intensive process and the determination of the material properties takes a long time (Ellendt and Mädler 2018). Therefore, to optimize the determination of material properties new test methods which are quick and reliable are needed. The use of laser-induced shockwaves has proven to be a promising concept due to its high through-put capability. Czotscher et al. developed a method using a CO_2-Laser to ignite a shockwave above a spherical indenter made of Al_2O_3 which is pushed into a metal surface by the force of the expanding pressure wave. An indentation in the surface is left behind and can be measured regarding the indentation diameter, indentation depth, pile-up height and other parameters (Czotscher 2018). These can then be analysed and used to determine the mechanical properties of the indented material i.e. hardness (Czotscher et al. 2019) or tensile strength (Czotscher et al. 2020). With this method it has thus far been possible to achieve up to 90 indentations per minute (Valentino 2021). Compared to the conventional methods of material testing, this is already a huge improvement. Brinell for example needs at least ten seconds for most steels but for softer materials even 30 seconds or more for one indentation (DIN 2015). Another method for measuring hardness is Vickers which takes between 10 to 15 seconds for each indentation (DIN 2019). For both methods this is only the indentation time itself, the positioning, initial force, etc. are not accounted for. Therefore, laser-induced shockwaves have already proven to be a viable method for high through-put material testing. There is still potential for a higher through-put with higher repetition rates. This paper demonstrates the concept of moving specimen during the indentation process and enables up to 900 and even 1800 indentations per minute for some materials.

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2. Experimental set up

The set up for the experiments is shown in Fig. 1. The focusing mirror guides the laser beam in the direction of the pressure cell with a focal length of 200 mm. The shockwave was ignited inside the pressure cell to guide the pressure wave to the indenter and achieve the maximum force transmission for the indentation process. The specimen height including embedment was around 20 mm with the Z-table being adjusted accordingly that the focal point was on top of the indenter. The pulse energy of 5 J was chosen because it showed the highest reproducibility for the test. Using a 3 mm Al_2O_3 as indenter material was decided due to it being the material that showed the highest wear resistance. The embedded metal specimen had a size of 30 mm x 30 mm x 12 mm and were warm embedded in a melamine resin including glass filler. The specimen surface was prepared with a 3 µm diamant polish resulting in roughness ranging from 0.01 µm for iron and the steels to 0.5 µm for EN AW-1050A. Overall six different materials have been tested: EN AW-1050A, EN AW-5083 H111, EN AW-6082 T651, Iron, C15 + C and 42CrMo4 + QT. The goal of these experiments was to apply a constant movement speed of the specimen during the indentation process which would increase the through-put significantly. Therefore, seven different velocities have been tested: 0 mm/min, 300 mm/min, 600 mm/min, 900 mm/min, 1200 mm/min, 1500 mm/min and 1800 mm/min.

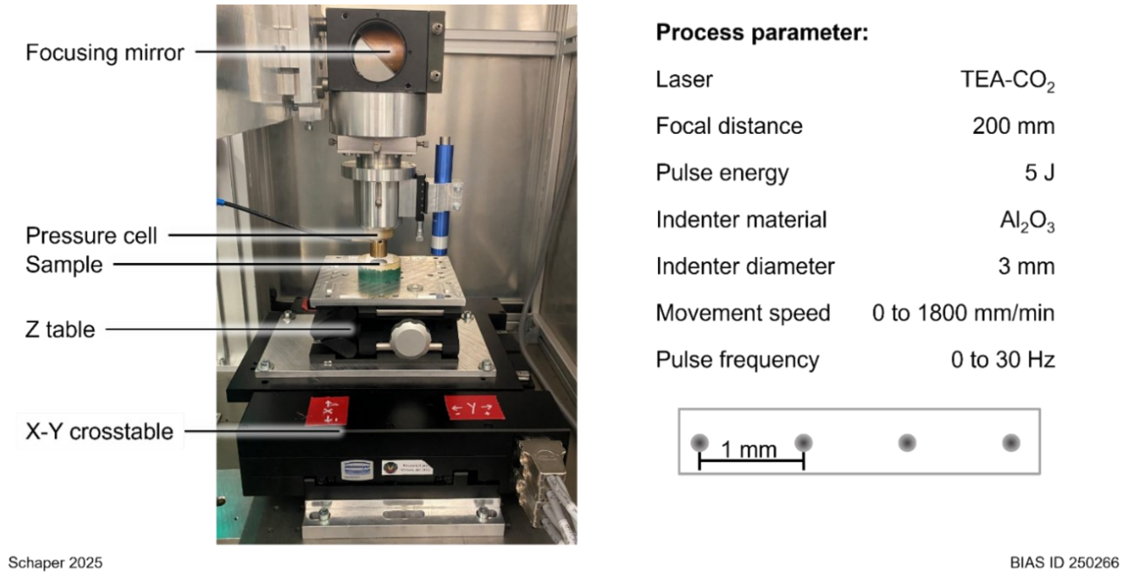

Fig. 1. Experimental set up

In Fig. 2 the testing procedure is illustrated. Before the indentation process the pressure cell needs to be rinsed with Argon to ensure that no particles are disturbing the shockwave ignition and therefore influence the indentation process. After cleaning, the indentation process begins with a constant movement of the X-Y-table. The pulse frequency depends on

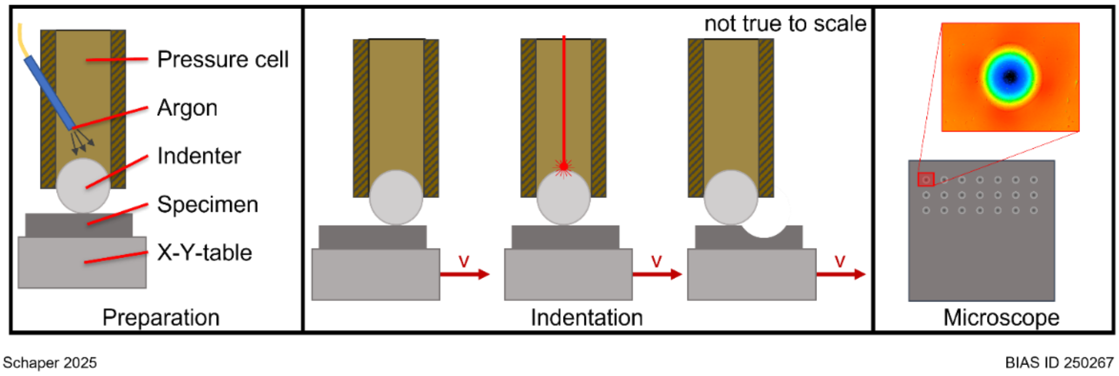

Fig. 2. Flow chart laser induced shockwave indentation test

the movement speed because the distance between each indentation was defined to be 1 mm. This resulted in a frequency of 30 Hz at the maximum movement speed of 1800 mm/min with a linear reduction of 5 Hz per 300 mm/min slower movement speed. After an indentation the indenter bounces upwards into the pressure cell. To measure the bounce time of the indenter until it is back in the correct position a Phantom VEO 410L highspeed camera with a frame rate of 20,000 frames per second was used. Afterwards, images of the indentations were taken using a confocal microscope (Model VK-9700 by Keyence) with a 20x magnification lens. The indentation diameter and the indentation depth were measured using the VK-Analyzer Software by Keyence.

3. Results

The results show a reduction in indentation diameter if the specimen is moving at a constant speed compared to the static process. Fig. 3 shows an example of two indentations created in an aluminum alloy: The left was created while the specimen was static and the right at a speed of 1800 mm/min. It is a visibly smaller and shallower indentation but else there does not seem to be a visual deviation.

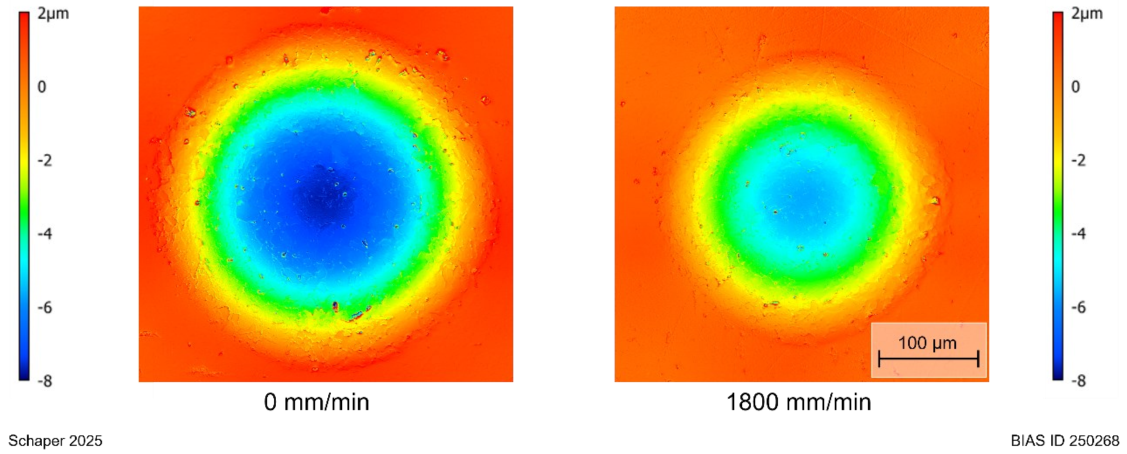

Fig. 3. Indentations created in EN AW-1050A without moving specimen and with a specimen velocity of 1800 mm/min

Fig. 4 compares the indentation diameters of all tested materials at different movement speeds. Only one test series was not able to produce any indentations which was 42CrMo4 + QT at 1800 mm/min. All materials had the largest indentation

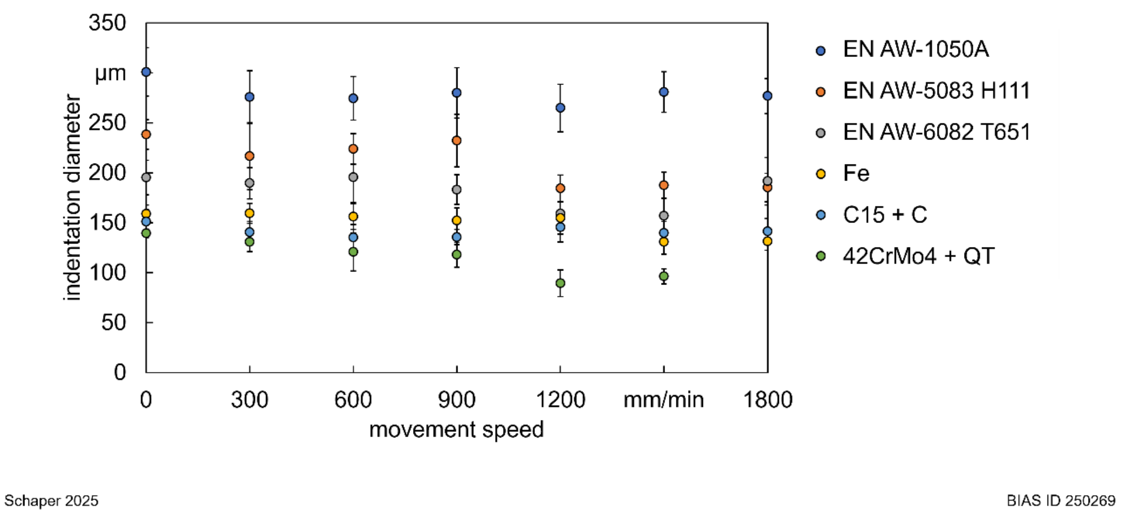

Fig. 4. Indentation diameter at different movement speeds

diameters when the specimens were not moving. With moving specimen during indentation all materials showed a decrease in diameter. For example, the indentation diameter of EN AW-1050A is 302.31 ± 26.44 µm at 0 mm/min and 276.78 ± 24.46 µm at 300 mm/min. However, this decrease was not linear with higher movement speeds. A similar behavior showed C15 + C which also had a relatively constant indentation diameter across all movement speeds after the first decrease. EN AW-6082 T651, EN AW-5083 H111 and 42CrMo4 + QT show a significant reduction after the movement speed reaches 900 mm/min. Iron shows a big decrease of the indentation diameter at movement speeds higher than 1200 mm/min.

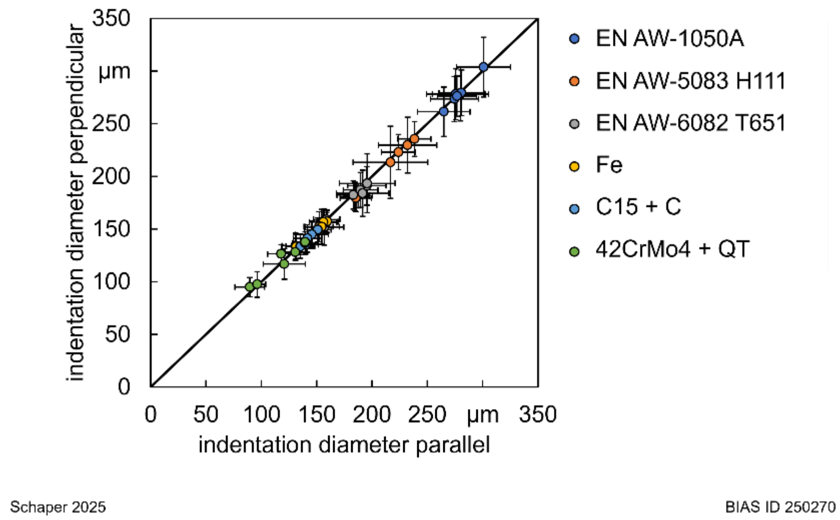

Fig. 5. Comparison of indentation diameter perpendicular to parallel of the movement direction

Although the indentation diameters are smaller, the movement of the specimen does not lead to elliptical indentations. Elliptical indentations could influence the calculated hardness value due to the indentation diameter being an important parameter for the calculation. As shown in Fig. 5 the indentation diameter parallel to the movement direction and the indentation diameter perpendicular to the movement direction are similar.

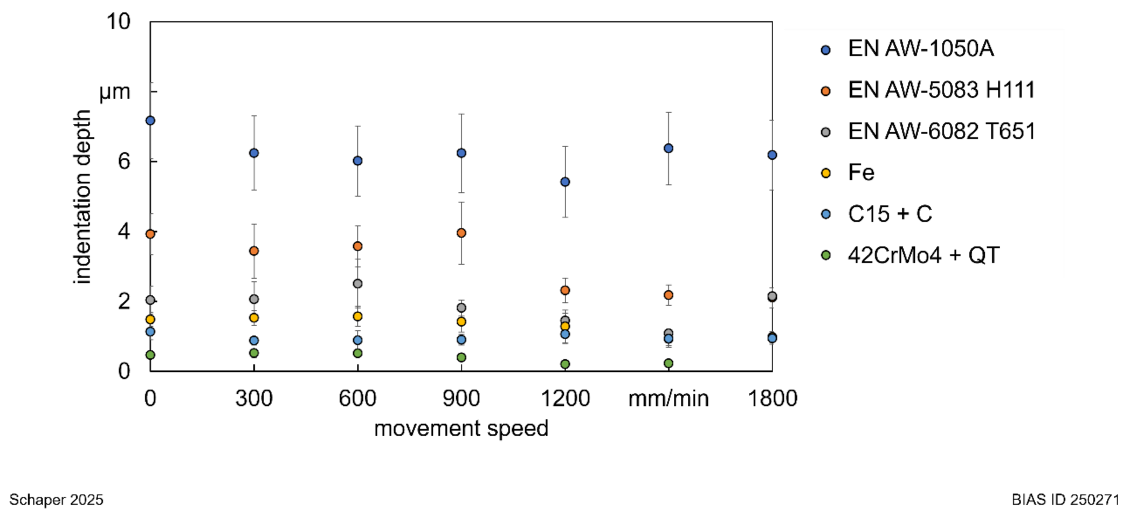

Fig. 6. Indentation depth at different movement speeds

The indentation depth (Fig. 6) varies similarly to the indentation diameter: A decrease from the static tests to those with a constant movement for all tested materials. Also, EN AW-1050A and C15 + C showed the most constant indentation depths across all movement speeds. The other tested materials show significant decrease in indentation depth after 900 mm/min although this is a relatively larger deviation than for the indentation diameter decrease. After the large decrease at 900 mm/min the indentation depth stays relatively constant.

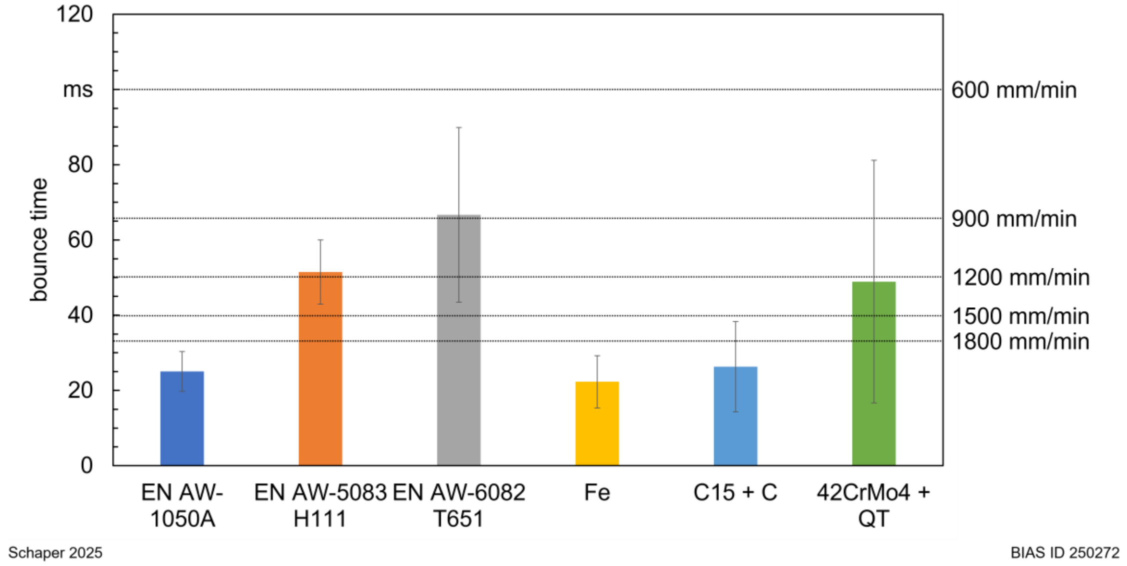

Fig. 7. Bounce time of the indenter

After being pushed into the material surface the indenter is bouncing upwards into the pressure cell. The time it takes for the indenter to be back at the metal surface is shown in Fig. 7. The differences between the materials are significant. For EN AW-1050A, Iron and C15 + C the bounce time is less than 30 ms. The graph also shows the time between pulses for the different movement speeds. The bounce time for EN AW-1050A, Iron and C15 + C is smaller than the time between pulses for all speeds. On the other hand, the indenter is not able to be back in position for the other three materials until a movement speed of 1200 mm/min and 900 mm/min.

4. Discussion

The results indicate that the laser-induced shockwave indentation test can also be performed with a constant movement of the specimen. Although, the indentation diameter and indentation depth are largest when the specimen is not moving and decrease with moving specimen the standard deviation stays constant, and the indentation parameters are reproducible. Furthermore, the indentations did not show a trend of being more elliptical at higher movement speeds which could have had an influence on the calculation of the material properties. The force application time amounts to under 20 µs (Valentino et al. 2021) which means that at 1800 mm/min the specimen moves a maximum distance of 0.6 µm. Compared to the overall indentation diameters ranging from 100 µm to 330 µm with standard deviations in the 10s of µm the movement speed is too low to lead to elliptical indentations. Although the standard deviation of the indentation size was constant across all movement speeds some materials showed a significant decrease in indentation diameter and indentation depth after 900 mm/min or 1200 mm/min. The materials which had this sudden decrease have also the highest bounce time for the indenter. It is possible that the indentation process has a material-dependent maximum speed. If the indenter is still in the air the shockwave ignition does not happen on top of the indenter which leads to failed indentations. This suggests that some materials can be tested at higher speeds than others simply due to the material-dependent bounce behavior. Overall, the results up to a movement speed of 900 mm/min show the same reproducibility as with static specimen. 900 mm/min equates to 900 indentations per minute which is compared to the testing speed from Valentino et al. of 90 indentations per minute (Valentino 2021) a 10x higher through-put. Compared to Brinell (DIN 2015) and Vickers (DIN 2019) this is an increase of 450x and 150x respectively. For some materials as EN AW-1050A, C15 + C and Iron the experiments even reached a through-put of 1800 indentations per minute.

5. Conclusion

The experiments showed that the through-put of the laser-induced shockwaves indentation test to determine material properties can be significantly increased by using an approach with moving specimen. This paper shows that it is possible to perform the laser-induced indentation test with 900 or even 1800 indentations per minute for some materials. The tests had the same reproducibility as the static indentation process even though the indentation diameter and indentation depth were generally a bit smaller. The bounce time of the indenter seem to limit the maximum test rate and is material dependent.

Acknowledgements

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