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LASER INDUCED SHOCK WAVES IN DEFORMATION PROCESSING

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ABSTRACT

Processes based on laser induced shock waves in deformation processing are reviewed in this paper. One widely used process is laser shock processing (LSP) for mechanical surface hardening, which is presented on the basis of a literature inquiry. Two further processes are laser stretch forming and assistance of laser induced shock waves in bending of hybrid blanks. These two processes are presented on the basis of own investigations and experimental results.

Keywords: Laser shock processing, bending, stretch forming

INTRODUCTION

The possibility to generate shock waves by laser pulses was discovered in the early 60s by [1, 2]. Further investigations resulted in laser induced shock waves with increased impact, which were able to cause compressive stresses higher than the yield strength of metals [3, 4]. Laboratories in the USA and France then started with feasibility studies to apply laser shock processing for modification of material properties as an alternative to shot peening and deep rolling [5]. Most investigations on this topic are done with pulsed Nd:YAG or Nd:glass-lasers, since they provide the highest energy density, but [6] showed that excimer lasers can also be used as well as pulsed CO_2-lasers as it is shown by own investigations [27, 28].

PRINCIPLE OF LASER INDUCED SHOCK WAVES

Single laser pulses can generate shock waves, if the power density exceeds a certain threshold. The shock wave is a result of ablation of material layers due to intensive absorption of laser radiation. The material surface originates a phase transformation from solid to vapour. The plasma is an outcome of the gas phase, which absorbs the energy directly from the laser radiation and from the reflection of the material surface. The plasma causes a shock wave by its expansion. The generation of shock waves can be realized by two different methods: Direct and confined ablation (Fig. 1). During direct ablation the plasma expands undamped in the surrounding atmosphere. The process of confined ablation includes a water, glass or quartz overlay (transparent for the wave length) on the top of the surface of the specimen, which decreases the expansion in the surrounding atmosphere and causes up to ten times higher pressure on the material surface. Also melting and material removal are reduced [6, 7, 5].

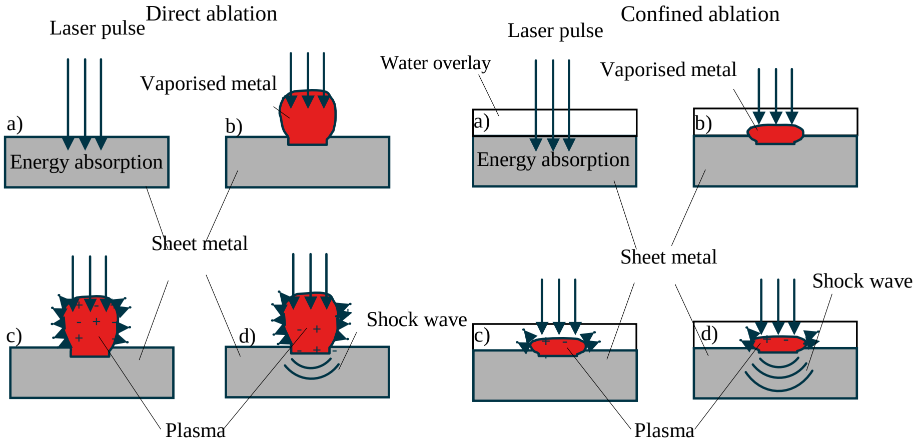


Fig. 1: Principle of laser induced shock waves [6]

Laser absorbent coatings (for i.g. black paint) can be used as a sacrificial layer to increase the pressure and to protect the material from damage caused by ablation and melting. This protection decreases the ablation and melting [8].

LASER SHOCK PROCESSING (LSP)

Laser shock processing, also known as laser shock peening, lasershot^{SM} peening or laser peening, is one of three processes of laser induced shock waves in deformation processing. LSP is similar to shot peening, but the shots are replaced by laser pulses. The pressure of the laser induced shock waves can causes residual stresses in a depth of several millimetres, since local plastic forming causes stretching of a small area, which stands under pressure by the surrounding elastically formed material after release of the pressure (Fig. 2).

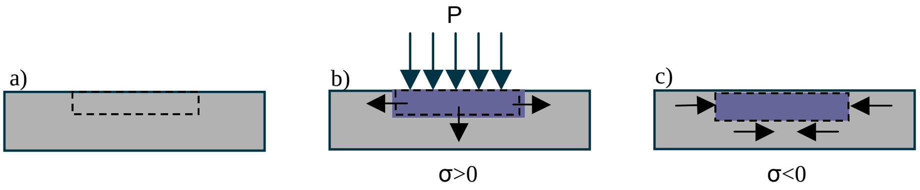


Fig. 2: Principle hardening by induced pressure [7]

It was figured out that compressive residual stresses of 70-80 % of the yield strength could be applied into aluminium alloys up to 1-2 mm in depth by LSP [6]. Hence, fatigue life and strength can be increased to a level higher than that of shot peening or deep rolling. It was generally found that LSP has no disadvantages compared to conventional processes in terms of mechanical properties: The roughness for LSP is significantly lower than for shot peening. Additionally there are no geometrical limits for areas to be treated by LSP as long as the area is visible [8, 5]. The fretting fatigue around fastener holes could be doubled through LSP in 7075-T6 aluminium alloy as [5] reports. Also stress corrosion cracking for stainless steel can be enhanced by LSP, whereby austenitic steels seem to be more suitable than martensitic steels [9]. Residual stresses produced by LSP can harden the surface of metal specimens, but the shock hardening effect decreases with increasing distance from the surface [5].

Modelling of LSP. The modelling work of LSP consists mainly of the modelling of shock pressure, the modelling of the residual stresses and the modelling of stress/strain evolution. For the analysis of the shock pressure there are some models, in which it was assumed that the laser irradiation is uniform and therefore shock propagation in the confining medium and the target is one-dimensional [10, 11]. In Morales's calculation system SHOCKLAS a one-dimensional model was used for the estimation of the pressure wave applied to the target material in LSP process [12]. In order to increase the model accuracy in micro-scale LSP, an improved modelling method for the analysis of shock pressure was developed, in which the fraction of plasma internal energy is used to increase the pressure of plasma and the radial expansion of plasma were taken into account [13].

FEM method was firstly used by [14] to calculate the residual stresses in LSP [5]. Later [15] developed an axis symmetric FEM model for the calculation of residual stresses induced by laser peening. In the model, with consideration of the hydrodynamic attenuation of shock waves and the elastic-plastic behaviour of the material, some parameters were taken into account such as: the shock yield strength of the metal Hogoniot Elastic Limit (HEL) and the Hugoniot curves. In comparison with the experimental results on 12Cr steel and 7075—T7351 aluminium alloy, his work showed good agreement [15].

Shock wave propagation generated by fast impact of an amplitude p in a duration of t in the work piece is a basic phenomenon in LSP. With regarding to the high strain-rate, which can exceed $10^6 s^{-1}$ within the target material, generated in LSP, some assumptions are applied in [14] for the modelling such as: materials can be modelled as elastic-perfectly plastic, all plastic deformation occurs at the same high strain-rate, and a linear equation of state is valid.

It is known that the temperature fields are needed to calculate the stresses in LSP and the surface absorptivity is affected by the surface temperature. [16] developed a mathematical model to study the effect of laser irradiance and its time modulation on the temperature distributions in the work piece and plasma plume. It is shown that the irradiance rate has more effect on the material temperature than the actual irradiance I(r, t) [16].

Materials properties of LSP. Laser shock processing has mainly been done on Aluminium alloys, but also titanium alloys, steel and copper have been successfully treated with LSP. Extensive investigations were done in fatigue life enhancement on 6061-T6 and 2024-T3 aluminium [17, 18, 19] alloys as well as on Ti-6Al-4V [20]. The improvement of fatigue strength for welded joints of 18 Ni-marging steel by 17 % [21] and for welded joints of 5456 aluminium [10] is reported.

The hardening by LSP has been done on aluminium alloys with significant improvement of non heat-treatable 5086-H32, 2024-T3 and 7075-T73. The hardness of weld zones of 5086-H32 aluminium could be increased to the level of the base material [5]. [22] investigated hardening of mild and stainless steel. The hardness could be increased 1.7 times compared to the base alloy hardness, whereby the increase of hardness is due to dislocations generated in the shock affected region. Pitting corrosion behaviour of stainless steel has been improved through LSP by [23]. It is assumed that residual stresses and work hardening are the reason of corrosion improvement, mainly by interface-like effects around the inclusions.

Applications of LSP. Since fatigue life and strength can significantly be increased through LSP, a high interest on applications for heavy loaded parts can be reported. General Electrics received more than 20 patents on LSP. High cost, low volume parts such as compressor blades, turbine fan blades, rotor components, discs, gear shafts and bearing components are well known applications for LSP [8, 5, 24]. Turbine fan blades were laser peened in order to increase the durability and resistance to foreign object damage. Fastener holes in aircraft skins can be treated by LSP to repair micro cracks [5]. Future applications for LSP are seen in micro electromechanical systems (MEMS) such as micro engines and micro-switches made of copper and aluminum in order to increase fatigue life and wear resistance [25].

LASER STRETCH-FORMING

Laser stretch-forming – discovered last year – is a new process based on laser induced shock waves. In contradiction to common laser forming of sheet metal, where thermal mechanisms cause bending of the sheet metal, the new process is based on a non-thermal forming mechanism [26, 27, 28]. The shock wave is the responsible energy source for this forming process. Hence, the forming behaviour can be compared to that of a high speed forming process like electromagnetic forming or explosive forming. The laser induced shock wave can be used in principle for all sheet metal forming processes as long as the parts are in micro- or mesoscopic range.

In laser stretch-forming the sheet metal is wet by a water film of 2 mm in height in order to generate a confined plasma, placed on a circular die and clamped by a blank holder. In a next step a single excimer or CO_2-laser pulse hits the sheet metal and causes forming of the sheet to a hemispherical dome, Fig. 3.

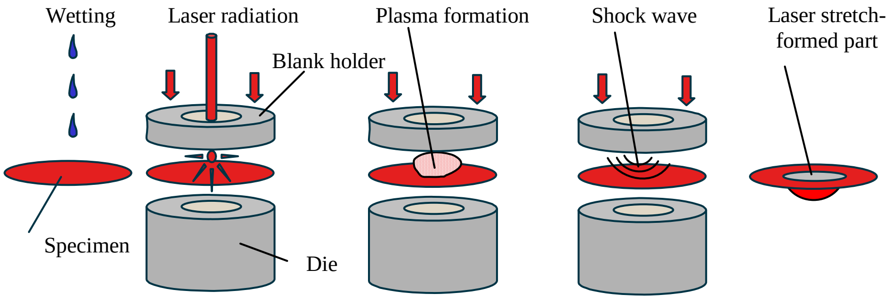


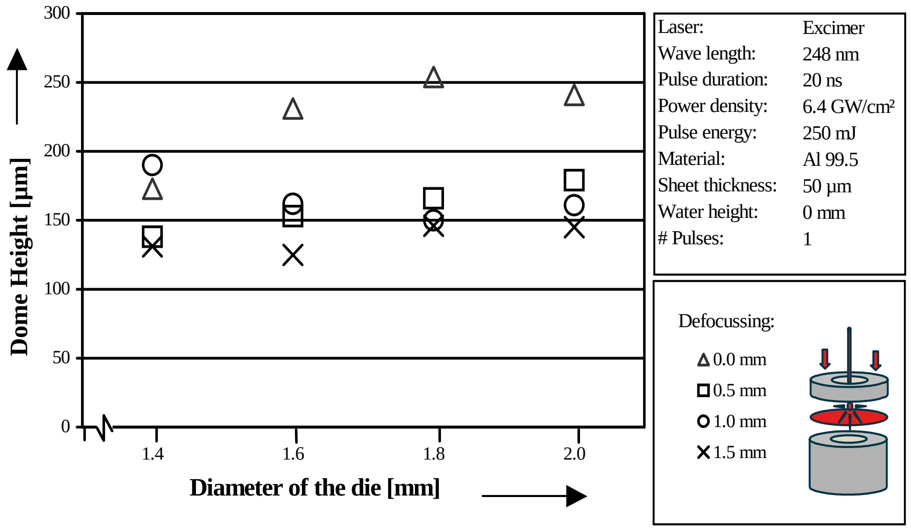
Fig. 3: Schematical process of non-thermal laser stretch-forming

Experimental investigations with excimer laser. Laser induced stretch-forming experiments were carried out with variation of the parameters defocussing, water height, number of pulses, power density and material. The used excimer laser has a wave length of 248 nm and a pulse duration of 20 ns. The maximum pulse energy is 250 mJ and the maximum power density is 6.4 GW/cm², whereby a power density of 0.1 GW/cm² is sufficient to ignite a plasma [29]. The dome height of the laser stretch-formed parts was used as a degree of forming, presuming a uniform dome shape.

Influence of defocussing and water film. The defocussing is defined as distance between work piece and focus of the laser beam, whereby the value is positive, if the focus is above the work piece, and negative, if the focus is below the work piece surface. The highest energy density is at a defocussing of zero. Therefore, the maximum applied stress of the shock wave can be found at a defocussing of zero.

Single laser pulses on an aluminium foil of 50 µm in thickness were carried out with different ranges of defocussing with and without a water film. The maximum dome height of laser stretch-formed parts without the use of a water film is reached in the focus, where the dome height is 250 µm at a die diameter of 1.8 mm, Fig. 4**Error! Reference source not found.**. The dome height of other experiments with a defocussing of +0.5 to +1.5 mm is significantly lower. It has to be said that the parts, which were formed in the focus without a water film, did not constitute an uniform shape, but a peak, similar to the example in Fig 6b), so that these parts are scrap.

The same experiments were carried out with a 2 mm water film. In these experiments it was not taken into account that the laser light is diffracted at the transition point from air to water and thus the focus is shifted by approximately 1 mm towards the work piece since the refraction index for water is higher than for air. These experiments produced consistently uniform shaped parts with a dome height of 277 µm at a die diameter of 1.8 mm and a defocussing of +0.5 mm, see Fig. 5. Experiments with other ranges of defocussing resulted in lower dome heights, which means that the best working point is reached when a 2 mm water film is applied at a defocussing of +0.5 mm relative to the focal positon in air.



Laser:	Excimer
Wave length:	248 nm
Pulse duration:	20 ns
Power density:	6.4 GW/cm²
Pulse energy:	250 mJ
Material:	Al 99.5
Sheet thickness:	50 µm
Water height:	0 mm
# Pulses:	1

Fig. 4: Dome height of laser stretch-formed parts depending on the defocussing (no water film)

Influence of number of pulses. Stretch-forming by a single laser pulse usually leads to a uniform dome shape, if a water film is used, see Fig 6a). Two and more laser pulses lead to local forming, Fig 6b). More than seven pulses in this experiment lead to perforation of the sheet. The effect of local forming could be explained by the fact that the surfaces of the parts are locally pre-damaged by the first laser pulse, due to ablation. This leads to surface modification, resulting in higher local absorptivity, Fig. 6c). Hence, the second laser pulse causes significantly higher ablation than the first laser pulse, so local thinning is induced. Subsequently, deformation is located at the thinned area. The increased ablation might also be the reason for the non uniform forming of laser stretch-formed parts without a water film – as described in the previous chapter – since water reduces ablation.

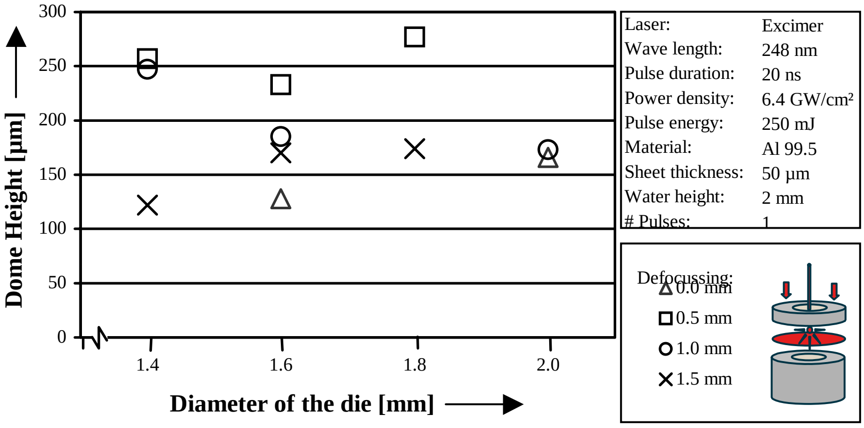
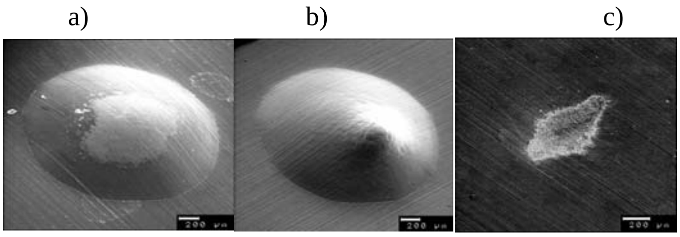


Fig. 5: Dome height of laser stretch-formed parts depending on the defocussing (with use of a water film)

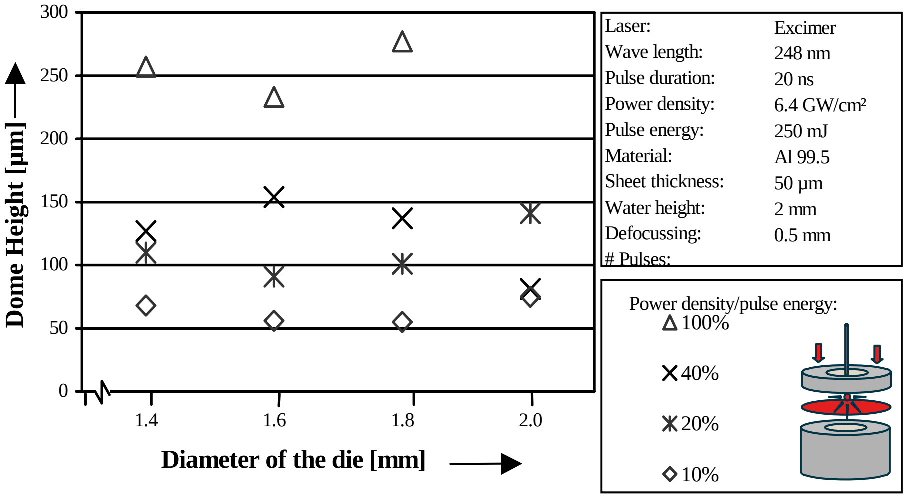


Laser:	Excimer
Wave length:	248 nm
Pulse duration:	20 ns
Power density:	6.4 GW/cm²
Pulse energy:	250 mJ
Material:	Al 99.5
Sheet thickness:	50 µm
Water height:	2 mm
Diameter of die:	1.4 mm
Defocussing:	0.5 mm

Fig. 6: Shape of laser stretch-formed parts with a) one and b) two pulses; c) spot area, one puls

Influence of power density. The power density is proportional to the pulse energy and decisive for the forming result. The pulse energy of 250 mJ and thus the power density is reduced down to the tenth part in the following experiments.

As expected, the dome height decreases with decreasing pulse energy. However, the forming still takes place at 10 % of the maximum power density, since 10 % means six times the minimum power density for plasma ignition,Fig. 7. The decrease of the power density decreases the velocity of the shock wave and thus the available forming energy.



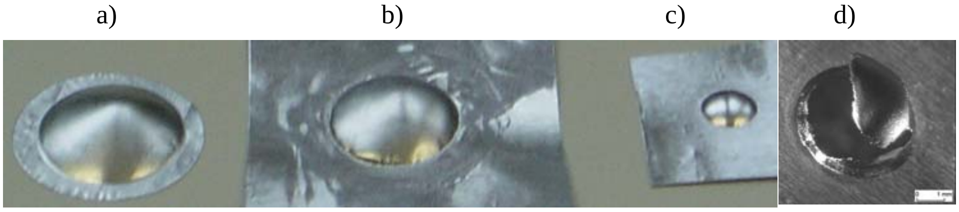
Laser:	Excimer
Wave length:	248 nm
Pulse duration:	20 ns
Power density:	6.4 GW/cm²
Pulse energy:	250 mJ
Material:	Al 99.5
Sheet thickness:	50 µm
Water height:	2 mm
Defocussing:	0.5 mm
# Pulses:	

Fig. 7: Dome height of laser stretch-formed parts depending on the pulse energy

Influence of material. In addition to the experiments performed on Al99.5, experiments on stainless steel have been carried out. The dome height of stretch-formed parts made of stainless steel remain below 25 µm, whereby parts of Al 99.5 reached a dome height of more than 250 µm. One reason for this phenomenon is that the yield strength of the stainless steel is twice the yield strength of Al99.5. However, the reduction of the sheet thickness of the stainless steel by 50 % did not lead to higher dome heights. Another reason could be that the oxide film of the aluminium sheet causes a faster ignition of the plasma and hence a more powerful shock wave.

Experimental investiagations with TEA-CO_2-Laser. Since the laser forming with excimer laser is connected with some disadvantages such as significant ablation and limitation on one pulse, further experiments have been carried out using a pulsed TEA-CO_2-laser. The wave length of this CO_2-laser is 40 times longer than the wave length of the used excimer laser. Therefore the ablation is significantly reduced.

This means that parts with diameters larger than 2 mm could be formed significantly, since several pulses could be applied now. In Fig 8. laser stretch-formed parts with diameters of 4, 11 and 12.3 mm are shown. The shape of the dome with 4 mm in diameter is spherical in contrast to the larger parts, which tend to form a cone. The experiments show that the dome height of the part with 4 mm in diameter increases with the number of laser pulses and approaches a certain limit asymptotically. Beyond this limit fracture occurs in the fringe area, since the capacity of deformation is reached, see Fig. 8d).



a) ∅12.3 mm; height 2.4 mm b) ∅11 mm; height 1.9 mm, c)/d) ∅4 mm; height 0.84mm

Fig. 8: Stretch-formed parts, produced with 50 CO_2-laser pulses

ASSISTANCE OF LASER INDUCED SHOCK WAVES IN BENDING OF HYBRID BLANKS

The assistance of laser induced shock waves in bending processes is the third process and was also discovered last year [30]. As a result of the request for weight savings on materials for the automotive- and aviation industry, hybrid blanks become nowadays more and more important. Bending of hybrid blanks is needed and a weakness at the same time. Particularly when the position of the welding seam is located in the forming area, for example at deep drawed cups composed of welded aluminium/steel blanks in I-joint. Fig. 9. shows such a cup with a crack in the welding seam in the tensile stress zone.

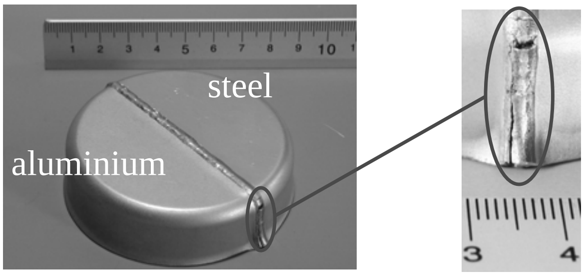
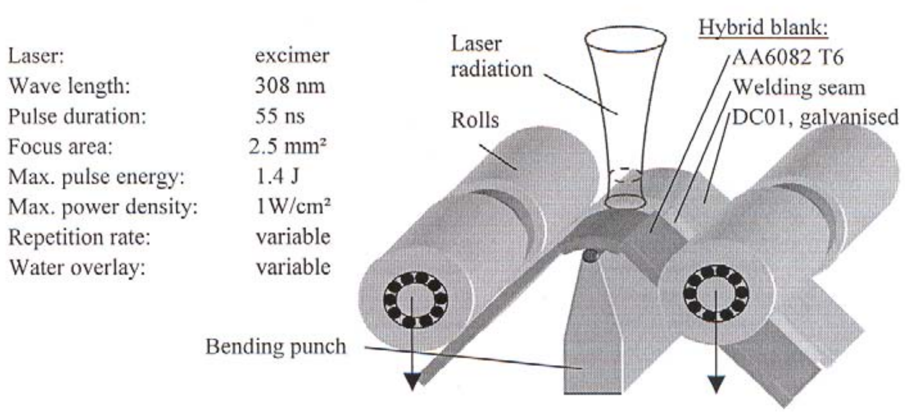


Fig. 9: Deep drawn aluminium/steel I-joint

Goal of the process is to increase the formability of welded aluminium/steel blanks through change of the stress conditions in the welding area during the bending process through treatment with laser pulses. The laser induced shock waves in the welding seam cause compressive stresses orthogonal to the tensile stress induced by the bending process. This causes a decrease of the mean normal stress during the bending process and thus an increase of formability in the critical area [31].

Samples and experimental setup. The hybrid blanks are produced at BIAS by laser beam welding [32]. The welded material is AA6082 aluminium alloy (state of heat treatment T6, thickness 1 mm) and galvanised steel DC01 (thickness 1 mm). As filler metal AlSi12 was used. The welding seam has a superelevation of 0.45 mm.



Laser:	excimer
Wave length:	308 nm
Pulse duration:	55 ns
Focus area:	2.5 mm²
Max. pulse energy:	1.4 J
Max. power density:	1W/cm²
Repetition rate:	variable
Water overlay:	variable

Fig.10: Principle of bending with laser induces shock waves of hybrid blanks

The experimental setup is orientated to the three point bending test according to DIN EN ISO 7438. The laser welded hybrid blank is bent over a punch with a radius of 1 mm. The bending force is induced by two flexible rolls, Fig. 10. In the sector of the welding seam, the punch and the rolls are equipped with a notch to assure a constant connection to the sample. On a certain bending angle cracking will occur in the hybrid blank welding seam in the tensile stress affected zone. The bending equipment is positioned in a water basin to realize a water overlay for the confined ablation on the sample surface. The pulse rate can be varied and is related to the roll feed, which can also be seen as the punch travel (in relative motion to the rolls).

Bending experiments without laser radiation. Reference experiments obtained that hybrid blanks can be bent to an angle of 54 °. This average value contains a deviation of ± 9 °. This comparatively high deviation is caused by the laser welding process due to stochastic fluctuations of the process dynamics.

Bending experiments with pulsed laser radiation. The treatment of hybrid blank samples during the bending process with excimer laser radiation with direct ablation (water overlay 0 mm) shows an increase of the bending angle to 71 °± 9 ° at a repetition rate of 10 pulses per 1 mm punch travel, see Fig. 11. The increase of the bending angle with the increase of the repetition rate is caused by the expansion of the time frame where the compressive stress is available and the forming limit is extended. The decrease of the bending angle with a further increase of the repetition rate above 10 pulses per 1 mm core movement is not yet clarified.

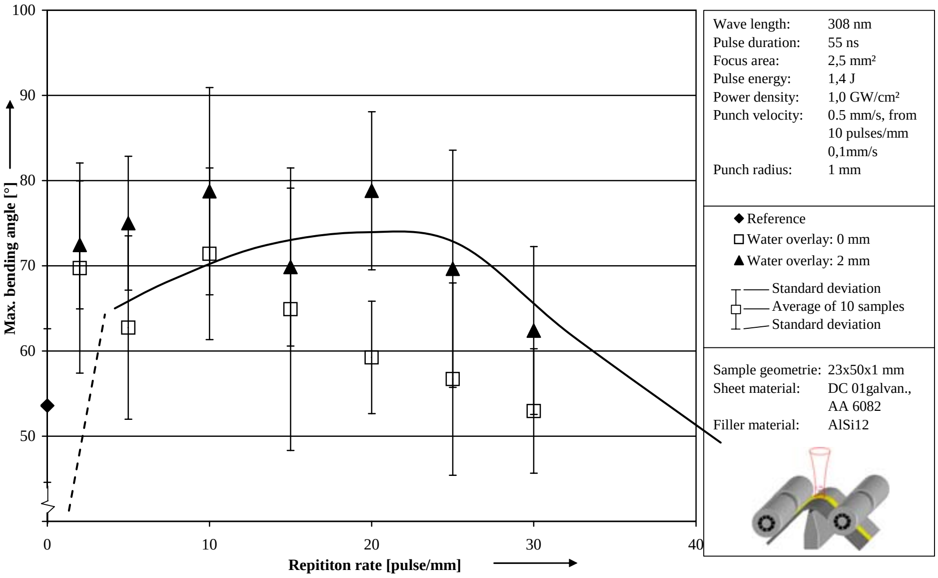


Fig. 11: Influence of the repetition rate and water overlay to the max bending angle

An even higher increase of the maximum bending angle can be reached by the process of confined ablation with a 2 mm water overlay. The maximum bending angle is 79 °± 9 ° at 10 pulses per 1 mm punch travel, Fig. 11. The confined ablation causes shock waves with more energy as direct ablation. Consequently, the mean normal stress decreases and the forming limit increases compared to the direct ablation. That is why higher bending angles are obtained with confined ablation. Due to the deviation of ± 9 ° a significance test has been made. The statistic analysis via t-test shows, that the maximum bending angle at a repetition rate of 10 pulses per 1 mm punch travel is at least 17 ° higher than for the reference samples with a probability of 95 %. The dependence of the maximum bending angle on the size of the induced shock waves can also be seen by the variation of the power density of the laser beam. With an increase of power density on the same base conditions an increase in the compressive stress and thus an increase in the forming limit is given. Further experimental investigations showed an increase of the max. bending angle along with the power density.

CONCLUSIONS

Laser induced shock waves are currently used in industry for LSP to harden metal surfaces mechanically in order to increase fatigue strength and wear resistance. LSP is a technologically advantageous but more expensive process compared to shot peening or deep rolling. Two further processes for laser induced shock waves have been discovered recently. One of them is laser stretch-forming, were uniform shaped domes with heights over 250 µm and diameters of 1.4 mm for Al99.5 foils with 50 µm in thickness have been made by excimer laser pulses. Promising results have also been shown with CO_2-lasers. The third process for laser induced shock waves is the assistance in bending processes, where weld seams tend to tear due to excess forming. The laser induced shock waves can superpose compressive stresses, which leads to a decrease of the mean normal stress, which leads to an increase of the forming limit in the critical zone. In general, it has been found that transparent layers are helpful for the use of laser induced shock wave, since ablation is reduced and the impact of shock waves significantly increased.

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