High speed joining process by laser shock forming for the micro range

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Abstract

The importance to implement more functionality on the same space pushes miniaturization and makes hybrid joints under various conditions, also in the micro range, necessary. Conventional joining processes, which are used in macro range, cannot be easily transferred to micro range dimensions. In this work a new high speed joining method for the micro range is presented, which is realized by a plastic forming process based on TEA-CO_2-Laser induced shockwaves. In a first step it is shown how sheet-sheet joints can be realized with this method. The experimental results illustrate the possibilities as well as the limits of the joining process by laser shock forming. Also the possible defects which can occur during the joining process are presented. Especially fracture of material at the edge. This is explained by the sharp edges in the joining area, which are caused by the production process of the specimen.

Keywords

High speed forming, Laser shock forming, Joining by forming

1 Introduction

Resource efficiency, reduction of production costs and function compaction are reasons of miniaturization. This makes also hybrid joints for micro range necessary. Conventional joining processes, which are used in macro range, cannot be easily transferred to smaller dimensions. With the ongoing trend of miniaturization so-called size effects appear [1], which inhibit sometimes the use of conventional manufacturing processes in total, or they can be used only with restrictions in micro range.

Typical joining processes for thin sheets of dissimilar materials are welding and brazing processes [2]. SHADOW® welding technique is a one of the processes which is used for joining of thin metal sheets with a material thickness <5 µm [3]. However, joining of dissimilar materials can result in formation of diffusion based intermetallic phases, which are characterized by high hardness and high brittle behaviour. Furthermore these processes are thermal based, which can influence the geometry of the components through distortion. In case of micro engineering these problems by thermal influences are particularly significant, since there is a high density of technical elements to be carried out next to heat sensitive components.

Another solution for joining thin metal sheets of dissimilar materials is explosion welding [4]. The advantages of these processes are that they do not lead to typical heat affected zones or distortion and the occurrence of intermetallic phases is minimized [5]. One approach for manufacturing thin metallic hybrid joints by non-contact impact joining was done by Nd:YAG-laser induced shock waves [6]. A thin metal foil (thickness ≤ 200 µm) was placed on a solid joining partner tilted by a process specific angle. For the increase of the shockwave and for protecting the surface against thermal influence an ablation layer was applied. Finally the foil is accelerated by laser induced shock wave in direction of the solid body. Due to high pressure in the contact area the metallurgical bond was achieved. Thereby no intermetallic phases were observed and an increased micro hardness along the boundary layer after the joining could be measured [7].

How joining by laser shock forming using a TEA-CO_2 laser can be realized is presented in former publications [8]. Using a TEA-CO_2 laser enables a simple process handling and short process times without need of an ablation layer. This kind of shock wave formation is known since the 70s, e.g. [9]. Due to laser treatment free electrons are generated by thermo emission out of the surface [10]. The number of free electrons depends on focus size, laser pulse intensity and surface material [10]. These free electrons absorb energy by inverse bremsstrahlung absorption and can produce further ions and electrons by impact processes until an optical breakdown and thus a plasma formation is achieved [11]. The inverse bremsstrahlung increases with the square of the wavelength accomplishing a nearly complete absorption of the longer wavelength of CO_2-laser light by the plasma. If the energy density of the laser pulse exceeds a certain threshold, the fast expansion of the plasma forms a shock wave [12], which is initiated ~8 mm above surface [8]. This shock wave moves spherically [13]. The shock wave pressure, which is in the range of some MPa [14], leads to a forming of the surface [15]. The laser shock forming process first was used for deep drawing of copper and aluminium sheets [16] and later for joining process [8]. Thus this process is promising for hybrid joints in the micro range and the increasing need of micro joints i.e. in precision mechanics and electronic industry. In this work the process window of the joining process of aluminium and steel is presented.

2 Experimental setup

For the joining process a pulsed TEA-CO_2-laser (wavelength:10.6 µm) with a pulse duration of 100 ns, a spot size of 0.04 cm^2 and a laser pulse energy up to 6 J per pulse is used. The principle experimental setup is shown in Fig. 1. The setup consists out of 5 basic elements: the blank holder, Joining Partner I and Joining Partner II, a spacer and the bottom of the tool. The Joining Partner I and Joining Partner II are positioned upon each other. Joining Partner I is made out of aluminium with a thickness $t_{Partner\ I}$ of 20 µm or 50 µm. Joining Partner II is made out of stainless steel with a thickness of $t_{PartnerII}$ of 25 µm up to 300 µm and has a hole which is the diameter of with a diameter of 2 mm or 4 mm and is specified as *d* the diameter of the joining area. Both parts are produced by a laser cutting process with a Nd:YAG short pulse laser, which ensures reproducible specimen geometries. Aiming to provide space for material flow of Joining Partner I to create an undercut, a spacer is located between Joining Partner II and the bottom of the tool. The spacer thickness (in the following t_{spacer}) is varied from 25 µm to 300 µm and the diameter of the spacer hole is 1 mm bigger than the hole of the used Joining Partner II. The blank holder is holding the partners in position during the process while the blank holder force is over the clamping force. This leads to a pure stretch drawing process. In the tools bottom ventilation holes are implemented, so that air below the specimens is not disturbing forming of the material. This tool ensures an exact positioning of the specimens and reproducible experimental conditions through alignment pins and bedstops.

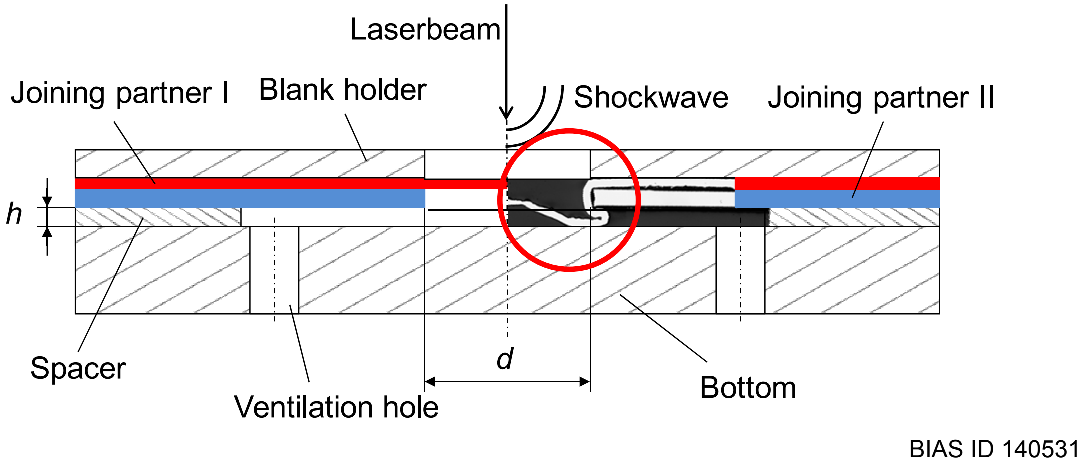

***Figure 1**: Experimental setup*

The laser irradiates on Joining Partner I with the focus lying on the surface. This leads to plasma formation about 8 mm above the surface [8]. The resulting shockwave forms the material in the joining area accomplishing an undercut which presents the joint itself, as shown in Fig. 1 inside the circle. The number of laser pulses is varied for different material thicknesses of Joining Partner I. For material thickness of 20 µm the pulses are varied from 10 up to 50 shots. For material thickness of 50 µm laser pulses between 50 and 200 are used. The repetition rate of the laser pulses is 20 Hz, and for each parameter set 5 experiments are carried out.

3 Results

3.1 Joining geometries and failure behavior

By varying the process parameters different joining results could be observed. These results are classified in three different main types, which are: joining could be achieved, no joining could be achieved because no undercut was created and material failure in the joining area. For the first main type: joining could be achieved, there are two possibilities, which are shown in Fig. 2.

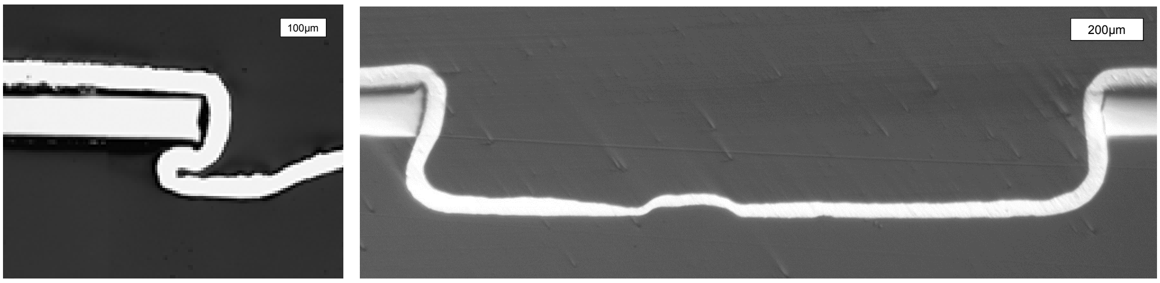

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***Figure 2**: cross section of undercut bigger than double the material thickness (left) and small undercut (right)*

The first one is an undercut depth, which is more than double the material thickness and this undercut depth is constant over the whole joining area. The second one is a very small undercut depth which is smaller than the material thickness as shown in Fig. 2 on the right side. From the cross section of the joints it can be seen that the joint is achieved due to mechanical clamping of the upper sheet to the lower one. Material fracture during the process can occur in two different locations, in the bottom of the forming area or at the edge of Joining Partner II. These failure behaviors are shown in Fig. 3.

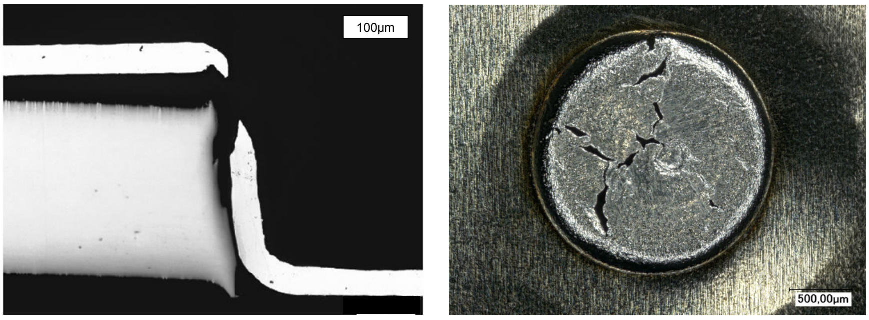

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***Figure 3**: material failure, broken in the edge (left) and broken in the bottom (right)*

3.2 Process windows

For these experiments a joint is defined as a material fracture free joining area which is able to carry their proper weight. For each parameter set five experiments were carried out. As long as all five experiments result in a joint, this point is marked as “good joint”. For less than five joints the process is not reproducible and therefore not feasible for industrial applications. These points are marked as “not reproducible”. The points where no joint could be achieved, or a material failure appeared are marked as “no joint”.

Fig. 4 shows a schematic process window. For this process window the used laser pulses are varied above the different spacer thicknesses. The area marked as “A” shows the parameter, which leads to a good joining result. In area “B”, which is lying left and below the process window, no undercut could be observed. Area “C” and “D” are the areas where material failure occures. This kind of process window is made for different material thicknesses.

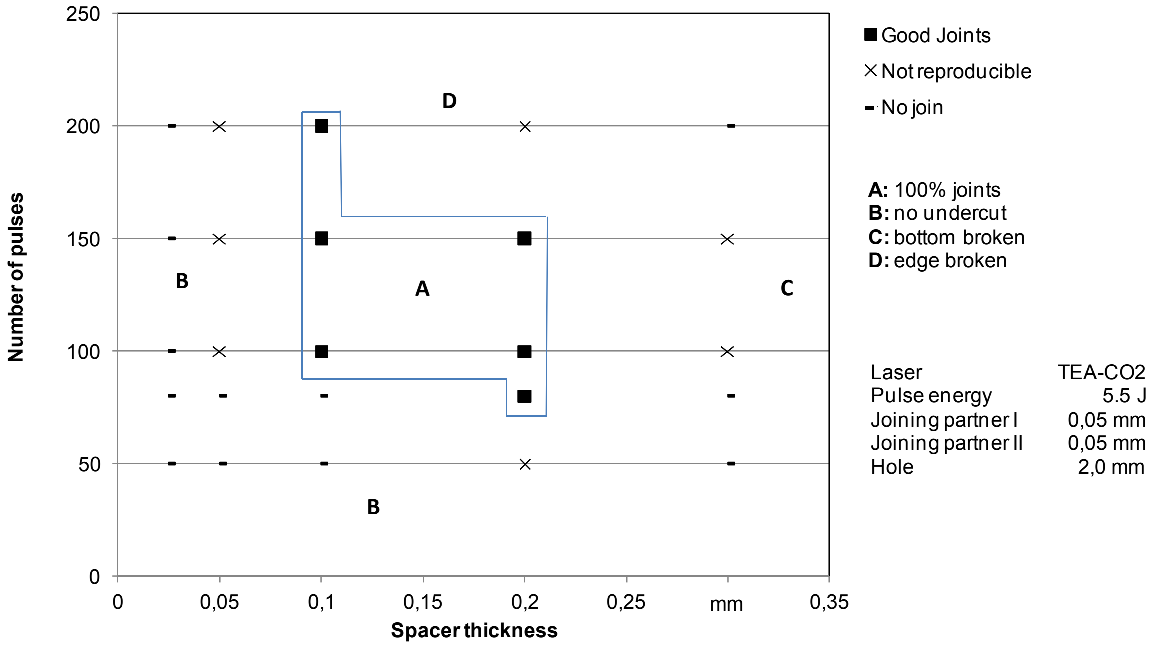

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Figure 4: *Exemplary process window*

In order to analyse the process behavior over different material thicknesses process windows are compared with each other. Therefore the limits of the process window needs to be described. One approach of describing the lower limit of the process window is shown in Fig. 5. For the illustration of this curve the lowest points of the process window are taken. These are for Fig. 4 the datapoints for 100 pulses with a spacer thickness of 0,1 mm and 80 pulses with a thickness of 0,2 mm. For comparing the other joining geometries, these parameters need to be scaled to a comparable value. Therefore the used laser pulses are divided through the material thickness of Joining Partner I. The same approach is used for the spacer thickness. With these two relative values a comparison of the different process windows to each other is possible, asshown in Fig. 5.

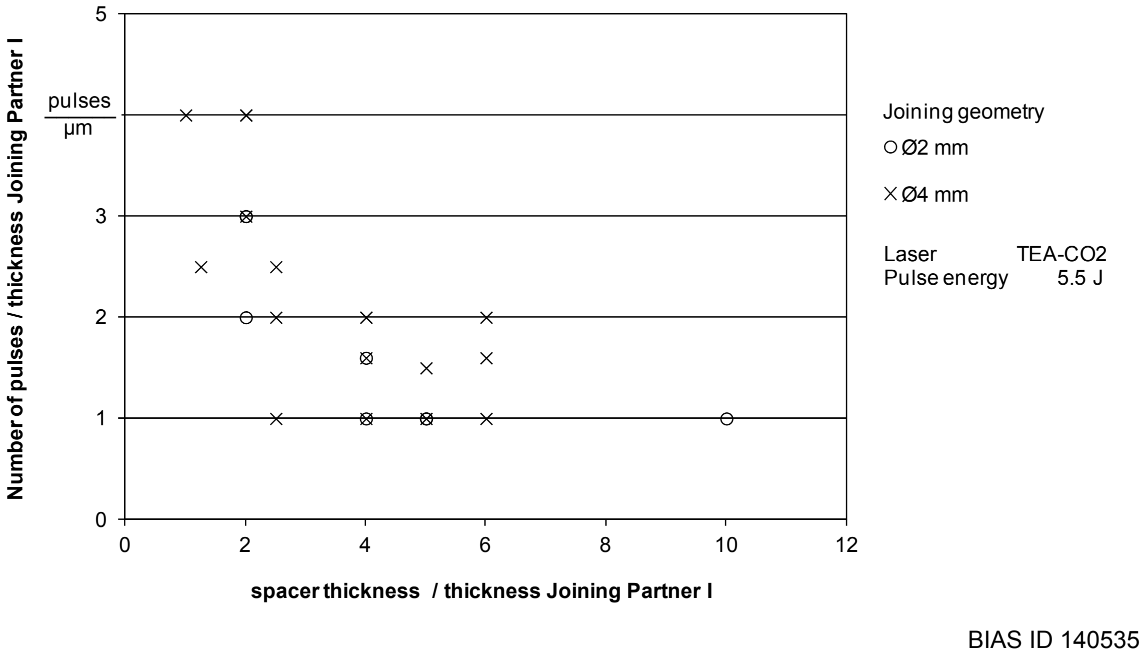

***Figure 5**: Needed laser pulses over spacer to Joining Partner I ratio*

It can be seen that for a bigger t_{spacer} / $t_{Partner\ I}$ ratio less energy is needed to create a joint. The amount of laser pulses which are needed, decreases exponentially to a value of 1 pulse / µm.

The ratio t_{spacer} / $t_{Partner\ I}$ has also an upper limit. When the total distance from Joining Partner I to the tool bottom reaches a certain distance, material fracture of Joining Partner I occurs. For the description the mean value for these limits are calculated and presented in Table 1.

Ø joining area	Thickness Joining Partner I	Mean height to material failure
2 mm	20 µm	187 µm
	50 µm	225 µm
4 mm	20 µm	137 µm
	50 µm	433 µm

***Table 1**:* Mean height as the sum of Joining Partner I and Spacer Thickness where material failure occurs

It can be seen that for a thickness of 20 µm the height for both geometries are in the same range, while for the thickness of 50 µm the height to material failure is nearly factor two bigger for a diameter of 4 mm.

4 Discussion

The results of this work illustrate the possibilities as well as the limits of the joining by laser shock forming. On one hand, the creation of joints is possible with all used joining geometries of 2 mm and 4 mm and on the other hand there are limits, especially with thinner material, where more fractures occur. For the process window shown in Fig. 4 different limits of the process are presented.

The upper limit of the Process window is given by material failure. The joining process can be seen as a stretch drawing process. During a stretch drawing process the material, which is needed for increasing the surface, is taken from the material thickness. If the strain of the material is getting too high the material will crack. So the material failure is a result of too much induced strains. Especially material failure at the edge is a result of a sharp edge from the steel sheet, during the process. Beside this it results from a combination of applied laser pulses and a sharp edge which leads to stress concentration. Sharp edges at the hole are a result from the laser cutting process, where the material melts during the process and burr at the edge is created. Bottom tear in the material is occurring, when the distance between Joining Partner I and the bottom is too high. The mean values of these limits are shown in table 1. Differences in the limits for the different material thicknesses can be explained by the lower forming limit curve of thinner material [17]. When the material is touching the bottom of the tool before a bottom tear occur the material is supported by the bottom, which leads to lower induced tensile stresses in the bottom of the joining area trough the shockwave. This means that the induced stresses through a shockwave are higher in the groove and edge than in the bottom which leads to material fracture in the edge.

One influence of the difference in the maximum height to the bottom between the joining geometries is that the material failure material failure is not only occurring in the bottom. Material failures are also occurring in the edge of Joining Partner II, which is influencing the result of the maximum height to material failure.

In Fig. 5 it is shown that for a larger t_{spacer} / $t_{Partner\ I}$ ratio less energy or laser pulses are needed to create a joint. This fact can be explained by the geometry of the experimental setup and the joining geometry. For the creation of an undercut there should be enough space between Joining Partner II and the bottom of the tooling which should be more than double the thickness of Joining Partner I. This can be seen in the ratio of spacer to Joining Partner I. If the ratio is smaller than two there will be a resistance for the material flow into the space to create an undercut. This resistance can be overcome by using more laser pulses, but will only result in a small undercut depth. If the ratio from spacer to Joining Partner I is getting bigger the amount of necessary shockwaves is reduced. The contact surface, on which the pressure wave acts, is dimensioned by the die diameter and the spacer height. The effective force which is induced by the shockwave increases with the spacer height, which leads to less shockwaves needed to create an undercut.

5 Conclusion

By an experimental approach using different thicknesses of metal sheets and different size of joint geometries it was shown that joining of aluminium to stainless steel is possible by the means of laser induced shock waves. For nearly each combination of material thicknesses a process window could be detected. From the cross section of the joints it can be concluded that the joint strength is achieved due to mechanical clamping of the upper sheet to the lower one. Also could be concluded that for bigger spacer thickness to thickness of Joining Partner I ratio less laser pulses are needed for the creation of an undercut and hence for the joining process.

Acknowledgments

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