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Areas of application for TEA CO_2-Laser induced shock waves

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Abstract

Increasing batch size and shorter lifecycle in micro manufacturing is a challenge for production processes. Conventional processes have limits regarding the technical feasibility for producing micro parts, due to so-called size effects. Therefore, a new flexible production approach using TEA-CO_2-laser induced shock waves for manufacturing micro parts is presented in this paper. For thin sheet in the range of 15 µm to 100 µm materials there are some technical challenges using a conventional mechanical process. The right tool alignment, for forming, punching and blanking processes, between punch and die is an increasing challenge when the process dimensions are decreasing. Additionally, in a punching process the clearance between punch and die is such a critical parameter. The size of a suitable cutting clearance correlates with the sheet thickness, e.g. for a fine blanking process 0.5 % of the material thickness, which results for 20 µm in clearance dimension of just 0.1 µm. Therefore, it is shown how a laser shock process in micro range can replace conventional forming, punching and blanking processes. For thermal joining processes, there are restrictions due to the principle of joining, especially for the use in clean rooms or regarding the creation of intermetallic phases for hybrid joints. Therefore, laser induced shock waves can be used to join different sheets by a plastic forming process. This technology enables the joining of different sheet materials with thicknesses between 20 µm and 300 µm. The manufacturing of these joints is an incremental process where several laser induced shock waves are needed to form an undercut, which presents the joint itself. The joining of aluminum/steel and aluminum/copper joints is shown in this paper. For different thicknesses ranging from 15 µm to 100 µm of Al99.5-sheet perforations were successfully generated. The punching geometry is also not limited to circular holes. Rectangular perforations were proved to be applicable as well. Methods and approaches to use a laser as a flexible tool for forming, cutting and joining processes for the micro range are presented in this work.

Keywords: laser shock forming, mechanical joining, laser shock cutting

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1. Introduction

Increasing batch size and shorter lifecycles in micro manufacturing is a challenge for production processes. Conventional processes have limits regarding the technical feasibility and flexibility for producing micro parts, due to so-called size effects (Vollertsen et al., 2009).

Punching, joining, blanking and forming processes have large industrial relevance to the production of small metal parts. Geiger mentioned that potential fields of application are lead frame structures, connecting the die of a microchip with a circuit board in the electronics industry, injection nozzles for combustion engines or rinser sheets (Geiger et al., 2001). These application fields are still active, but due to miniaturization the structures which needs to be produced are still getting smaller. Two main obstacles make the miniaturization of conventional mechanical process difficult. One is the fabrication of tools with a high geometrical accuracy and the other is the accurate alignment of the tools (Yi et al. 2006).

However, a very accurate defined alignment between punch and die is an important parameter to determine the quality of a punching or blanking process. Under standard process conditions, the ratio of die clearance to work piece thickness is about 5%. This means the required die clearance for a 20 µm thick sheet is 1 µm. Therefore, the alignment between punch and die hole should be within 1 µm, and the straightness error in the punch motion must be less than 1 µm during a punch stroke of several millimeters, too (Joo et al., 2005). It requires a lot effort, precision and time to manufacture and adjust such tool sets, thus it is cost intensive. Process parameters are influencing the accuracy of the tool sets, like thermal influences during process and dynamic behavior of the tooling machine. This could lead to excessive wear of the tools and therefore result in a change of the tool geometry. Flosky et al. show an exemplary demonstration of excessive wear of a combined blanking and deep drawing tool caused by a positioning error (Flosky et al.,2014). However, not just the decreased lifetime of the tools is a problem of the resulting wear. Along with the wear the tool geometry and the cutting clearance changes as well.

Laser shock forming is a well know process, where laser shock treatment is extended to laser shock forming by a TEA-CO2-laser (Schulze Niehoff et al., 2005). Due to laser irradiation, free electrons are generated by thermo-emission out of the surface (Demtröder, 2010). The number of free electrons depends on focus size, laser pulse intensity and surface material (Demtröder, 2010). These free electrons absorb energy by inverse bremsstrahlung absorption and can produce further ions and electrons by impact processes until an optical breakdown and a plasma formation is achieved (Miziolek et al. 2006). 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. This kind of shock wave formation is known since the 70s, e.g. (Barchukov et al. 1974). If the energy density of the laser pulse exceeds a certain threshold, the fast expansion of the plasma forms a shock wave (O´Keefe et al., 1973), which is initiated above the surface (Barchukov et al., 1974). This shock wave moves spherically (Walter et al., 2007). The pressure of the shock wave forms the surface, e.g. (Zhang et al. 2004). During the laser shock forming process, pressure peaks in the range of some MPa can be achieved (Vollertsen et al., 2009). By a laser shock bending process with a maximum pulse energy of 5.5 J and a forming velocity of 40 m/s strain rates of $3 \cdot 10^3$ s^{-1} could be determined. By cone-shaped blank holder, which limits the spreading of the shock wave, the pressure can be increased (Wielage et al., 2010). The pressure wave has a high tolerance against the focal position, therefore a correction of the focal position during a process with several pulses is not necessary (Vollertsen et al., 2009). Several pulses can be applied at the same position in order to achieve a high forming degree without increasing the energy density beyond ablation limit. Laser shock forming achieves higher strains than quasi-static forming methods, because of the high speed forming by the shock wave (Vollertsen et al., 2009).

For thermal joining processes there are restrictions due to the principle of joining, especially for the use in clean rooms or regarding the creation of intermetallic phases for hybrid joints. Therefore, laser induced shock waves are used to join different sheets by a plastic forming process. This technology enables the joining of different sheet materials with thicknesses between 20 µm and 300 µm (Veenaas, 2014). The manufacturing of these joints is an incremental process where between 10 and 500 (dependent from the used material and material thickness) laser induced shock waves are needed to form an undercut, which presents the joint itself.

By using the laser induced shockwave as a tool, a punch in mechanical forming process is no longer required. One of the advantages of this procedure is, that no friction occurs at the position of force application. Additionally it is not necessary to invest a lot of effort in the high geometrical accuracy of manufacturing and adjusting the tool alignment anymore. Furthermore, the laser shock setup is robust, because it is relatively insensitive to changes of the laser focus and lateral shifting. Veenaas (2013) showed, that a displacement of a few millimeters can be tolerated. In this paper it is shown, how laser shock treatment can be extended to laser shock forming, cutting and joining processes.

2. Experimental setup

2.1. Laser shock forming

The principle of laser shock forming process, which was used by Wielage, is shown in figure 1 (Wielage, 2009). A circular blank out of Al99.5 with a thickness of 50 µm and a diameter of 6 mm is placed on the die. The blank holder is placed onto the blank with a defined blank holder force. In a next step, laser pulses of a TEACO2- laser irradiate the specimen with the focus located on the blank surface. The high energy density of the laser radiation initiates ionization of the close-by atmosphere and thus plasma formation takes place. The propagation of the plasma causes a shock wave, if the energy density of the laser pulse exceeds a certain threshold. The sample is formed by the shock wave pressure.

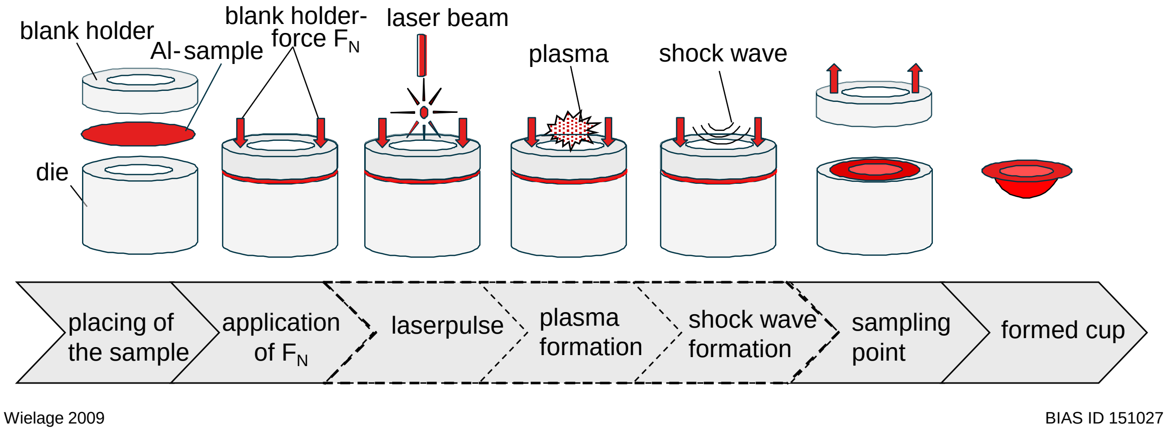


Fig. 1. Schematic setup for laser shock forming process

2.2. Laser shock cutting

The tool setup used for the punching experiments is shown in figure 2, left side. It consists of a sharp-edged die with an inner diameter of 2 mm, a blank holder with an inner diameter of 5 mm and a chamfered counterpunch. The counterpunch supports the sheet material in the center of the hole to prevent uncontrolled rupture and to concentrate the force to the cutting edge of the die. The counterpunch is chamfered to provide a cavity near the cutting edge where sheet material can flow too. This punching process is well suited to generate perforations in sheet material but the resulting blank quality was not sufficient. To achieve cut out blanks from good quality the setup for blanking process has to be used. The experimental setup used for blanking operations is illustrated on the right side of figure 2. In this setup, not the sharp edge of a die is used to realize cutting of the sheet material. A jutting sharp-edged punch is used instead. At the beginning of the test the sheet material is placed on a spacer ring so the sheet lies slightly above the punch, without any clamping or preloading. Jutting of the punch and a spacer are necessary to ensure that there is enough space left for the formed and afterwards cut sheet material to flow to. In all experiments silicon oil was used as lubricant to prevent adhesive wear.

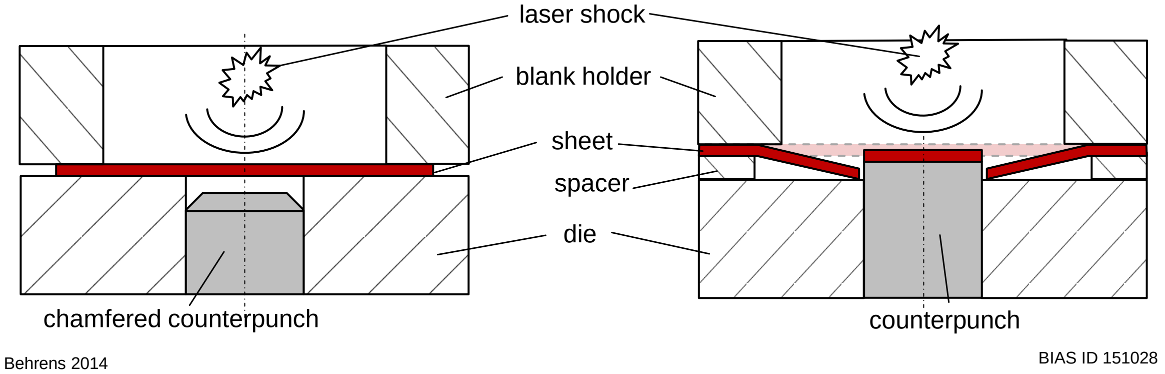
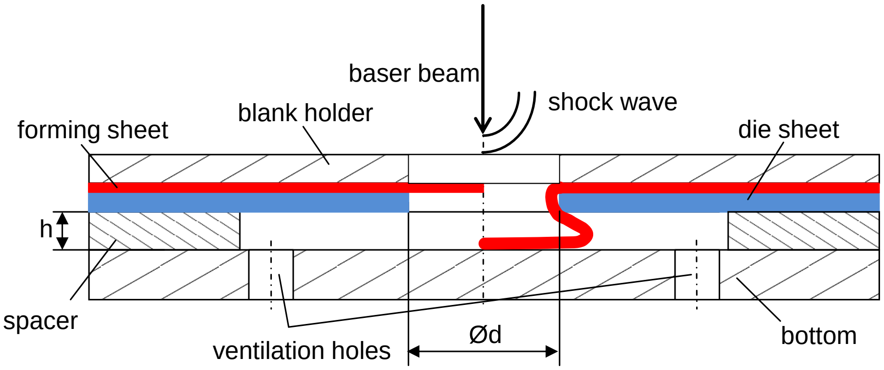


Fig. 2. (left) experimental setup for punching; (right) experimental setup for blanking

2.3. Laser shock joining

The experimental setup for joining by laser shock forming is shown in figure 3 (Veenaas, 2013). The setup consists out of five elements: the blank holder, the forming sheet and die sheet as joining materials, a spacer and the bottom of the tool. The forming and die sheet are positioned upon each other with a small overlap. The die sheet includes a hole with a diameter d for the material flow of the forming sheet to create the undercut. This hole is made by a laser cutting process and designates the geometry of the joint. As die sheet stainless steel (1.4301) with a thickness of 100 µm is used. For the forming sheet aluminum Al99.5 with a thickness of 50 µm is taken. In order to enable material flow for the undercut formation there is a spacer between the two joining materials and the bottom. The height of the spacer is variable. The blank holder is holding down the joining partners during the process with a force of 25 N. The laser irradiates on the forming sheet with the focus on the surface and creates the plasma for the laser shockwave. This shockwave forms the material in the joining area compared to the laser shock forming. Due to the fact, that the material is blocked to the bottom it creates an undercut which presents the joint itself.



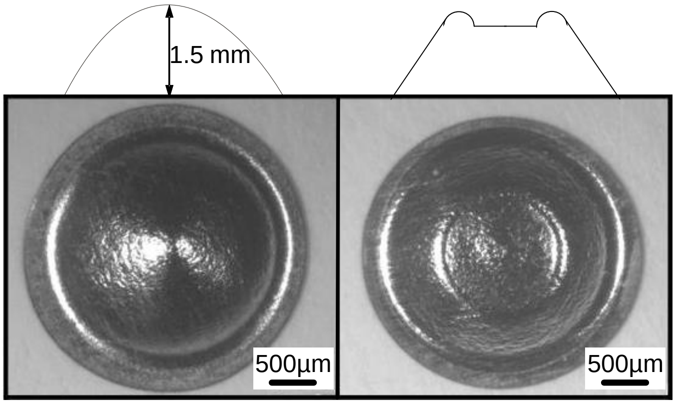
Veenaas 2013 BIAS ID 131068

Fig. 3. schematic setup for laser shock joining

3. Results and discussion

3.1. Laser shock forming

With laser shock forming deep drawn cups can be produced within one pulse with non-complex shapes and free forms as shown in figure 4, whereas the free formed specimens showed cone shapes (Wielage, 2008). It has been shown that with this TEA-CO_2 laser shock deep drawing process copper and aluminum sheets of thicknesses of 50 µm and 100 µm can be formed (Vollertsen, 2009). Due to the absence of a punch no friction between the punch and the sheet can lead the formed sheet. Therefore, laser shock deep drawing is more sensitive to partial draw-in. It is shown that this problem can be overcome by using a counterpunch (Wielage, 2008).



material	Al99.5
material thickness	50 µm
pulse energy	5.6 J
used laser pulses free forming	1
used laser pulses with counter punch	35

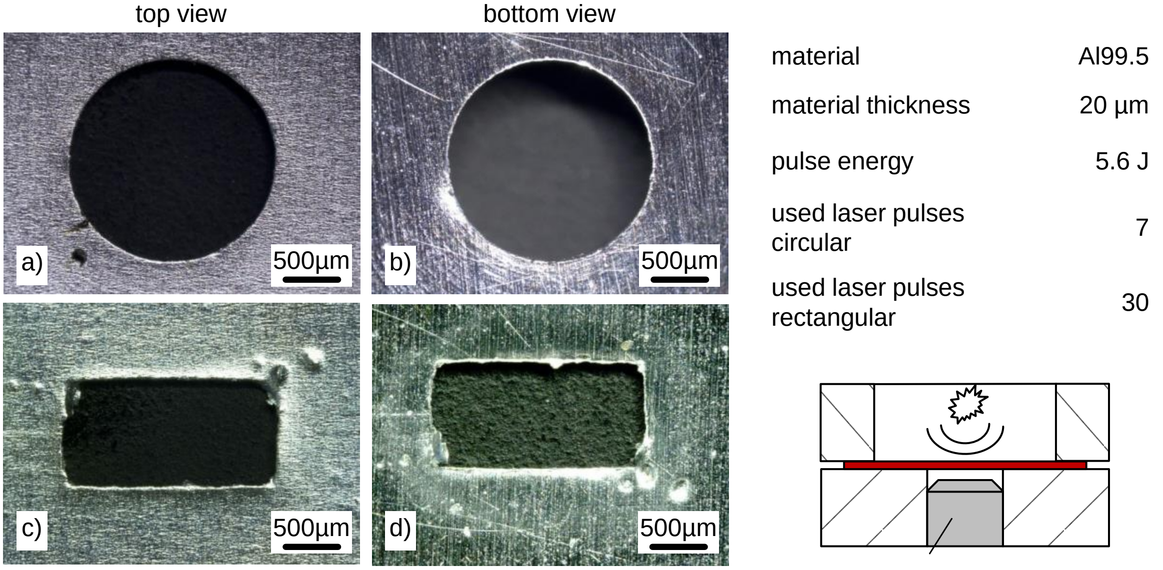
Wielage 2009 BIAS ID 151029

Fig. 4. (left) free formed cup Al99.5-50 µm-sheet; (b) formed cup with counterpunch Al99.5-50 µm-sheet

3.2. Laser shock cutting

The quality of the perforations, as shown in figure 5, in light microscope top and bottom view is good and uniform. No scrap material was remaining in contact with the cutting edge and no fracture or crack formation into the surrounded sheet material could be detected for all setups with a circular geometry. Dependent from the sheet thickness, a different number of laser pulses were necessary to achieve complete separated material. For 15 µm thick Al99.5 sheet material 8 laser pulses were necessary to guarantee a reliable cutting. 7 laser pulses were necessary to achieve a complete separation of the cut-outs from the surrounded sheet when 20 µm thick sheet material was used. For 50 µm thickness 55 shots and for 100 µm thickness 1000 shots had to be used to achieve good hole geometries.

Since rotation-symmetric perforations have proven feasible, rectangular shaped perforations were investigated as well. The die cavity size as well as the size of the counterpunch is 1 mm x 2 mm while the remaining tool setup is kept unchanged. Light microscope images in figure 5 show the front and back side of a 20 µm thick perforated sheet after 30 pulses. Therefore it is also possible to generate non-circular geometries, even though the removal of corner material seems to require optimization of the cutting parameters. In contrast to manufacturing of rotation-symmetric perforations, it can also be noticed that the number of shots, necessary to achieve a complete separation of the scrap material, considerably increased from 7 to 30, even though the sheet thickness was kept constant and the cutting path length is similar to that of the circular holes with a diameter of 2 mm.



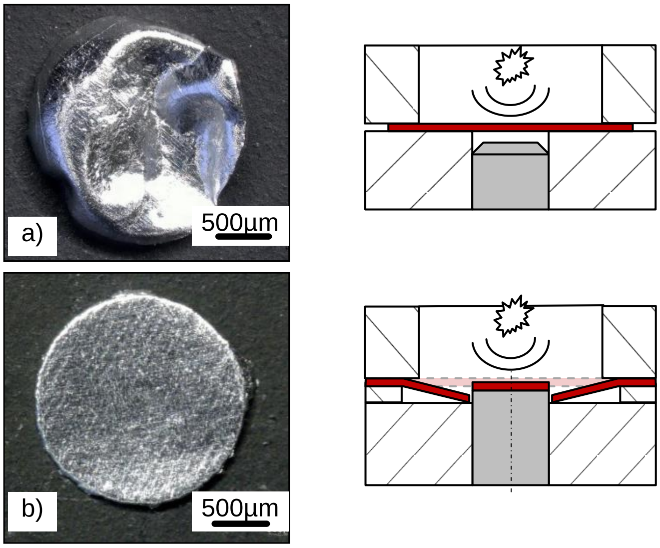
material	Al99.5
material thickness	20 µm
pulse energy	5.6 J
used laser pulses circular	7
used laser pulses rectangular	30

Behrens 2014

BIAS ID 151030

Fig. 5. (a) (b) circular perforation in Al99.5-20 µm-sheet; (c) (d) rectangular perforation in Al99.5-20 µm-sheet

While the manufacturing of perforations in different sheets are reproducible, using the experimental setup for punching, the shape and geometry of the cut out blank is insufficient for a further application as a component part (see figure 6). In order to realize blanks in good quality the tool setup needed to be modified as described (see figure 2). Application of the tool setup for blanking led to good cut out blanks (see figure 6). In contrast to the unmodified setup, blanks with closed cutting path, without deformation of the blank material could be achieved. For Al99.5 with a thickness of 15 µm and 20 µm, only one laser pulse was necessary to obtain completely separated blanks. However, this modified setup led to undefined deformation of the surrounded perforated sheet material. Therefore, dependent from the desired application the suitable setup for punching or blanking has to be selected respectively. Either the perforation quality or the blank quality is of particular interest. If good perforations are desired, the tool setup for punching has to be used and the blanked material is scrap. If the blanked part should be used as a component part, the setup for Blanking has to be selected and the surrounded sheet material has to be tolerated as defective.



material	Al99.5
material thickness	20 µm
pulse energy	5.6 J
used laser pulses punching	7
used laser pulses blanking	35
diameter	2 mm

Behrens 2014

BIAS ID 151031

Fig. 6. (top) circular blank using punching setup; (bottom) circular blank using blanking setup

For all tested material thicknesses, good perforation results could be determined. For thinner sheets (15 µm, 20 µm), just seven to eight shock pulses were necessary to achieve high quality perforations. This is of particular interest because these materials react sensitive in mechanical punching and a small number of laser shocks are accompanied by short processing times. The laser shock cutting might therefore be a good alternative for very thin materials because the high geometrical accuracy requirements for the tools in mechanical punching can be avoided and simultaneously a fast cutting can be ensured. It shows the potential of the laser shock cutting. This is additionally substantiated by the fact that the laser shock setup is relatively insensitive to changes of the laser focus and lateral shifting. In contrast to mechanical cutting of very thin material, a displacement of a few millimeters can be tolerated.

3.3. Laser shock joining

A hybrid joint between 50 µm Al99.5 and 100 µm stainless steel could be achieved with the use of 200 laser pulses. For the die sheet a hole diameter of 4 mm is used. A tensile test of this joint is made. The maximum shearing force of 26.7 N is achieved. The failure behavior, which occurs during the tensile tests, is presented in figure 6. It can clearly be seen, that the material is shearing off in the joining area and the joint is not falling apart. Moreover, the material behind the joining area of the forming sheet was bended up during the tensile tests.

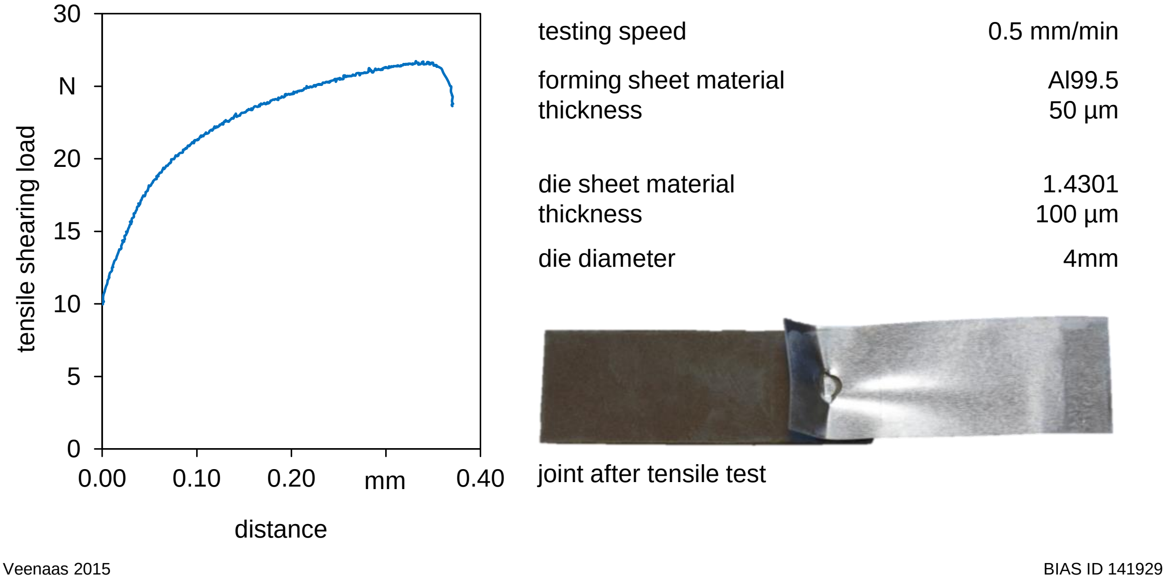


Fig. 6. (left) Tensile test at joint, (right) broken specimen after tensile test

To verify the achieved shearing force F_c of the test an estimate of the upper limit is made. The failure behavior of the specimens can be assumed as shearing-off the material in the joining area. The shear stress τ_a in this area can be calculated by:

$$\tau_a = \frac{F_C}{A} \tag{1}$$

The area A which is loaded is:

$$A = \pi\,\frac{d_o^2 - d_i^2}{4} \tag{2}$$

The outer diameter is d_o = 4 mm and the inner diameter is d_i = 3.9 mm for a material thickness of 50 µm. For an Aluminum sheet of 50 µm the tensile strength is σ_m = 72 MPa (Vollertsen, 2013). The allowed shear stress τ_a is about:

$$\tau_a \approx 0.7\,\sigma_m \tag{3}$$

By inserting the equations (2) and (3) in (1) the maximum shearing force F_c of this joint can be calculated by:

$$F_C = 0.7\,\sigma_m\,\pi\,\frac{d_o^2 - d_i^2}{4} \tag{4}$$

Thus the maximum possible applicable force of this joint is F_C = 30.4 N. The maximum force of the experiments of F_E = 26.7 N reached already 88 % of the calculated maximum possible force. The calculated and experimental determined values show a good agreement and indicate the potential of this joining process.

4. Conclusions

Methods and approaches to use a laser as a flexible tool are presented in this work. It could be shown, that laser induced shockwaves can be used for forming, blanking, punching and joining processes without thermal influences.

- Especially, the possibilities of laser forming processes for small components from 1 mm to 20 mm the laser is a powerful tool and an alternative for conventional forming processes. Higher strains can be achieved and no friction between punch and work piece appears.
- Laser shock cutting is a method to achieve perforations in thin sheet materials. A punch is not necessary, which leads to bigger tolerances for the production of tools. Besides, it is shown that the possible cutting geometries are not limited to rotation-symmetric cutting paths. Rectangular shapes are feasible as well.
- Joining of thin sheets in micro range is possible by laser induced shock waves. Especially for hybrid joints this technique is favorable. The strength of the joints are in the range of the material strength as calculated and experimental results show a good agreement.

Acknowledgements

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