INVESTIGATING THE JOINING OF PMMA PLASTIC TO STEEL BY Nd:YAG LASER

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Resume

Due to the effort of weight reduction in the manufacturing of vehicles, the application and therefore the joining of different materials such as plastics and metals plays more and more important role in the development of the joining processes nowadays. In this research work, the joining of PMMA plastic sheets and unalloyed steel pins was investigated. The authors applied Nd:YAG laser beam to create the bond, and tensile tests were carried out to analyse how the strength of the joint is influenced by the heating time, the penetration depth of the steel workpieces in the plastic and the surface roughness of steel. The observed bubble formation and the tearing characteristics were also studied.

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1. Introduction

Nowadays, plastics are applied more and more widely in the constructions because of their advantageous features like low density, corrosion resistance or electrical insulating properties. Nevertheless, the metals are still the most common used structural materials. Therefore in many cases we need to join metals and plastics in our structures. Metal-plastic hybrid joints occur in many of our constructions, just as well as in our vehicles [1]. The weight reduction is in the focus of the automotive industrial developments, and so applying low density materials like plastics becomes more important [2]. The plastic parts in the vehicles are not only the coverings and the upholstery items, but often structural, load-bearing components as well [3]. These parts have to be bonded to the metal sheets of the car body and in such a way that the strength of the manufactured hybrid part remains unchanged or becomes even better. The weight should be lower as compared to the steel part with the same function.

Generally, metal-plastic hybrid joints can be produced without or with heat input. Usually the technologies applied in the industry for this purpose work without heat input. Such technologies are screwing, riveting and the most commonly used gluing. The disadvantages of mechanical fasteners are inter alia that they are difficult to automate. Adhesives give a solution for this problem but they have their own disadvantages: the long bonding time and the harmful volatile compounds. Technologies operating with heat input are for example moulded-in threads or laser joining [4]. The injection moulding technology can satisfy special demands, but this makes this method expensive and can only ensure a low flexibility of production [5, 6].

Applying laser in case of plastic to plastic or metal to metal joining is an existing process, but examples for hybrid bonds can be seen only recently [7, 8]. In this technology the laser beam is used directly to establish the bond, without any additive materials: the plastic takes the heat from the laser irradiated metal and after cooling down a bond is created between the two materials [9, 10].

In our research work steel pins and PMMA plastic plates were bonded by an Nd:YAG laser source. Our aim was to create pin-to-plate hybrid joints in order to determine the process window for applicable bonds and the effect of different factors (heating time, penetration depth, surface roughness, bubble formation) on the formation and the strength of the joint.

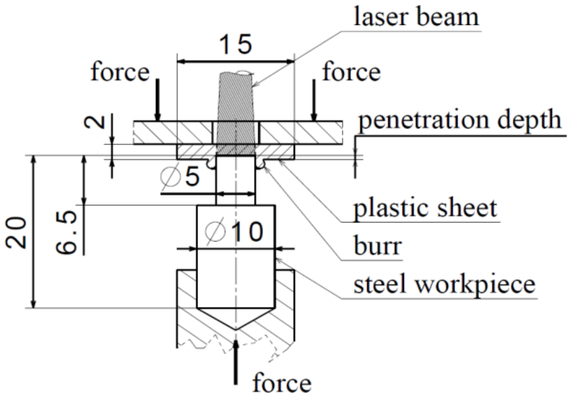


Fig. 1. Schematic view of experimental setup

2. Experiments

In the experiments the material of the steel pin was an unalloyed S235 structural steel and the plastic material was poly methyl metacrylate (Acriplex - PMMA XT – A-Plast Ltd.). We chose this type of plastic because of its good bond strength results during the preliminary experiments and because of its transparency: the connection area can be observed easily. The geometry of plastic sheet was *15 x 15 x 2 mm.*

The laser beam source was a LASAG SLS 200 type, pulse mode Nd:YAG laser with maximal pulse power of $P_{max} = 5.5\ kW$ and with an average power of $P_a = 220\ W$. The power distribution of the laser beam was Gaussian ($TEM_{0,0}$). The applied laser settings were the following: $f = 100\ Hz$, $t_p = 0.5\ ms$, $E_p = 2\ J$, where f is the pulse frequency, t_p is the pulse duration time and E_p is the pulse energy. The diameter of the laser spot on the surface of the steel pin was *5 mm*. There was no movement during the process. Argon shielding gas was used and the amount was *4.75 l/min*. The experimental setup can be seen in Fig. 1.

The face and lateral surface of the steel pin was manufactured by the same turning parameters and the surface roughness was measured on the lateral surface. The average surface roughness (R_a) range of the workpieces was between 0.8 to 2.5 micrometers. Before the experiments the heights of steel pin and the plastic was measured separately and after the common height of the bonded samples was measured to calculate the penetration depth.

Before the experiment the steel pins were cleaned with acetone and after evaporation of the cleaning material the samples were put into a special clamping unit, the plastic sheet was placed on the top of the steel part. During this process the steel part was connected with a clamping force produced by a spring. The spring force was *3.2 N*. The sample was irradiated from the plastic side. The plastic is highly transparent (90 %) for the laser beam, so the beam transmitted through the plastic and was mainly absorbed by the steel surface. The steel was heated directly and the face surface transferred the heat to the plastic. The plastic became softer and finally melted due to inputted heat. The softened material flowed back along the lateral surface of the pin and formed a burr ring at the entrance hole. At the end of the process, the steel pin penetrated into the sheet and was surrounded by a burr ring. After cooling, a joint was created.

During the joining process the formation of bubbles could be observed next to the steel pin at the face and at the lateral surface, too. To be able to describe this phenomenon the number of the created bubbles and the bubble area correlating to the area of face surface of pin were determined.

In further cases we modified our clamping unit to be able to realize a limited penetration. The steel pin was set at *0.2 mm* penetration and the heating was continued during a given heating time.

The effect of the surface roughness on the tear force was also examined: steel workpieces with different surface roughness, from $R_a = 0.5\ \mu m$ till $R_a = 10\ \mu m$ were manufactured by turning process. Roughness values were measured by a Mitutoyo surftest 301 surface roughness tester. In these cases the heating time was constant: 6 seconds.

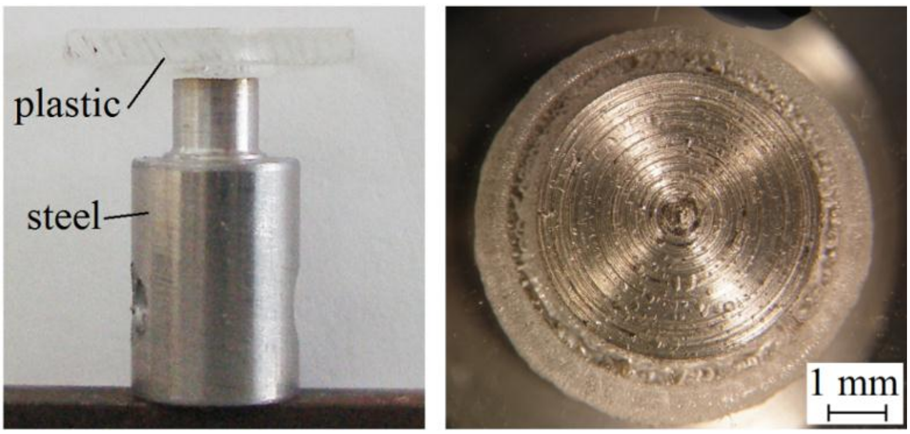
To investigate the bonding force, the workpieces were torn, the force was measured with a force tester PCE FG 500. The tester records the force values in function of time. The workpieces were torn after two days. The tearing speed was *25 mm / min*. In the results we gave the force values because the determination of the bonding area was not obvious. Therefore the maximal tearing force was used to characterise the strength of the joint.

2. Results

The effect of heating time (t_h) on the penetration depth and the tearing force was investigated. As a first step, the process window was determined in which the joint can be created. The shortest time when a joint could be created was *3 s*. Shorter heating time did not enable the development of a joint between the pieces. The longest time was *7 seconds*, because at a longer heating time the steel pin could go through the whole thickness of the plastic sheet, so that the measured penetration became bigger than *2 mm*. Therefore the applied heating time values were *3*, *4*, *5*, *6* and *7 seconds*. In Fig. 2, the photo of side and the top view of a joint are shown.

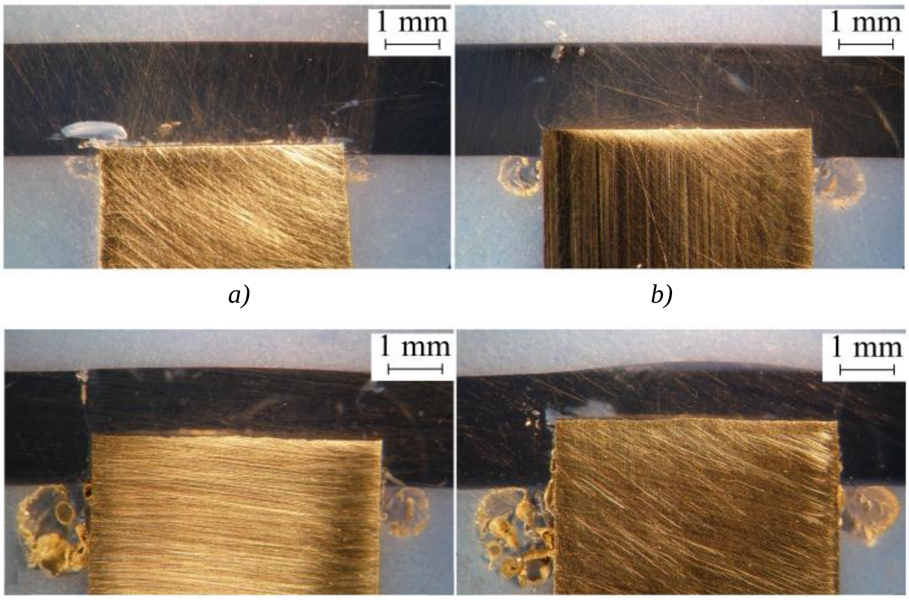
The cross sectional views of the created bonds at heating times of *3* to *6 seconds* are shown in Fig. 3. (In this case the plastic part looks dark because the joint was moulded in a resin in order to fix the parts during the sample preparation process.) In the figure an increasing penetration of the steel pin into the plastic sheet can be observed and an increasing amount of melted plastic formed a burr at the entrance hole, next to the steel and plastic surface. At deeper penetration, a hump arises at the upper side of the plastic, and the surface does not remain flat.

In Fig. 4 we can see the developing of tearing force in time as well as the typical tensile curves at each heating time. The force increases to the point of maximal value, thereafter it falls fast, but in case of longer heating times it does not become zero immediately, a second maximum can be seen. At heating times of *5*, *6* and *7 seconds* the force decreases slowly until the plastic sheet is separated from the steel.



a) *b)*

Fig. 2. The photo of the laser assisted hybrid joint, (a) side view, (b) top view
(full colour version available online)



a) *b)*

c) *d)*

Fig. 3. Cross-section of the created bond at different heating times: (a) 3 s, (b) 4 s, (c) 5 s and (d) 6 s
(full colour version available online)

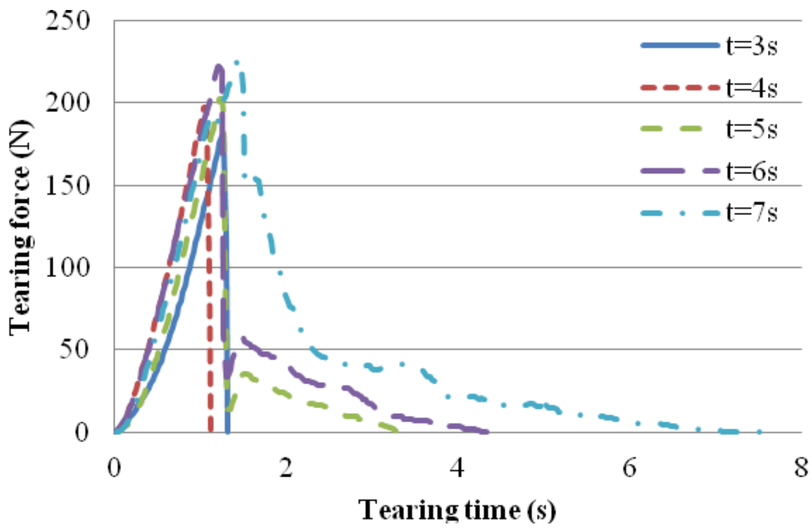


Fig. 4. Tearing force development in function of time
(full colour version available online)

At heating times of *3* and *4 second*, the penetration is low (around *0.1* to *0.2 mm*) hence only the face side of the pin can take part in the bond. When the face side breaks off from the plastic, the force falls immediately to zero. At a longer heating time (deeper penetration), after the first drop the lateral side of the pin is still connected to the PMMA in the created hole. It takes some more seconds to separate the two parts completely. The value of the second force peak increases with the penetration depth. This can be caused by friction between the plastic and steel surfaces because of the shrinkage of plastic after cooling down, but the phenomenon needs further investigation.

The penetration depth as a function of heating time can be seen in Figure 5: the average penetration and the standard deviation were marked on the diagram, and the values are calculated from three measurements. If the steel is heated longer, the penetration increases: the temperature of the plastic rises in the environment of the steel, and the material softens. Accordingly, the longer the heating time, the deeper the steel pin penetration into the plastic due to the operating clamping force.

The maximal tearing force is plotted in Fig. 6 against the heating time. A similar tendency can be identified as in Fig. 4. The maximal tearing force is getting higher if we apply a longer heating time, the average maximal force increases with the heating time from *150 N* to *230 N*. This can be explained by the deeper penetration: the contact surface grows, resulting in a higher maximum force. At heating times of *3* and *4 seconds* the deviation is higher, which should come from the lower penetration: if just the face side surface takes part in the bond the connection is not as robust as if the lateral surface plays a role as well. At deeper penetration depth range the deviation is lower.

In Fig. 7 the maximal tearing force is represented as a function of penetration. If the penetration is deeper the tearing force is higher. This phenomenon concludes from the Figures 5 and 6 and the deviation can be explained as earlier. The growth rate of the maximal force has a slowing tendency with the penetration depth, which may be caused by the formation of bubbles and the weakening of the plastic part.

If the heating takes longer the increasing formation of bubbles can be observed at the steel surface, presented in Fig. 8.

These bubbles hinder the plastic forming a bond at the whole surface of the pin, and weaken the joint. The area of the bubbles grows when the material is heated to a higher temperature. In Figure 9 we can see the number of the bubbles as a function of the size of the bubble area compared to the size of the face surface. At the beginning of the process, many bubbles are formed, but their size is small. The size and the amount of the bubbles grows until the heating time of *5 s*, thereafter at heating times of *6 s* and *7 s* the area rate increases still, while their quantity decreases. In this case the bubbles size still grows so that they unite with each other and the number of bubbles begins to fall. At the heating time range of our experiments the influence of the penetration is still higher as compared to the weakening effect of the bubbles and the increasing tendency of tear force is remained.

The role of bubbles in the evolution of tensile strength was investigated by the limited penetration. In Figs. 10 and 11 the penetration and the tearing force are represented as a function of heating time in case of free and limited penetration setups. At limited setup the penetration depth was a constant *0.2 mm* as it can be seen in Figure 10.

In Fig. 11 we can see that the tearing forces are lower and the deviations of the forces are higher by longer heating times, as compared to the results with free penetration. If there is not a compressive force during the whole process the bubble formation is enhanced and their size grows faster as it is presented in the case of free penetration experiments shown in Figure 8. The phenomenon of bubble formation at same heating time (t_h = *6 s*) with and without applying compressive force is shown in Fig. 12. As a conclusion we can say that a compressive force is needed along the whole process to achieve a good bond strength.

A further phenomenon can be observed after tearing samples made with heating times of *3* and *4 seconds*. In many cases plastic remains at the face side of the steel pin and the tearing occurs not in the interface but also in the plastic base material. This indicates a strong contact between the materials. By heating times of *5* to *7 seconds* this phenomenon is hindered by bubble formation: the bubbles separate the plastic material from the inside. Therefore only a thin plastic layer can be seen with the imprints of the created bubbles. The wetting ability of different materials could play an important role in the bond [11, 12]. The steel pin with and without remained plastic is shown in Figure 13.

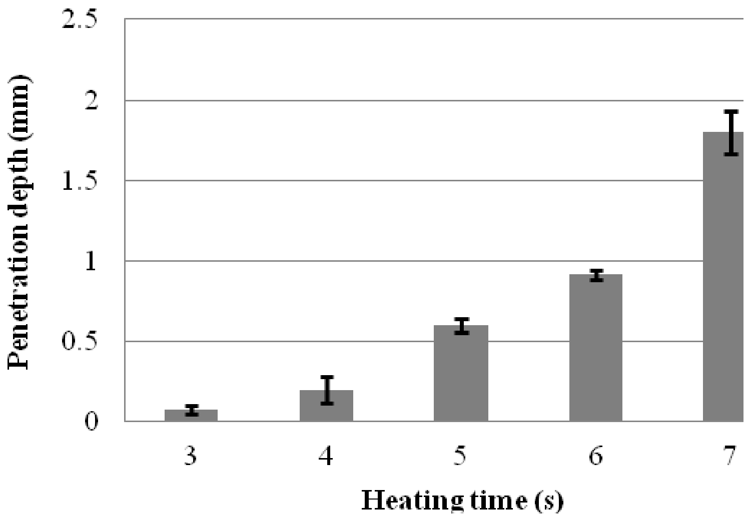


Fig. 5. Effect of heating time on penetration depth

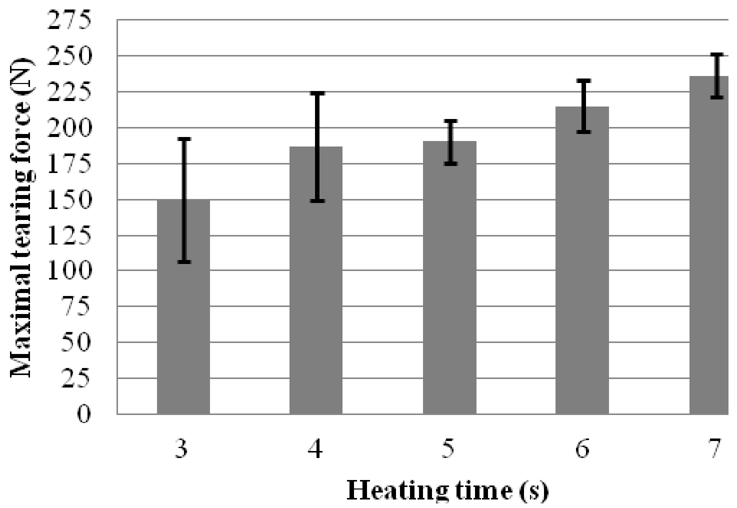


Fig. 6. Effect of heating time on tearing force

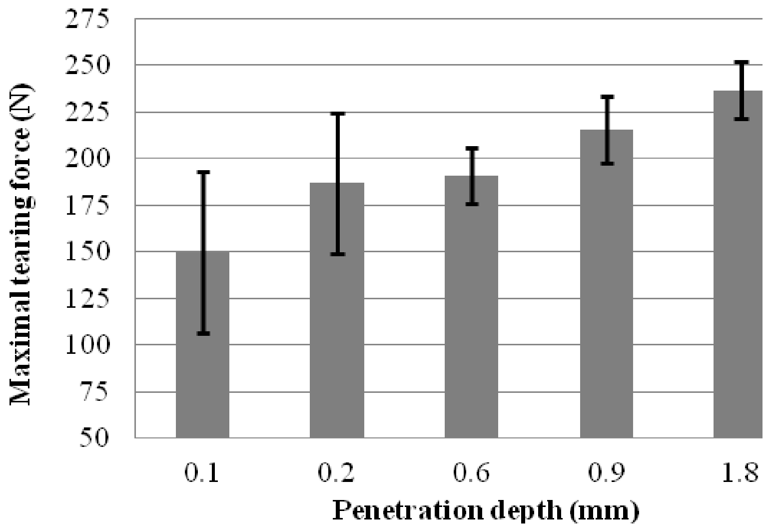
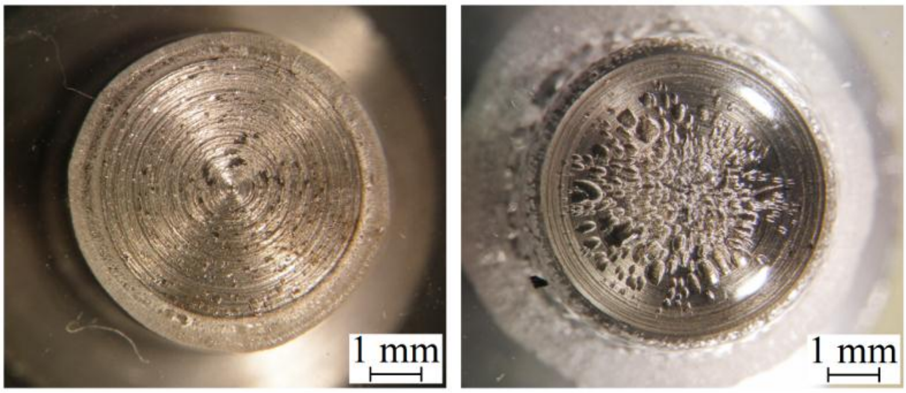


Fig. 7. Effect of penetration on tearing force



a) b)

Fig. 8. Bubble formation at heating times of 3 s (a) and 7 s (b)
(full colour version available online)

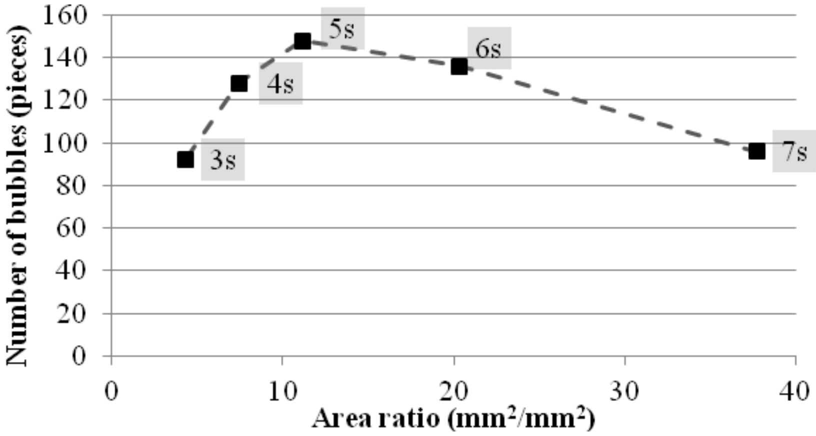


Fig. 9. The number of created bubbles as a function of bubble-face surface area ratio

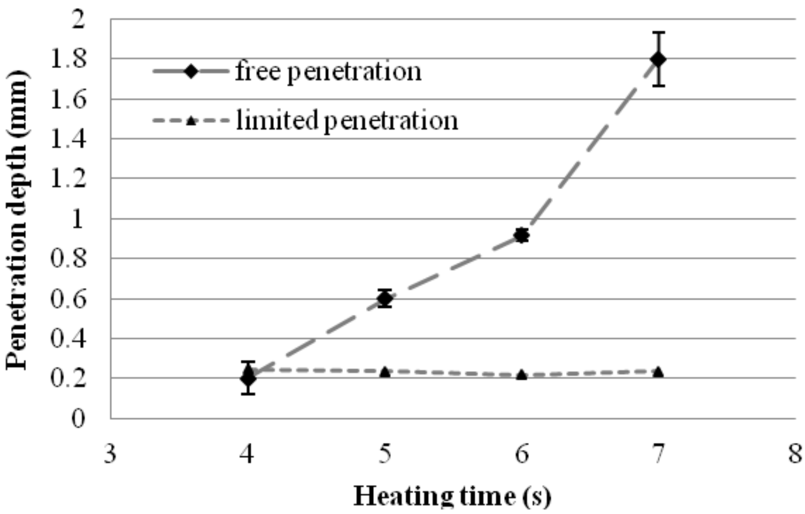


Fig. 10. Penetration values in case of limited and free penetration as a function of heating time

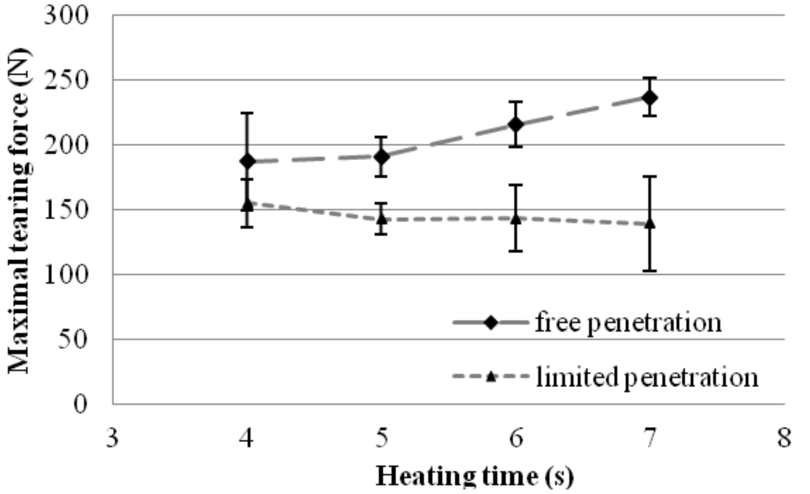
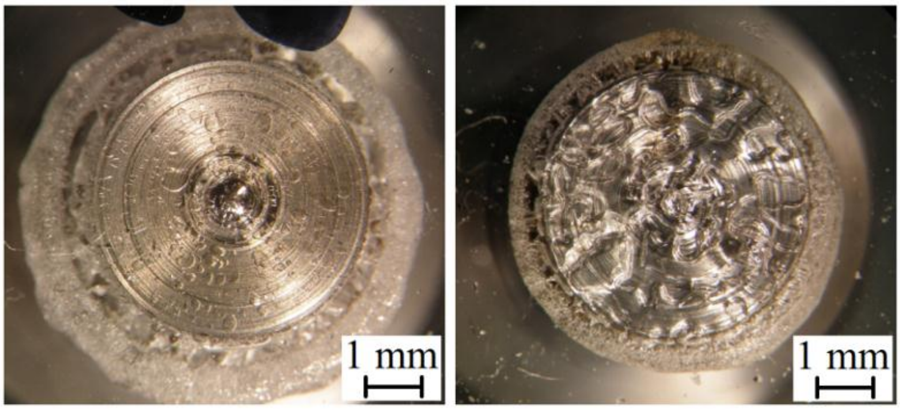
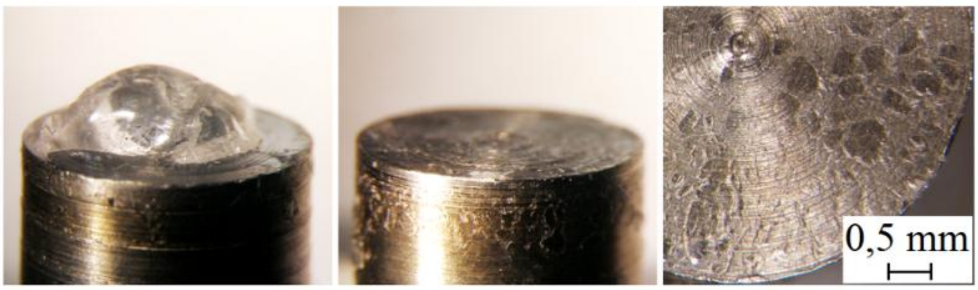


Fig. 11. Maximal tear force in case of limited and free penetration as a function of heating time



a) b)

Fig. 12. Bubble formation in case of free and limited penetration ($t_{heating}$ = 6 s)
(full colour version available online)



a) b) c)

Fig. 13. Plastic remained on the steel face surface (a) heating time = 4 s, side view, (b) heating time = 6 s, side view and (c) heating time = 6 s, top view
(full colour version available online)

The effect of surface roughness on the bond strength and on the penetration depth can be seen in Fig. 14 and Fig. 15. The tearing force shows a clearly increasing tendency when increasing the surface roughness as well as the penetration, maximal tearing force can reach even *400 N* as compared with the earlier results in which the maximal tearing forces were in the range of *200-250 N*. The surface roughness has an influence on the absorption of the laser energy, the flowing characteristics of plastic material close to the steel surface and the rate of the interlocking connection.

One part of the explanation of the increasing force tendency is the phenomenon of the enhanced interlocking. The PMMA takes up the surface shape of the steel pin after cooling down. The surface of a turned workpiece has a special shape: there are valleys and peaks and the size of this geometrical formation depends on the manufacturing settings like feed rate and tool geometry. This geometric feature is represented in the surface roughness. If the roughness is high, the higher peaks can indent deeper in the soft plastic material and a stronger form-closed connection can be achieved therefore a higher tearing force can be reached. The contact between steel and PMMA is shown in Fig. 16, at 3 different average roughness values.

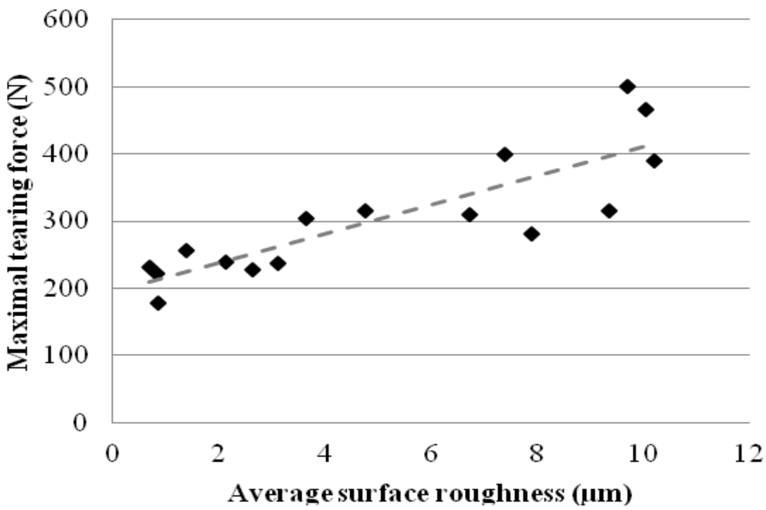


Fig. 14. Effect of surface roughness on maximal tearing force

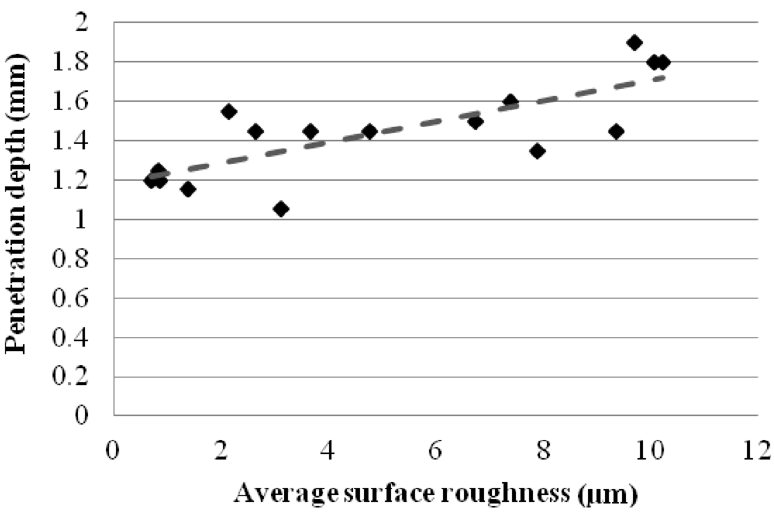
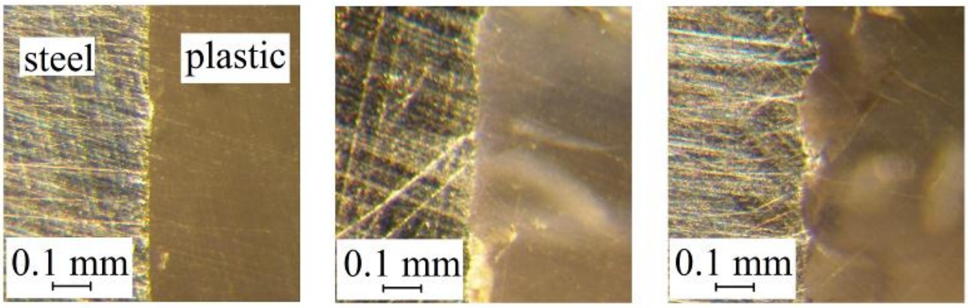


Fig. 15. Effect of surface roughness on penetration depth



a) b) c)

Fig. 16. Cross sectional view of bonds on the lateral surface.
Average roughness values are 0.68 µm (a), 6.35 µm (b) and 9.09 µm (c)
(full colour version available online)

On the other hand the increasing tendency of tearing force can be explained by the increasing penetration due to the higher absorption of the laser energy. This results in a higher temperature at the same heating time and causes a faster melting of plastic and a deeper penetration.

3. Conclusions

Summarising the results of this research work – the laser assisted hybrid joining of steel pins and PMMA plastic plates and the examination of different influencing factors – the following can be concluded:

- The joint between steel and PMMA can be created by pulsed mode Nd:YAG laser source in the presented setup and the process window is determined.
- Bubble formation was detected during the joint creation which was stronger when the heating time was longer. The number of the bubbles has a maximum in the investigated range and the area of bubbles increased continuously with the heating time.
- In the development of bond strength the face and the lateral surface of the pins play an important role.
- The increasing heating time increases the penetration depth and the strength of the joint, too.
- The higher the surface roughness the higher the penetration depth and the strength of the joint because of the deeper penetration and the stronger interlocking.
- The clamping force has an important role in the bubble formation and in the development of the strength of the joint because at limited penetration the plastic material gets overheated.

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