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Experimental investigations on laser-based hot-melt bonding and injection molding for laser-structured metal plastic hybrids

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Abstract

The use of thermoplastics in lightweight construction is continuing to grow. This implies the need for suitable joining techniques to combine thermoplastics with other materials, such as metals, to gain tailored multi-material parts. In this paper latest results of experimental investigations on laser-based hot-melt bonding and injection molding for laser-structured metal plastic hybrids are presented. As materials stainless steel and short-fiber reinforced polyamide are used. The stainless steel surface is structured with a nanosecond pulse laser before joining to improve the mechanical adhesion between the dissimilar materials. Thereby, different structure depths in the range between 16.6 ± 1.2 µm and 66.5 ± 2.5 µm as well as different hatch distances between 70 and 300 µm are realized. The laser-based joining process is carried out irradiating the metallic surface multiple times. Positioned below the metal in T-joint configuration, the thermoplastic melts as a result of heat transfer and acts as hot-melt. Besides, hybrid joints are manufactured using injection molding. For experiments, the mold temperature as well as the melt temperature are varied. Regardless of the joining process, the hybrid joints are mechanically characterized by tensile tests. The results demonstrate that for both joining processes strong laser-structured metal plastic hybrids can be realized.

Keywords: Laser-based hot-melt bonding; injection molding; multi-material design; laser structuring

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1. Introduction

In recent years, the global population has grown rapidly, and a strong densification of urban areas occurred (Gude, M., et al., 2015). Densely populated cities and urban regions are responsible for almost 80 % of global greenhouse gas emissions and therefore contribute greatly to climate change (Max-Planck-Gesellschaft, 2011). To reduce greenhouse gases in traffic, regulation of CO_2 emissions from new passenger cars and light commercial vehicles has been made at European level (Institut für Kraftfahrzeuge, 2014). Due to the increasing political and social pressure, car manufacturers have to reduce the CO_2 emissions of their vehicles. An essential key to this is reducing the vehicle weight by a resource-efficient lightweight design, which is characterized by the use of the right materials to the right place in combination with appropriate manufacturing technologies (Gude, M., et al., 2015). For this purpose, tailored multi-material parts consisting of plastics and metals are increasingly used. The broad profile of properties of thermoplastics can be specifically extended by the combination with metals. In this case, the overall properties of the part can be improved by the best of both materials. The main challenge is the realization of joining techniques for these hybrid lightweight components that are taking the different material properties into account. Therefore, in this paper latest results of experimental investigations on laser-based hot-melt bonding and injection molding for laser-structured metal plastic hybrids are presented.

2. Performed process chains and experimental setups used

In this paper, joining of metal plastic hybrids is realized by two types of processes (see Fig. 1): In-Mold Assembly (IMA) and Post-Mold Assembly (PMA). The manufactured hybrids consists of stainless steel (1.4301, thickness = 1.5 mm) and polyamide 6 with a glass-fiber content of 30 % (PA6-GF30). The tested T-joints have a length of 20 mm and a width of 6 mm.

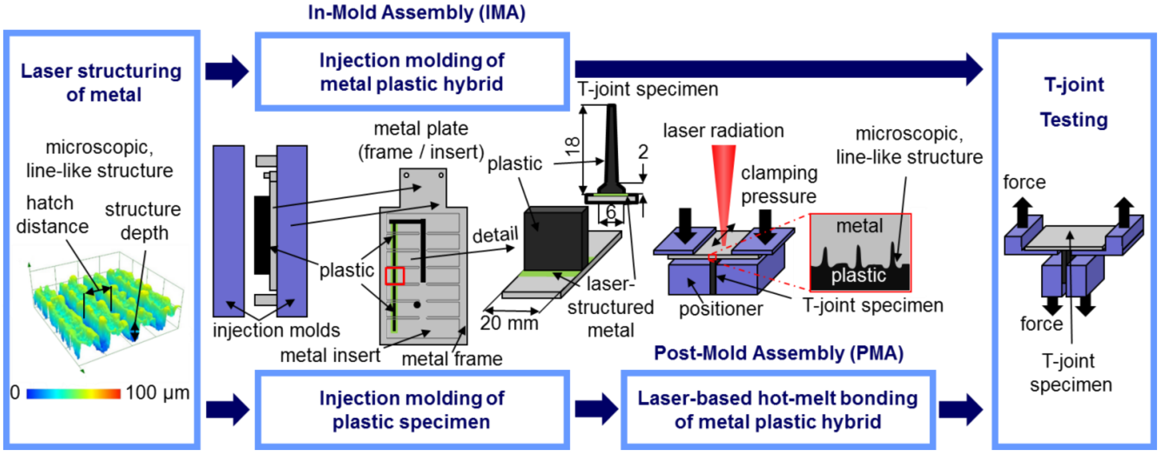

Fig. 1. Schematic illustration of the performed processes

Before joining, the stainless steel is structured with a nanosecond pulse laser with a wavelength of 1064 nm and a beam diameter of about 40 µm to realize a microscopic line-like structure (see Fig. 1, left side) improving mechanical adhesion between the dissimilar materials. For the experiments, a repetition rate of 60 kHz and an average laser power of about 10 W are used. The deflection of the gaussian beam is realized by a galvano scanner, whereby different structure depths in the range between 16.6 ± 1.2 µm and 66.5 ± 2.5 µm are generated by scanning the surface multiple times with a scan speed of 300 mm/s. Besides the hatch distance which defines the distance between two structures is varied between 70 and 300 µm.

During the IMA process the joint between thermoplastic and metal is directly created in an injection molding tool with a mold temperature of 100 °C. For this purpose a metallic plate consisting of a frame and an insert is positioned in the mold. In the next step plastic compound is injected with a pressure of 1418 bar and a speed of 50 cm^3. Thereby, the melt temperature is 280 °C. The holding pressure takes values between 650 and 400 bar and lasts for 11.5 s. After 40 s cooling, a loadable joint between the dissimilar materials is formed and the part is ejected. Finally, the metallic insert with the attached plastic is cut into T-joint specimens (see Fig. 1, middle). Investigating the influence of processing temperature on the joint the mold temperature (80, 100, 120 °C) as well as the melt temperature (260, 280, 300°C) are varied.

The experimental setup for PMA consisting of a disk laser with a wavelength of 1030 nm, a scanner optic and a clamping device for T-joints. During laser-based joining, laser radiation is absorbed by the stainless steel surface which leads to an increase of the material temperature. The experiments are conducted by laser scanning the metallic specimen multiple times. The number of scans in which the specimens are heated varies between 6 and 14. Positioned below the metal, the thermoplastic melts as a result of heat transfer. The thermoplastic melt wets the metal surface. After cooling, the dissimilar materials are joined together. Thus, the thermoplastic joining partner fulfills adhesive as well as part properties. For experiments, beam diameter, laser power and velocity are kept constant at 5 mm, 500 W and 100 mm/s.

3. Results and discussion

3.1. Influence of joining parameters

In Fig. 2 the measured breaking force for laser-structured metal plastic hybrids using injection molding are displayed. For experiments, a structure depth of 45.6 ± 5.1 µm in combination with a hatch distance of 70 µm is used. The breaking force vary in dependency of the mold temperature between 720.5 ± 336.1 N and 1047.0 ± 221.3N (see Fig. 2a). Taking the high standard deviations into account there seems to be no clear trend weather mass temperature influence the joint significantly. The same statement can be said about the influence of mold temperature. In this case, the breaking force reaches values in the range of 695.9 ± 165.4 N and 1018.8 ± 25.4 N (see Fig. 2b). Considering the joint cross-section, the tensile strength of all injection molded hybrids vary between 6 to 9 MPa. For all injection molded samples an adhesion fracture is visible. Due to the vertical tensile load, the plastic can be completely pulled out of the structure. After testing, the extracted thermoplastic shows the negative shape of the line-like structured metallic surface.

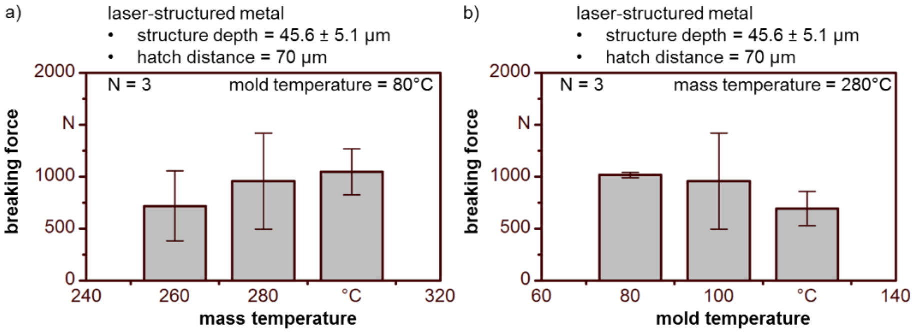

Fig. 2. Results for breaking force depending on different joining parameters: (a) mass temperature, (b) mold temperature

For experiments using laser-based hot-melt bonding, also metallic samples with a structure depth of 45.6 ± 5.1 µm in combination with a hatch distance of 70 µm are used. Thereby, the breaking force depends significantly on the number of scans. From 6 up to 10 scans the breaking force rises from 578.7 ± 202.9 N to 1374.5 ± 237.5 N. The calculated tensile shear strength reach values between 5 and 11 MPa. However, it has to be mentioned that only for 6 and 8 number of scans an adhesion fracture occurs. For higher number of scans a mixed respectively cohesion fracture takes place, whereby residues of thermoplastic remain on the laser-structured metal surface. Due to this fact no further increase of the breaking force can be realized and a plateau is reached (see Fig. 3).

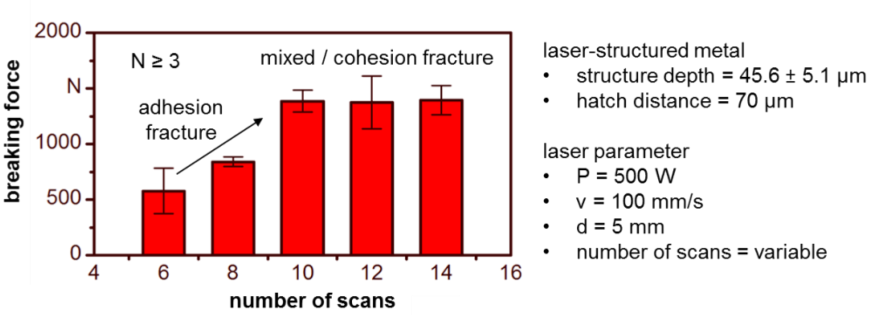

Fig. 3. Results for breaking force depending on number of scans

3.2. Influence of surface treatment

After investigating the influence of joining parameters the effect of surface treatment on the joints is investigated. Therefore, the joining parameters are kept constant and the hatch distance as well as the structure depth are varied. For injection molding experiments, a mass and mold temperature of 280 °C and 100 °C are used. For laser-based hot-melt bonding the specimens are realized by scanning the metallic surface 8 times. For the performed experiments, the maximum breaking force (laser-based hot-melt bonding: 962.5 ± 154.2 N, injection molding: 1134.2 ± 119.1 N) is achieved for a hatch distance of 100 µm. Specimens with a hatch distance of 70 µm reach slightly lower values. With increasing hatch distance the breaking force drops significantly, especially for injection molding. A joint of unstructured samples could not be realized. Based on the experiments, the hatch distance should not be less than 200 µm (see Fig. 4a).

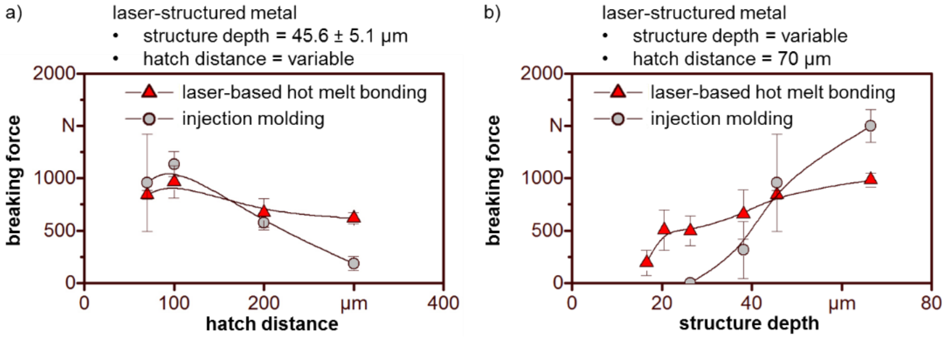

Fig. 4. Results for breaking force depending on laser structuring parameters: (a) hatch distance, (b) structure depth

Besides, the structure depth has a significant influence on the breaking force (see Fig. 4b). With increasing structure depth the breaking force rises. For laser-based hot-melt bonding already smaller structure depths lead to an increase in breaking force, whereby for injection molding a threshold value of about 40 µm is necessary for strong joints. In this experiments, the highest breaking force of 1499.5 ± 158.2 N is realized for a structure depth of 66.5 ± 2.5 µm using injection molding. The related value for tensile strength is about 12.5 MPa. For laser-based hot-melt bonding a maximum breaking force of 982.0 ± 66.6 respectively a tensile strength of 8.2 MPa is reached.

4. Summary and conclusion

In conclusion, the reported results demonstrate that laser-based hot-melt bonding and injection molding for metal plastic hybrids have high potential to promote the use of multi-material lightweight applications in future. However, therefore a laser-structuring of the metallic part is necessary to improve the adhesion between the dissimilar materials due to mechanical interlocking. Based on the performed experiments for microscopic line-like structures the hatch distance should be in the range of 100 to 200 µm and the structure depths should be above 40 µm.

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