Joining of plastic-metal hybrid components by overmoulding of specially designed form-closure elements

S. Wurzbacher¹, S. Gach², U. Reisgen², C. Hopmann¹

Ecological and economic aspects nowadays increasingly require the development of weight-reduced designs and energy-efficient production processes. Particularly in the field of modern vehicle or aircraft construction, developers endeavour to take into account the ever more extensive customer requirements for safety and comfort by using lightweight construction. In many lightweight construction applications, alongside the classic material steel, plastics and the light metals aluminium, magnesium and titanium are being used. Due to a wide variety of requirements, the combination of different material classes to form hybrids will become even more important in the future. Injection moulding is an established method to join plastic-metal hybrid components. In the present study, the potentials of electron beam structuring by means of surfi-sculpt, an electron beam material processing technology, on different lightweight materials for the generation of form-fit elements in plastic-metal-hybrid components to be used to join both materials by overmoulding are analysed. The analysis is performed by means of tensile shear test specimens.

Keywords: Plastic-metal-hybrids / surfi-sculpt process / electron beam welding (EBW) / form-closure joining / injection moulding

Ökologische und wirtschaftliche Aspekte erfordern heutzutage zunehmend die Entwicklung gewichtsreduzierter Konstruktionen und energieeffizienter Produktionsverfahren. Vor allem im Bereich des modernen Fahrzeug- oder Flugzeugbaus sind die Entwickler bemüht, durch Leichtbauweisen die immer umfangreicheren Anforderungen der Kunden nach Sicherheit und Komfort in ihren Konstruktionen zu berücksichtigen. In vielen Leichtbauanwendungen kommen neben dem klassischen Werkstoff Stahl zunehmend Kunststoffe und die Leichtmetalle Aluminium, Magnesium und Titan zum Einsatz. Aufgrund verschiedenster Anforderungen wird die Kombination mehrerer Werkstoffklassen zu Hybriden in Zukunft noch wichtiger werden. Das Spritzgießverfahren ist ein etabliertes Verfahren zur Herstellung von Kunststoff-Metall-Hybridbauteilen. In der vorliegenden Studie werden die Potenziale des Elektronenstrahlstrukturierens mittels Surfi-Sculpt auf unterschiedlichen Leichtbauwerkstoffen zur Erzeugung formschlüssiger Elemente in Kunststoff-Me-

¹ RWTH Aachen University, Institute for Plastics Processing (IKV) in Industry and Craft at RWTH Aachen University, Seffenter Weg 201, 52074 AACHEN, GERMANY
² RWTH Aachen University, Welding and Joining Institute (ISF), Pontstraße 49, 52062 AACHEN, GERMANY

Corresponding author: S. Gach, RWTH Aachen University, Welding and Joining Institute (ISF), Pontstraße 49, 52062 AACHEN, GERMANY, E-Mail: gach@isf.rwth-aachen.de

© 2021 The Authors. Materialwissenschaft und Werkstofftechnik published by Wiley-VCH GmbH www.wiley-vch.de/home/muw
tall-Hybridbauteilen analysiert, mit denen beide Werkstoffe durch Hinterspritzen verbunden werden können. Die Auswertung erfolgt mittels Zugscherproben.

Schlüsselwörter: Kunststoff-Metall-Hybridbauteile / Surfi-Sculpt-Process / Elektronenstrahlschweißen (EBW) / formschlüssiges Fügen / Spritzgießen

1 Introduction

The ever-increasing challenges facing engineering solutions can frequently no longer be met by just one material class. The combination of different material classes to so-called hybrids enables the utilization of multiple specific material advantages [1–3]. The increase in popularity of these hybrid constructions is mostly driven by cost-neutral lightweight design, often in combination with higher mechanical part properties. Promising combinations are metallic materials such as steel or aluminium with engineering thermoplastics [3–5]. Metals offer high strength and stiffness which can be easily functionalized with the high design freedom of low density plastics, in particular by injection moulding [4, 5]. Looking into the future of plastic-metal-hybrids, the utilization of lightweight metals such as magnesium wrought alloys or titanium will extend the possible weight reduction.

Today, so-called in-mould assembly processes should be the focus of production and research for joining plastic-metal-hybrids because downstream joining steps which are necessary in the post-mould assembly can be avoided and production costs can be reduced [4, 6]. The prefabricated metal component is inserted into the injection mould and joined directly in the plastic forming process. This combined process is widely known as over- or back-moulding for many material combinations.

The joining technology used is decisive for the quality of the mechanical properties and for the economical production of the final hybrid components [6]. Research in the field of post-mould-assembly shows that due to longer joining times and higher melt temperatures in the boundary surface, a direct-adhesion between the dissimilar material properties of plastics and metals can be enabled [7, 8]. Due to the processing boundary conditions of in-mould assembly, especially the solidified layers in the mould filling phase, an adhesive joint can only be achieved by the use of adhesion promoters [6]. However, the number of adhesion promoter systems available on the market is limited to a few plastic-metal combinations [3–5, 9, 10]. This is the main reason why mostly form-fit elements are used for joining plastic-metal hybrids in in-mould-assembly processes. There are several techniques to create form-closure elements on the joining surface. In this article, the approach to specially designed form-closure elements produced by electron beam using the surfi-sculpt process on the metal surface is investigated for in-mould assembly. Having in mind the possible weight reduction, the focus is on the material combination of magnesium wrought alloy as well as commonly used metals and the engineering thermoplastic polyamide. In conducting this study, the effect of structuring parameters on different metals and the resulting bonding strength after joining by overmoulding will be determined. Preliminary results are presented, and the implications for more detailed joining studies are discussed.

2 State of the art

2.1 Form-fit elements for joining plastic-metal hybrids

The form-fit elements, established since the 1990s, are through-moulding points, beams with undercuts and overmoulded edges which form a permanent joint between the two materials [3, 11–14], Figure 1 left. Especially through-moulding points which are rivet-like connections, are an established industry standard as form-fit elements. For this, an opening needs to be provided in the metal component through which the plastic flows during injection moulding. Due to the elaborate production of openings in the metal component, a small amount of larger joining points is common. This leads to inhomogeneous stress distribution in comparison to adhesive joints and thus over-dimensioning becomes necessary which mitigates possible weight reduction [5, 11, 12].
In comparison to the localized force application of form-fit elements, the full surface connection in adhesive-bonded plastic-metal-hybrid components leads to rigidity increases of 206% for torsion and 56% for 3-point bending [15]. This explains why one of the main objectives for the research on plastic-metal hybrids is to reduce the size of form-fit elements and to simultaneously increase the quantity per unit area. This is often described as microstructuring [7, 16, 17].

There are several different possibilities for producing microstructures on the surface of metals, which can be separated into subtraction-processes with structures lower than the metal surface, addition-processes with added material on to the surface and addition-and-subtraction-processes without added materials by moving material from below the surface into structures above the surface, Figure 1 right. The geometric and manufacturing complexity and also the possible metals for creating those micro-form-fit elements differ. Most subtraction-processes use high energy beam sources to create repeatable undercuts in the surface [7, 8, 16]. Due to their process characteristics only non-repeatable partial undercuts can be created with blasting processes or chemical etching [17–20]. Raised structures can be created by special welding processes like (cold metal transfer) pin welding or additive manufacturing directly on to the metal components surface [21, 22]. In comparison to subtraction-structures, these structures extend into the plastic component, whereby the entire plastic component contributes to the load-bearing capacity of the joint.

The advantage of addition-and-subtraction processes is that undercut structures in the material, comparable to micro-structuring, and additional raised structures above the surface can be created simultaneously [23]. This means that the otherwise planar joining surface is given a third dimension determined by the structure height and depth. In combination with the design principle for plastic parts which recommends small wall thickness to decrease cooling time, the joining volume could be increased to the whole plastic and metal thickness [5, 24]. This can also be problematic since the raised structure part can be seen as a flow obstacle which can lead to weld lines in the joining area and glass fibre reorientation.

In comparison to the joining processes of post-mould-assembly, when overmoulding form-fit elements, the same boundary conditions apply which prevent direct adhesion. So, when choosing process parameters it has to be taken into account that the contact temperature between the metal and the plastic melt is lower and, additionally, that the contact pressure is flow-length dependent [4]. Some of the processes to create form-fit elements are already used in the Post-Mould-Assembly of plastic-metal-hybrids or fibre reinforced plastic-metal hybrids by means of laser transmission welding or thermal direct joining [7, 25, 26]. The In-Mould-Assembly and its boundary conditions by overmoulding directly in the injection mould has not been subject of many investigations [14, 23, 27]. Especially the potential of using electron beam structuring to create addition-and-subtraction form-fit elements to join...
plastic-metal hybrids via In-Mould-Assembly has not been investigated.

2.2 Structuring lightweight materials by electron beam via surfi-sculpt

As discussed, addition-and-subtraction structures can be created using electron beam structuring. In general, electron beam material processing in a vacuum has been successfully used for many decades, e.g. for welding, hardening or coating. The energy required for electron beam welding or structuring is generated by the conversion of the kinetic energy of highly accelerated electrons when they are decelerated on impact with the surface of the material to be processed. As a result of the high power density at the point of impact, the material evaporates within approx. 20 milliseconds so that subsequent electrons can penetrate deeper into the material. A vapour-filled capillary is created. With the so-called deep weld effect, penetration depths of up to 300 mm can be achieved [28]. The essential components of an electron beam system are the beam generation, the beam guidance and forming as well as the working chamber. A thermally heated cathode provides electrons which are accelerated by a voltage field between anode and cathode [29]. To achieve the power density required for the process, the beam is bundled by several electromagnetic focusing lenses and focused on the workpiece surface. A deflection coil allows the beam to move in the x-y direction. In combination with the traverse paths of the workpiece manipulator, the beam is positioned. To prevent the beam from diverging, the process takes place in a vacuum. In contrast to the laser beam, the electron beam can be deflected in a defined manner (up to 50 kHz) by high-frequency magnetic fields, so that several melting baths can be built up simultaneously.

The structuring process with the electron beam is based on the surfi-sculpt process developed by TWI - The Welding Institute [30]. In this process, an electron beam melts the base material and by moving the electron beam the liquid melt is pushed aside where it solidifies, Figure 2. By repeating this step several times, more and more material is piled up and the desired surface structure is created. This surface structure is made up of an indentation were material is missing (substraction) and an elevated structure above the surface of the base material (addition).

Due to the small beam diameter of an electron beam (<300 μm), the fast beam deflection with high repetition accuracy and working in a vacuum, this process is predestined to generate defined structures. Two different techniques can be used to create structures. On the one hand, one structure can be completely manufactured before starting the next one. On the other hand, all structures in the working area can be produced quasi-simultaneously, whereby the working area is scanned several times with the beam.

3 Aim of the investigation

The aim of the presented study is to investigate the potential of addition-subtraction mould elements produced by means of electron beam structuring as a new joining technique for plastic-metal hybrids. A three-stage joining test was carried out to achieve the objective: First, the geometry of form-fit elements was analysed as a function of the structuring parameters for different metal materials. The second step was to investigate the overmouldability of electron beam structured metal blanks. In the last

Figure 2. Schematic representation of the erection of surfi-sculpt structures by electron beam.
step, tensile shear tests were carried out to determine the adhesive strength of the joining approach investigated.

4 Materials and experimental methodologies

The surfisculpt process was performed on a universal chamber beam welding machine type K7, build by pro-beam GmbH & Co. KGaA, Gilching, Germany.

The acceleration voltage used in all tests was 120 kV. For the metal blanks, metal sheets of 1.5 mm thickness were used. The magnesium wrought alloy (ME20) was extruded by TWI GmbH, Dortmund, Germany, the rolled stainless steel (1.4301) and aluminium (AlMg2) sheets were supplied by Rosen Metall-Service GmbH, Aachen, Germany. For the structuring analysis 27 × 100 mm² blanks were used. The structures were arranged in a single- or double-row of 10 structures according to the dimensions and erected quasi-simultaneously Figure 3, bottom left. By changing the building direction, the direction of the structures on the metal component were additionally changed.

To test the overmoulding of the structures and to measure the bonding strength under shear loading conditions, a tensile shear test specimen modified for plastic-metal hybrids from DIN EN 1465 was used, Figure 3 left. The width of the metal component was increased to 27 mm to ensure melt tightness around the overlapping area. Due to the lower tensile strength of the moulding compounds used, the thickness of the plastic component was increased to 4 mm thickness. The overlapping length was increased to 25 mm to test the effect of single- as well as double-row structures. The polyamide 6 moulding compound Durethan BKV 30 H2.0 (PA6-GF30) was produced by LANXESS Deutschland GmbH, Cologne, Germany, and the polypropylene moulding compound POLYFORT FPP 30 GFC (PP-GF30) by A. Schulman Inc., Fairlawn, Ohio, USA. Both were 30 wt-% short glass fibre filled. The compounds were moulded using an IntElect 100/520-340 smart injection moulding machine from Sumitomo (SHI) Demag Plastics Machinery GmbH, Schwaig, Germany. The moulding parameters were chosen according to the processing data sheets. If not described otherwise, the melt temperature for PA6 - GF30 was 280 °C, the mould temperature 100 °C, for PP-GF30 the melt temperature was 250 °C and the mould temperature 70 °C. The injection speed of 20 cm³/s results in a filling time of approx. 1 s and the holding pressure was set to approx. 60 % of the injection pressure to 400 bar.

Figure 3. Used tensile shear test specimen modified for plastic metal hybrids (top left); the used test setup (right) and the structure position in the overlapping area (bottom left).
for 6 s for the main trials. To analyse the effect of the injection moulding parameters on the structures additional trials with an increased injection speed of 40 cm/s and an increased holding pressure of 600 bar are carried out.

The mechanical tests were carried out using a universal testing machine Z010 by Zwick GmbH & Co. KG, Ulm, Germany. The test specimens were mounted in the testing machine, Figure 3 right. The testing speed of 2 mm/min results in failure in the time frame of 65±20 s given in DIN EN 1465. The measured breaking force was used to characterise the joint strength. By dividing the breaking force by the number of form-closure elements the mean force per structure was calculated.

5 Results

5.1 Analysis of the production of addition-and-subtraction form-fit elements by surfii-sculpt for overmoulding

Since surfii-sculpt is a melt-based construction process, the material-specific properties such as thermal conductivity of the solid material and its melt as well as viscosity or solidification behaviour etc. influence the geometric design of the structures constructed. This can be counteracted to a certain extent via the process parameters. The beam power (acceleration voltage [kV] multiplied by the beam current [mA]) determines the beam power and thus, as a result, the penetration depth. Consequently, this increases the elevation height of the structure per single beam welding cycle, but also the heat input at the same time. In this study, an acceleration voltage of 120 kV was selected for all tests.

The combination of running time [s] and deflection frequency [Hz] determines, on the one hand, the number of beam welding cycles at a single elevation structure and thus its height, while the frequency also influences the cooling time until the next beam welding cycle in which the material solidifies. If the material is still too hot in the following beam welding cycle, too much melt is formed and the previously erected structure melts.

To analyse the production of addition-and-subtraction form-fit elements, trials were carried out to build 10 structures which were arranged in a single-row and erected quasi-simultaneously within a few seconds, Figure 4. Thus, for each material, a suitable combination of heat input and heat dissipation has been selected from the parameters beam power, deflection frequency and cycle time.

The goal in setting the structures was an erection height of ca. 2 mm above the surface. A comparison of the energy input can be made by multiplying the acceleration voltage (in each case 120 kV) by the beam currents and the time. If this amount is divided by the number of structures (10), the energy input per individual structure is calculated. If the frequency is multiplied by the time, the result is the number of passes the beam makes over each structure.

Thus, the lowest energy input for stainless steel is 120 J for 50 overflows, the highest for aluminium is 158.4 J for 90 overflows, and the average energy input for magnesium is 144 J for 160 overflows. As a result, the steel forms filigree elevation structures which are rounded in the head area in a spherical shape, Figure 4 below. Aluminium basically shows comparable structures in shape and size as well as height. Only the base width of the structure, at 1.6 mm, is one fifth narrower than that of stainless steel (2.0 mm). The elevation structures in magnesium, on the other hand, differ significantly. They form columnar, pike-like structures that taper off to a point in the head. The height of 2.5 mm is by more than a quarter higher compared to steel or aluminium and forms an overhang on the side facing away from the beam, which leads to an undercut in the shaft area. The width of the base of the structure transverse to the direction of erection is comparable for all structures.

5.2 Feasibility analysis of overmoulding surfii-sculpt structures

The potential of joining plastic-metal hybrids by overmoulding surfii-sculpt structures on the three materials was subject to a feasibility analysis. For this, single- and double-rows of micro structures consisting of 10 structures each were over-moulded with PA6 - GF30, Figure 5. In case of the double-row specimen, the second rows structures are offset
by half the distance between two structures. The building direction of the microstructures was in plastic flow direction. All metal materials analysed could be joined by overmoulding without any visible failure of the structures. Additionally, the bonding strength depending on the material was measured in order to draw further conclusions about the joint.

Figure 4. Photographic representation of the investigated structures on magnesium ME20 (overview image and in cross section), measurement and exemplary parameters (top); single-row erection structure, consisting of 10 individual structures made of the investigated materials stainless steel, aluminium alloy AlMg2 and magnesium ME20, and the associated process parameters (bottom).

Figure 5. Measured breaking force by overmoulding one-row and two-row structures on stainless steel, aluminium and magnesium.
The stainless steel single-row specimen shows with 1.43 kN the lowest breaking force of the three materials tested. This results in a mean force of 142 N per structure. The breaking force for AlMg2 increases to 1.69 kN and to 2.06 kN for ME20. Even with the shorter length of the magnesium structures of 0.7 mm, the highest breaking forces were measured. This could lead back to the increased structure height and, therefore, to the larger joining volume. The results for stainless steel and aluminium show a low standard deviation of approx. 3.5%. For ME20 the standard deviation is higher, what may be a result from the short length because small length deviation in the structures would have a greater effect on the cross-sectional area in the transition to the metal blank. Increasing the number of structures from 10 to 20 by adding a second row, the breaking force could be doubled for stainless steel and aluminium. The results for magnesium show a lower breaking force per structure, but a clear indication cannot be given due to the standard deviation. This concludes in the result, that the second row absorbs as much force as the first one even under the effects of possible elongations in the joining area. It is noticeable that results for the bonding strength are contrary to the tensile strength of the structures material.

When analysing the fracture patterns, the higher ductility of the stainless steel in combination with the higher tensile strength leads to a deformation of the structures in tensile direction, Figure 6. This allows the structures to be pulled out of the moulding compound even with the undercut of 0.1 mm on the top section of the structure provided by the ball shape. The lower ductility of aluminium and magnesium leads to breakage of the structures at the transition. The plastic parts of the specimen show that the melt penetrates the indentations in the metal component. Those areas are raised on the plastic components. The composition of the joint regarding the indentation and elevation are further analysed in section 7 since a higher bonding strength could be achieved by increasing the undercuts in the indentation.

A thin layer of probably evaporated material is transferred to the plastic surface for aluminium and especially for magnesium. This could be avoided by cleaning steps after structuring.

Figure 6. Resulting fracture patterns after tensile shear testing of single-row specimen.
5.3 Effect of magnesium structures on the maximum tensile force

The feasibility analysis showed that by over-moulding the structures a joint can be formed. The breaking force for structures oriented in plastic flow direction, contrary to the tensile direction, could be doubled by doubling the amount of structures. A more in-depth study regarding the orientation of the structures was conducted with magnesium due to the structure height, Figure 7 left.

Since the structures feature as a bonding volume through the thickness of plastic component, the possibility of weld lines could decrease the mechanical potential of the joint. Based on the investigations with offset structures, additional investigations were carried out without offset since this could decrease the number of reorientations of the flow front. The experiment with aligned structures in tensile direction without the offset shows the same breaking force of around 209 N per structure. This means that the micro-flow barrier and forming of possible weld lines is not decisive for the breaking stress in the analysed specimen. A possible effect on the reduction of maximum flow length due to melt flow reorientation should still be investigated in future studies. By building the structures against the tensile direction, the breaking force is reduced by 22 % to 170 N. When the rows are built opposite to one another, the reduction is only 11 %.

Due to the simple scalability of the strength with the number of rows in the experiments performed, the reduction of the structure number to 5 was investigated. For this, only every second structure was built following the normal geometry of the structures. The force absorbed per structure is reduced to 117 N with this low amount of microform-closure elements. This suggests that there is a minimum number of structures per unit area to achieve a maximum force per structure. The ideal number of structures per surface area and also the distance between the structures should be investigated in more detail in the future.

5.4 Effect of the structure components on the joint strength

In the feasibility analysis it could be proven that the melt can penetrate into the indentations. When analysing the fracture pattern, raised areas are visible on the plastic surface. To analyse the filling of the indentation, a microsection of an overmoulded structure following the building direction was prepared, Figure 8 top. The microsection shows that the indentation is partially filled with plastic. The wavy flow front stops at around 0.7 mm. Due to the thinness of the slit, the holding pressure is not sufficient to compensate for shrinkage-related va- cuoles around the flow front.

Figure 7. Effect of the structure orientation (left) and the amount of structures (right) on the breaking force of plastic/magnesium hybrids.
This allows the assumption that the joint strength is composed of the two components of the structure: the indentation and the elevation. To analyse an increase in strength due to this effect, samples were prepared with cement-filled indentations and ground-down elevations, Figure 8 below. It was already shown that the complete structures for a row of 10 structures reach a breaking force of 206 N. With 117 N, the main breaking forces of the structure is provided from the elevated structure and only 65 N is provided by the indentation. This leads to a ratio of approximately 2:1. An additional 24 N must be provided by the interaction of both structures. When analysing the force of elongation diagram, a pull of the plastic material out of the indentation can be detected. Up to a certain elongation, the stiffness of both joints is the same. At 0.1 mm the elevation stiffness decreases. This could be explained by bending of the elevations in tensile direction. This bending is decreased when testing the complete structure. The results show that not only the elevation needs to be optimized to increase the strength of the joint. Instead both components should be analysed.

5.5 Effect of injection moulding on the joint strength

Since all tests were carried out with the ideal moulding parameters for the specimen and only one moulding compound, in further experiments the effect of the injection speed and the holding pressure were tested, Figure 9. From a higher injection speed results a higher injection pressure and by this the structures could be moulded in flow direction. By increasing the injection speed from 20 cm³/s to 60 cm³/s, the mean force per structure is not decreased significantly. By increasing the holding pressure it could be assumed that the indentations could be filled better. But also the increase of the holding pressure from 400 bar to 600 bar has no significant effect on the joint strength.

By changing the moulding compound to polypropylene, the breaking force is reduced by 43%. There are several effects that may lead to this reduction. The fracture surface is still at the transition of the elevation. Due to the lower strength of the polypropylene, the ratio of the elevation and the indentation in the total force at breakage could shift. This should be analysed in future research.
6 Conclusions

The addition-and-subtraction-processes without added materials can create micro-structures on metal surface which can be overmoulded to form a three-dimensional joint for plastic-metal hybrids. The joint strength is provided by the indentation, the elevation and the interaction between both structure parts. With the number of structures the joint strength increases for all analysed metals, but for magnesium the increase is non-linear.

The preliminary results shown in this paper show many points of interest for further research on this topic. The effect of the geometry of the structures and the number of structures per surface area should be investigated. Since the results show that the indentation has also an effect on the joint strength, not only the geometry of the elevation but also the geometry of indentation to increase undercuts should be analysed. Additionally, the effect of the injection moulding parameters, especially the holding pressure should be investigated in more detail. Regarding the structure layout in the joining area, the effect of the number of structures per unit area, the structure orientation and geometry on the forming of micro-weld lines, the glass fibre orientation and the maximum flow length should be analysed.

Acknowledgements

Open Access funding enabled and organized by Projekt DEAL.

7 References

[1] F. Henning, E. Möller, *Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung*, Hanser Verlag, München, 2020.
[2] F. Ashby, Y. Bréchet, *Acta materialia* 2003, 19, 5801.
[3] M. Grujicic, V. Sellappan, M.A. Omar, N. Seyr, A. Obieglo, M. Erdmann, J. Holzleitner, *Journal of Materials Processing Technology* 2008, 1, 363.
[4] T. Baranowski, R. Koch, B. Nießen, I. Wehmeyer, O. Farges, D. Drummer, *Handbuch Kunststoff-Metall-Hybridtechnik*, Lehrstuhl für Kunststoffverarbeitung, Erlangen, 2015.
[5] S.T. Amancio-Filho, L.A. Blaga, *Joining of Polymer-Metal Hybrid Structures*. Principles and Applications, John Wiley & Sons, Inc., Hoboken, 2018.
[6] G. Zhao, *Ph.D. Thesis*, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany, 2011.
[7] J. Rauschenberger, A. Cenigaonindia, J. Keseberg, D. Vogler, U. Gubler, F. Liébana, *High-Power Laser Materials Processing: La-
sers, Beam Delivery, Diagnostics, and Applications IV 2015, 3, 93560.
[8] K. Taki, S. Nakamura, T. Takayama, A. Nemoto, H. Ito, Microsystem Technology 2016, 22, 31.
[9] T. Malek, Kunststoffe 2010, 100, 80.
[10] M. Honkanen, M. Hoikkanen, M. Vippola, J. Vuorinen, T. Lepistö, Journal of Adhesion Science and Technology 2009, 12, 1747.
[11] G.W. Ehrenstein, Handbuch Kunststoff-Verbindungstechnik, Hanser Verlag, München, 2004.
[12] Rotheiser, Jordan. Joining of plastics: handbook for designers and engineers. Carl Hanser Verlag GmbH KG, München, 2015.
[13] H. Goldbach, B. Koch, Kunststoffe 1991, 91, 634.
[14] H. Paul, M. Luke, F. Henning, Composites Part B: Engineering 2015, 73, 158.
[15] P. Michel, H. Riepenhausen, presented at Kunststoffe im Automobilbau, Mannheim, Germany, March 2 - March 3, 2008.
[16] G. Habenicht, Kleben, Springer-Verlag, Berlin, Heidelberg, 2009.
[17] B. Bonpain, M. Stommel, International Journal of Adhesion and Adhesives 2018, 82, 290.
[18] E. Sancaktar, R.J. Gomatam, Journal of Adhesion Science Technology 2001, 15, 117.
[19] E. Staiger, M. Hild, R.-D. Hund, C. Cherif, S. Brünnling, A. Hardtmann, adhäsion KLEBEN & DICHTE 2014, 58, 32; DICHTE 2014, 58, 32.
[20] Y. Xie, J. Zhang, T. Zhou, Applied Surface Science 2019, 492, 570.
[21] S. Ucsnik, G. Kirov, Materials Science Forum 2011, 1, 465.
[22] R. Plettke, A. Schaub, C. Gröschel, C. Scheitler, M. Vetter, O. Hentschel, F. Ranft, M. Merklein, M. Schmidt, D. Drummer, Key Engineering Materials 2014, 1, 1468.
[23] S. Wurzbacher, C. Hopmann, C. Engelmann, Joining Plastics 2019, 13, 180.
[24] M. Jürgens, A. Nogueira, H. Lang, E. Homborgsmeier, K. Drechsler, Proceedings of Euro Hybrid Materials and Structures 2014, 1, 182.
[25] A. Cenigaonindia, F. Liébana, A. Lamikiz, Z. Echegoyen, Physics Procedia 2012, 39, 92.
[26] P. Mitschang, R. Velthuis, S. Emrich, M. Kopnarski, Journal of thermoplastic composite materials 2009, 6, 767.
[27] B. Huang, L. Sun, L. Li, L. Zhang, Y. Lin, J. Che, Journal of Materials Processing Technology 2017, 249, 407.
[28] H. Schultz, Elektronenstrahlschweißen 2, völlig überarb. und erw. Aufl., Kap. 3: Verhalten des Elektronenstrahls beim Eindringen in Metalle, Verl. für Schweissen und Verwandte Verfahren, DVS-Verlag, Düsseldorf, 2000.
[29] U. Reisgen, L. Stein, Fundamentals of joining technologies - Welding, brazing and adhesive bonding, DVS-Media, Düsseldorf, 2016.
[30] B. Dance, A.L. Buxton, presented at 7th International Conference on Beam Technology, Halle, April 17 – April 19, 2007.

Received in final form: February 23rd 2021