Influence of penetration depth on lap shear strength of induction welded steel/TP-FRPC joints

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Abstract
This study examines the influence of penetration depth of physically surface-treated steel sheets (steel 1.0330 and 1.0338) on bond strength of welded hybrid joints with thermoplastic fiber reinforced polymer composites (TP-FRPC). The quasi-static, discontinuous induction welding was used as joining method. The steel sheets were either treated by crosswise to the specimen length axis line-shaped, parallel laser structuring at a distance of 0.3 mm and 0.6 mm or by a compressed air blasting. Furthermore, the influence of holding time and consolidation pressure on bond strength was examined. To determine the bond strength, welded specimens were tested using tensile shear tests according to DIN 1465. It was found that each surface pretreatment has an individually suitable penetration depth. Based on these findings, guidelines can be issued stating that penetration depth is suitable for process control or as a quality assurance feature in hybrid induction welding.

1. Introduction

TP-FRPC become increasingly popular as an engineering material. The main advantages are the excellent lightweight design capabilities and their suitability for mass production. These factors contribute to an increase of the demand for efficient and weight-neutral joining techniques. Joining of TP-FRPC is well established and can easily be done by different welding technologies. Multi-material concepts require new joining concepts for hybrid structures. One concept is to use the excellent heating properties of metals by induction. The physics to create a stable bond is based on forming adhesive interactions and the creation of a form fit between the dissimilar materials. [1] [2]

The discontinuous induction welding of metals with TP-FRPC was developed at the Institut für Verbundwerkstoffe GmbH (IVW). The investigations presented in this study were carried out on a test rig as shown in Figure 1. A stamp applies the consolidation pressure generated by a pneumatic cylinder onto the adherends. A consolidation plate is integrated in the stamp, which is permeable to the electromagnetic field and thus does not heat-up itself during welding. Energy is induced in the metal, until a maximum temperature has been exceeded. Typically, temperature measurement is used to monitor or control the process. Monitoring of the surface temperature can either be carried out contactless by an optical measuring system, e.g. a pyrometer, or in the joining zone by means of thermocouples between the adherends. Reliable temperature measurement in discontinuous induction welding is difficult because the welding equipment usually covers the adherends completely and therefore an optical temperature measurement is often not possible. To find an alternative in-line process quality control method, the penetration depth is investigated in detail. The penetration depth is the difference between the thickness of both adherends before and the thickness of the joint region after welding.

In general the adherends can be positioned in two ways relative to the induction coil, either the metal or the FRPC facing the coil. In this study, the metallic adherend is placed on top of the FRPC to guarantee a high energy-input into the metal due to a short coupling distance. An additional advantage is the better pressure distribution in the welding zone due to the solid state of the metal even at the maximum process temperature. To minimize process time, the adherends are cooled by forced convection with compressed air after heating.

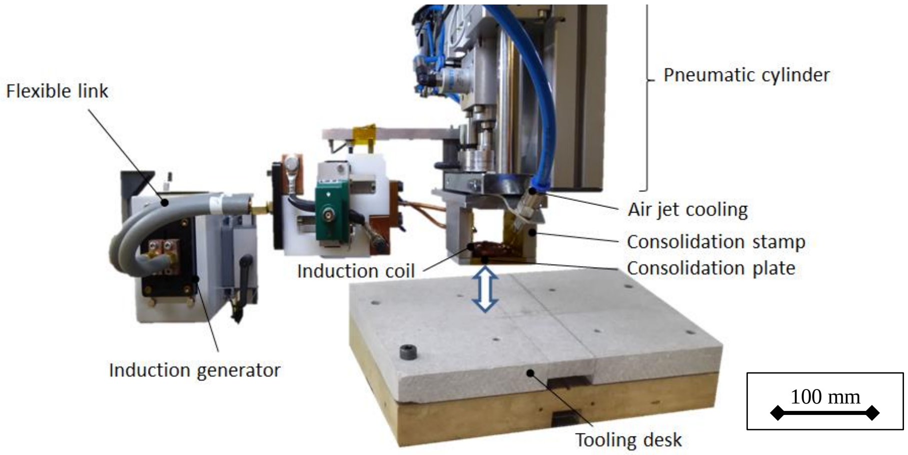


Figure 1. Discontinuous induction joining test rig

Aim of this study is to investigate the impact of different surface pre-treatments and process parameters on bond strength of steel welded with TP-FPRC compounds. In particular, the influence of penetration depth, heating time and consolidation pressure on bond strength are systematically investigated. The correlation between surface roughnesses of pre-treated metal on bond strength was also investigated.

2. Heating Mechanism

In induction welding, an electrical generator in combination with an inductor generates an alternating electromagnetic field (Figure 2). This electromagnetic field induce eddy currents in an electrically conductive material, like metals and heat them up as a result of resistance losses. If the metal is also magnetic, additional heat is generated by electrical hysteresis. The electromagnetic field transfers electrical energy without contact and generates heat directly in the metallic adhered. When enough energy has been induced into the metal, it achieves the joining temperature above the melting point of the thermoplastic polymer matrix. In the molten state, the polymer wets the treated contact surface of the metal and forms the connection mechanisms after cooling. The simultaneous application of a joining pressure onto the adherends improves a complete wetting of the metal surface by the polymer. [3][4]

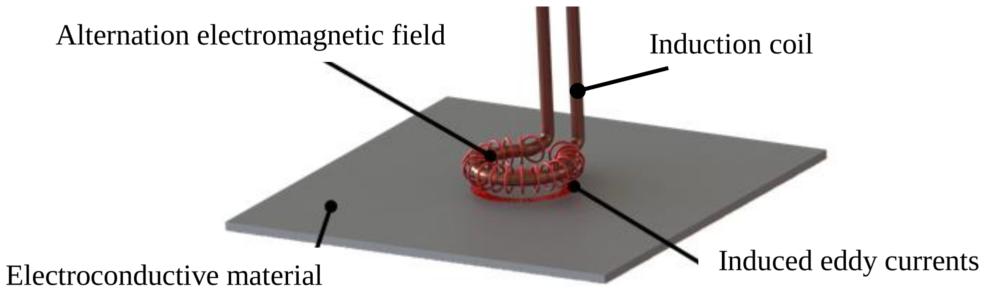


Figure 2. Inductive heating of electrical conductive materials

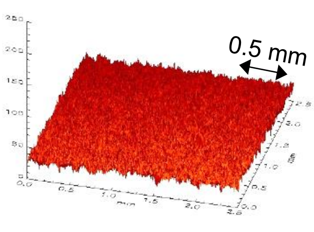
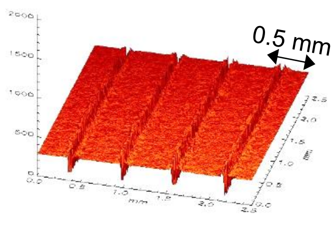
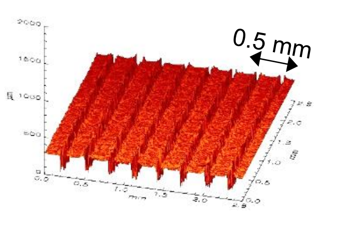
3. Materials and Surface Treatments

Two types of steel (1.0330 and 1.0338) as well as glass fiber reinforced polyamide 6 (GF/PA6) and glass mat reinforced polypropylene (GF/PP) were used. Thus, the difference between a polar (PA6) and a non-polar (PP) polymer can be investigated and, the difference between high (GF/PA6) and low (GF/PP) fiber volume content is considered. A more detailed characterization of the used materials is shown in Table 1 and Table 2. A surface characterization was carried out by means of white light profilometry. Table 2 also shows images of the scanned surfaces with the corresponding roughnesses.

Table 1. Used TP-FRPC organic sheets

Fiber reinforcement/ fiber vol. content	Glass fiber woven fabric, 3 layers symmetric twill fabric/ 47% vol.	Glass fiber woven fabric, 4 layers symmetric twill fabric/ 47%	Glass mat, chopped fiber, randomly oriented/ 23%
Matrix-polymer	Polyamide 6 (PA6)	Polyamide 6 (PA6)	Polypropylene (PP)
Manufacturer identification	Tepex® dynalite 102-RG600(3)	Tepex® dynalite 102-RG600(4)	D100F23-F1
Manufacturer	Bond Laminates	Bond Laminates	Quadrant Plastic Composites
Thickness	1.5 mm	2 mm	4.8 mm
Melting temperature	220 °C	220 °C	160°C
Acronym	GF/PA6 1.5 mm	GF/PA6 2 mm	GF/PP 4.8 mm

Table 2. Used steel alloys with corresponding physical surface treatment

Steel	1.0330		1.0338			
Surface pretreatment	Compressed air blasting		Laserstructuring, 0.6 mm structuring distance		Laserstructuring, 0.3 mm structuring distance	
Thickness	2 mm		1 mm		1 mm	
Surface roughness of pretreatment	Ra: 2.92 ±0.3 µm	Rz (ISO): 17.55±1,4 µm	Ra: 15.53±1.5 µm	Rz (ISO): 157.4±19.4 µm	Ra: 35.51±1.7 µm	Rz (ISO): 235.5±13.4 µm
Acronym	1.0330 CAB		1.0338 LS 0.6 mm		1.0338 LS 0.3 mm	
Surface scan						

The surfaces of the steel specimens were pre-treated by compressed air blasting (steel 1.0330) or laser-structuring (steel 1.0338). In contrast to steel 1.0330, the 1.0338 was galvanized. Blasting material was corundum (Cerablast, grain size: 250-355 µm). The laser structuring was carried out in line pattern crosswise to the specimen length axis by a water cooled IPG 1000 W single-mode fiber laser. The focusing optics has a focal length of f=330 mm, the resulting spot has a radius of 20 µm. Before joining, first the metal specimens were cleaned in an ultrasonic bath with the cleaning agent Tickopur TR 7 for 15 minutes. Moreover, the steel and TP-FRPC components were degreased by isopropanol before welding to obtain reproducible experimental conditions. The polyamide specimen were dried at 80 °C for 12 hours before welding and degreasing.

4. Experimental Set-up

The studies were carried out on a laboratory induction welding test rig (Figure 1). There test specimens were positioned horizontally on an aluminum tool, below the consolidation stamp. The stamp applies a constant consolidation pressure on the adherends during heating and cooling. Figure 3 shows a schematic sketch of the experimental set-up. The metal adherend faces the coil side. A further advantage is a more homogeneous temperature distribution in the joining zone, as the heat spots generated on the coil facing metal surface are homogenized in thickness direction because of the isotropic heat conduction of the metal. The maximum penetration depth was defined by geometrical restrictions.

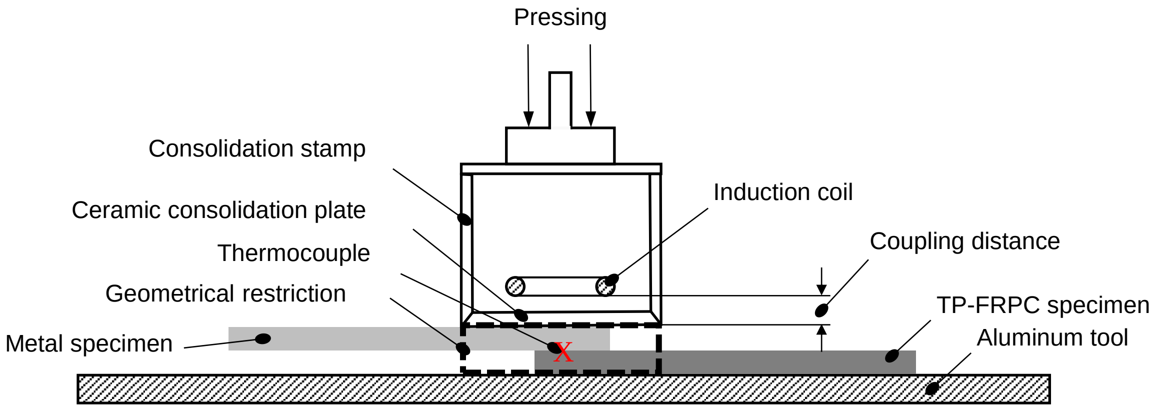


Figure 3. Schematic sketch of the discontinuous induction welding of hybrid lap shear specimen

The experiments were conducted by means of a circular pancake induction coil with a diameter of 35 mm and a coupling distance of 5 mm. As induction generator a TrueHeat HF 5010 from TRUMPF was used. All specimens were cooled with pressured air after heating with an air flow rate of 90 l/min. The temperature in the joining zone was measured by a thermocouple (Type E).
The bond strength was subsequently tested by lap shear tests according to DIN 1465. The thickness of the different organic and steel sheets varies according to Table 1. On the right-hand side in Figure 4, the test setup of the tensile shear test is shown schematically. An universal testing machine Zwick 1485 was used. The testing force was measured on the traverse, test length was 112.5 mm for steel 1.0338 and 47.5 mm for steel 1.0330, the test velocity was 1 mm/min. Hydraulic clamping devices were used for fixing the specimens in the testing machine. To avoid additional stresses in the bond when clamping the test specimens, spacers were used to compensate the offset at the clamping points.

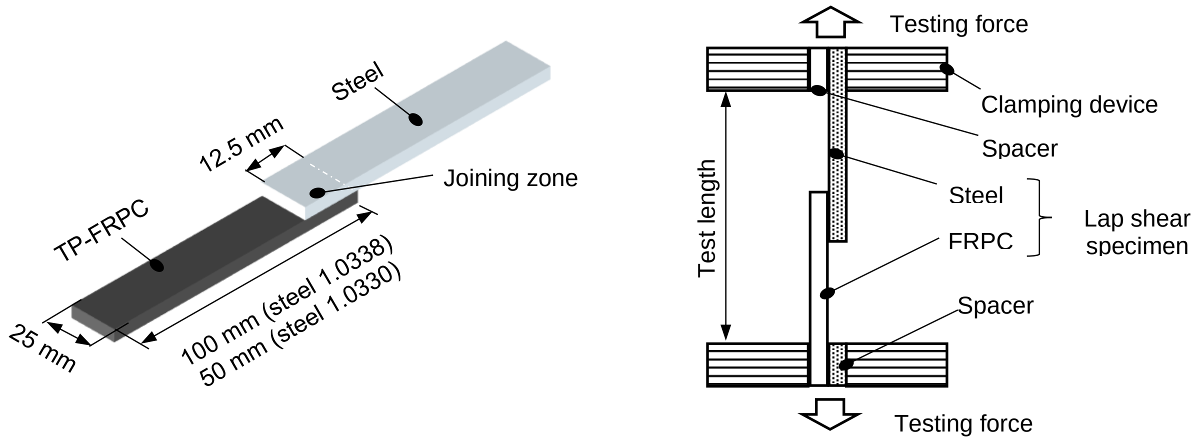


Figure 4. Dimensions of lap shear specimen according to DIN 1465 (left hand) and schematic sketch of the experimental set-up of lap shear test (right hand)

5. Results & Discussion

In order to get a comprehensive overview the influence of holding time, consolidation pressure and penetration depth as well as different surface pre-treatments on bond strength were investigated. Each test series consists of parameter sets. The difference between the parameter sets within a series is the variation of the process parameter to be examined. 5 test specimens were used for tensile shear tests; one specimen was used to prepare a cross section polished cut image of the joint.

Influence of consolidation pressure

The pressure in the joining zone results by a force, which is applied onto the metallic adherent by the stamp of the test rig. The force distributes homogeneously in the joining zone. This results in the consolidation pressure. Figure 5 shows the results of the influence of a variation of the consolidation pressure within the individual series. The results show that the bond strength is not influenced by variation of consolidation pressure, neither for different surface treatments nor different material combinations.

	Organic sheet and thickness	Steel & treatment	Penetration depth	Holding time	Temperature	Generator current
◆	GF/PA6 2 mm	1.0330 CAB	0.5 mm	1 s	275 °C	6 A
■	GF/PP 4.8 mm	1.0330 CAB	1.1 mm	1 s	225 °C	4 A
▲	GF/PA6 1.5 mm	1.0338 LS 0.6 mm	0.3 mm	10 s	290 °C	10 A

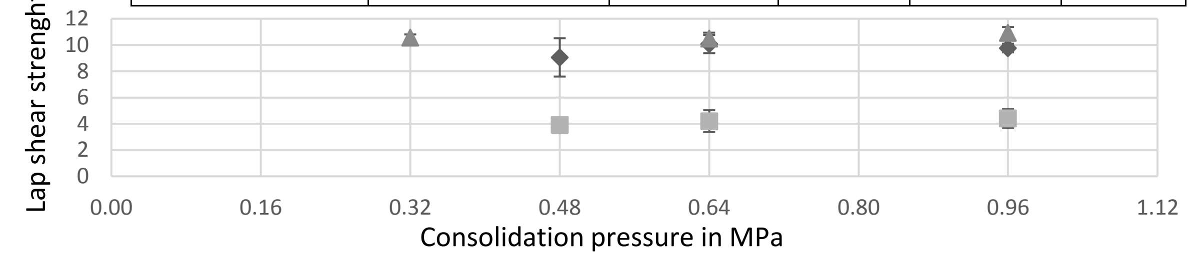


Figure 5. Influence of various consolidation pressures on bond strength

Influence of holding time

The holding time is the duration in which the defined penetration depth is kept constant at a temperature in the molten stage of the polymer. The material combinations of GF/PA6 2 mm and GF/PP 4.8 mm with 1.0330 CAB were investigated. The other welding parameters were not varied within each test series. The holding time has a primary influence on the volume of polymer that becomes molten. Figure 6 shows the results for 1 s, 20 s, and 40 s holding times on bond strength.

	Organic sheet and thickness	Steel & treatment	Penetration depth	Consolidation pressure	Temperature	Generator current
◆	GF/PP 4.8 mm	1.0330 CAB	1.1 mm	0.64 MPa	225 °C	4 A
■	GF/PA6 2 mm	1.0330 CAB	0.5 mm	0.64 MPa	275 °C	6 A

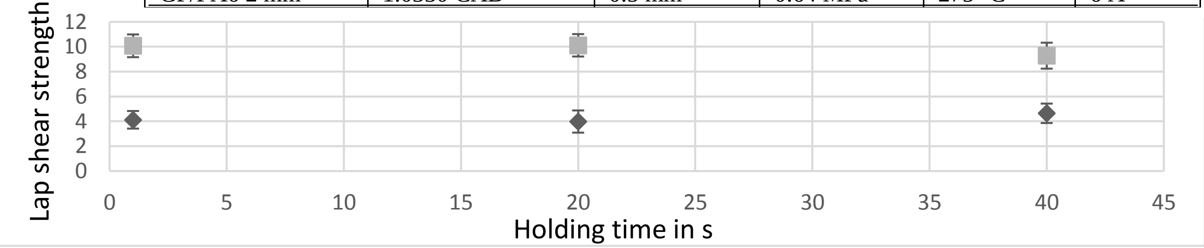


Figure 6. Influence of various holding times on bond strength

When comparing the holding times of 1 s and 20 s, neither the material combination of GF/PP with steel nor GF/PA6 with steel shows any significant influence on bond strength. The result shows that even the heating phase plus 1 second holding time is enough to melt at least the depth of 0.5 mm for GF/PA6 or 1.1 mm for GF/PP respectively. A further enlargement of the melting depth do not affect the bonding due to the restriction in penetration depth.

Influence of penetration depth

The penetration depth is the difference in thickness of the joining partners before and after welding, i. e. the path that the steel sheet is pressed into the FRPC. The results are summarized in Figure 7 and Figure 8.

	Organic sheet and thickness	Steel & treatment	Consolidation pressure	Holding time	Temperature	Generator current
···▲···	GF/PP 4.8 mm	1.0330 CAB	0.64 MPa	1 s	225 °C	4 A
—○—	GF/PA6 2 mm	1.0330 CAB	0.64 MPa	1 s	275 °C	6 A

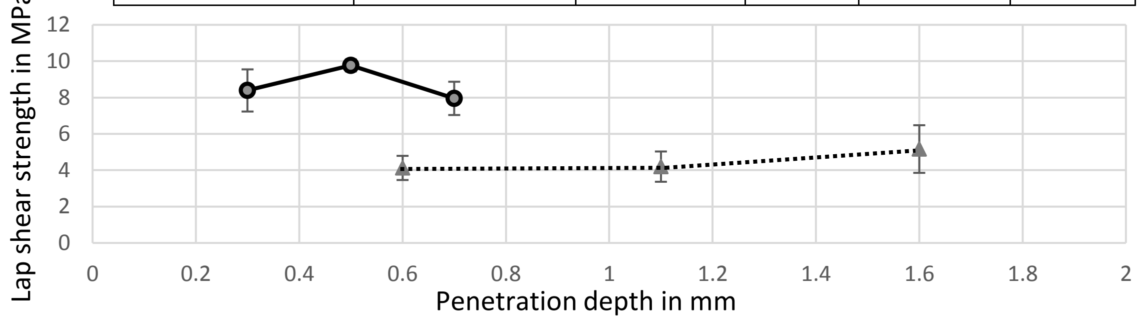


Figure 7. Influence of penetration depth on lap shear strength

GF/PA6 welded with compressed air blasted steel sheet shows an optimal penetration depth at 0.5 mm. In the case of GF/PP with compressed air blasted steel, an increase in penetration depth leads to slightly higher bond strength. This may be affected by the huge amount of molten PP gets pressed out the fiber structure. Nevertheless, penetration depths from 0.3 mm up to 1.6 mm lead to a strong deformation of the organic sheets during joining. To avoid deformation and investigate the minimum penetration depth additional tests with GF/PA6 1.5 mm welded to 1.0338 LS 0.6 and 1.0338 LS 0.3 with penetration depths from 0.02 to 0.2 mm were carried out (Figure 8).

	Organic sheet and thickness	Steel & treatment	Consolidation pressure	Holding time	Temperature	Current
···■···	GF/PA6 1.5 mm	1.0338 LS 0.6 mm	0.96 MPa	10 s	290 °C	10 A
—▲—	GF/PA6 1.5 mm	1.0338 LS 0.3 mm	0.96 MPa	10 s	290 °C	10 A

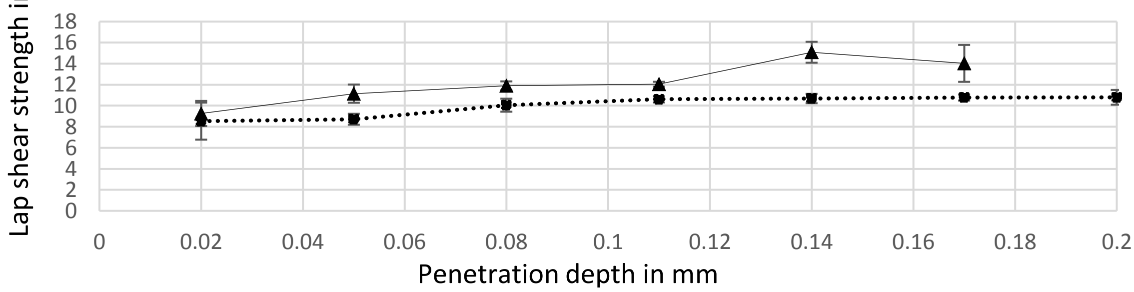


Figure 8. Influence of penetration depth on lap shear strength

Both structuring distances show a positive impact on joint strength for larger penetration depth. With a structuring distance of 0.3 mm, the highest joint strength is achieved at a penetration depth of 0.14 mm and 0.11 mm at a structuring distance of 0.6 mm respectively. No further increase of bond strength is found for higher penetration depths. A line distance of 0.3 mm results in higher bond strength than 0.6 mm. This can be explained by the higher area roughness (see Table 1). It is also noticeable that the standard deviation initially decreases with rising penetration path and increases again from a certain value onward.

Cross section polished cut image of the joints

Cross section polished cut image of the hybrid joints were made in order to evaluate the welding zone between steel and TP-FRPC. Figure 9 and Figure 10 show a cross section view of laser structured metal specimen with a structuring distance of 0.6 mm and 0.3 mm. The specimens were welded with identical parameter settings. It is evident that a closer structuring distance and the associated higher number of cavities lead to more voids in the joining zone. As a result, more matrix polymer from the TP-FRPC is required to completely fill the higher number of cavities. Nevertheless, the closer structuring distance leads to higher bond strength due to an increase of surface area and additional form closure.

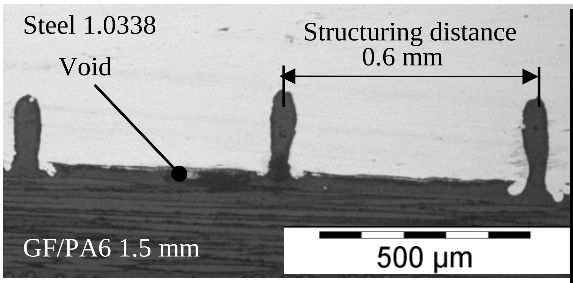


Figure 9. Penetration depth d=0.11 mm; Temperature T=290 °C; Pressure p=0.96 MPa

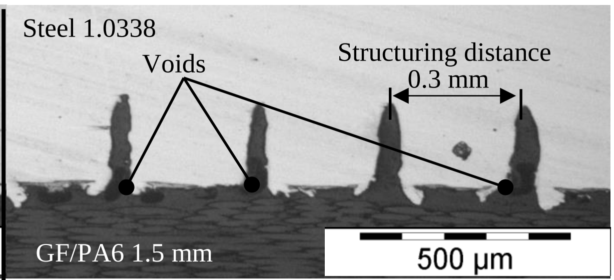


Figure 10. Penetration depth d=0.11 mm; Temperature T=290 °C; Pressure p=0.96 MPa

Figure 11 and Figure 12 show a cross section polished cut image of compressed air blasted 1.0330 metal specimens with GF/PP 4.8 mm and GF/PA6 2 mm. The area of contact between TP-FRPC in the joining zone is completely wetted with polymer. There are no voids in the joining zone. As the GF/PP 4.8 mm is produced isochor, it is not fully consolidated and therefore air inclusions are visible also after welding.

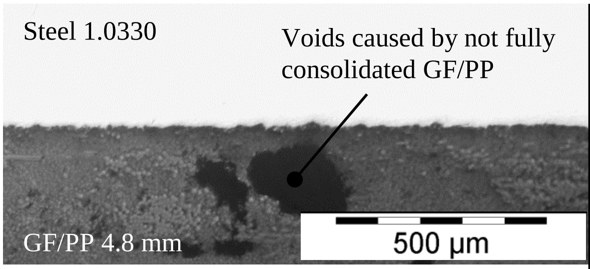


Figure 11. Penetration depth d = 1.1 mm; Current: I= 4 A; Pressure p= 0.64 MPa

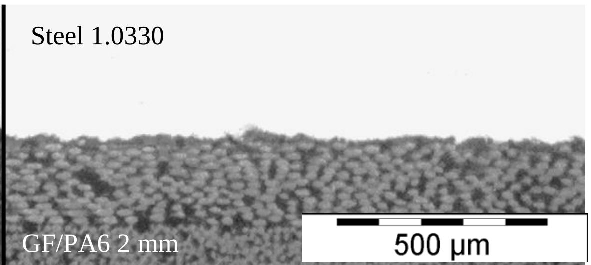


Figure 12. Penetration depth d = 0.5 mm; Current I=6 A; Pressure p= 0.64 MPa

6. Conclusion

The influence of the examined process parameters on the bond strength of welded hybrid joints is summarized in Table 3. It was found that each material combination with the appropriate surface treatment has an optimum parameter set.

Table 3. Summary of the influence of crucial process parameters on bond strength

Parameter	Influence on bond strength
Holding time ↑	No influence
Consolidation pressure↑	No influence
Penetration depth	High, optimum value
Surface treatment and material combination	High

The results of this study show that penetration depth is the most sensitive parameter on bond strength. This leads to the conclusion that measuring the penetration depth is a simple and robust method for process control in discontinuous induction welding.

Acknowledgments

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