Further Development on Joining of Metal and Fibre Components Using Semi-solid Forming Technology

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Abstract
Lightweight construction requires various combinations of metallic and fibre-based structures as well as adapted joining methods. In the case of automotive engineering, carbon structures such as roofs or transition humps have to be joined with quarter panels and floors. In this context, an innovative joining method for combining sheet metals with carbon textiles was developed at the Institute for Metal Forming Technology (IFU). First, fundamental investigations were conducted in order to create a material integrated interlock between one single carbon fabric layer and aluminium sheets based on the semi-solid forming technology. This paper deals with further investigations comprising sample heating control and the usage of multilayer carbon textiles.

Keywords: Bonding technology, Composite materials, MMC, Carbon fibres, Semi-solid forming, Lightweight construction, Gleeble 3800c

1 Introduction

These days, the trend toward lightweight construction is motivated by legal conditions concerning environmental protection, pollutant reduction, and conservation of natural resources. In this context, the usage of carbon fibre reinforced plastics (CFRP) increases due to its excellent mechanical properties and the relatively low density compared to metal materials. However, such new materials and advanced material combinations have to be integrated into established metal structures in the automotive industry. Therefore, suitable joining methods have to be developed to satisfy the demand for integrating various metallic and fibre-based structures together. Mechanical technologies such as riveting, screwing or clinching are of limited applicability due to resulting stress peaks and the damage to the primary loadbearing fibres [1]. At that moment, the most common joining method for CFRP components and sheet metals is adhesive bonding, which necessarily requires mandatory cleaning methods [2]. Furthermore, adhesive bonding is time-consuming due to the required previous cleaning and subsequent curing processes and is generally exposed to aging. Considering the trend to lightweight construction in architecture and automotive industry, current research activities at different places all over the world are focusing on carbon-metal-compounds and corresponding production techniques. The Bremen Fibre Institute currently investigates new concepts to realize Al-CFRP joints by using titanium loops or foils as a transition structure. Combinations of welding, casting, and textile technologies are applied for realising transition structures combining aluminium and CFRP components [3]. The gas pressure infiltration (GPI), developed by the Institute of Lightweight Engineering and Polymer Technology Dresden, represents another innovative method to combine carbon and metal structures. In this technique carbon fibre pre-products are infiltrated by aluminium in the liquid state [4].

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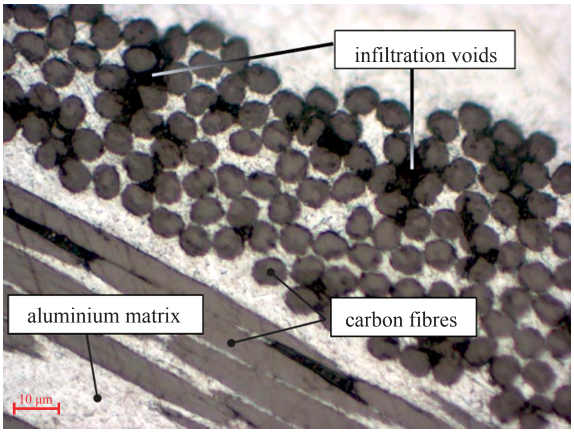

Figure 1: Micrograph of an aluminium-carbon-aluminium-compound.

Current research activities at the Institute for Metal Forming Technology (IFU) are focusing on semi-solid forming strategies for combining aluminium and carbon long fibres [5]. In this context, an innovative process was developed to substitute polymer matrix of CFRP parts using aluminium. The main objective of this work was to manage the reinforcement of CFRP parts in the area of load application and to enable additional joining processes in this section. For this purpose, rovings were stretched through the tool cavity and infiltrated by semi-solid metal [6], [7]. Subsequently, exposed fibre bundles were laminated using epoxy to accomplish a CFRP-aluminium compound. Continuing further research work, influence of process parameters such as amount of fibres, fibre pretension or content of liquid phase was determined. During these investigations, no negative impact on fibres' properties caused by process temperatures was observed [8]. Based on this, an innovative joining technique in order to join aluminium and carbon structures was developed at the IFU in 2014. First fundamental investigations demonstrated the feasibility, during which a material integrated interlock of one single carbon fabric layer and metal sheets of different metal materials was generated [9], [10]. The microsection in Figure 1 depicts two joined aluminium sheets together with a carbon textile monolayer in between. There is no identifiable boundary between the two blanks and only a few dark zones between the single fibres become visible, which are interpreted as infiltration voids.

Figure 2: Thermo-mechanical simulator Gleeble 3800c (Dynamic Systems Inc.) with control unit (left) and tension/compression module (right).

Current research work is concerned with the determination of optimal process parameters and the measurement of mechanical properties of the joint. The objective of the investigations addressed in this paper comprises the development of sample heating control systems and the application of carbon multilayers. In addition, the experimental setup and the materials used are presented.

2 Experimental Setup

2.1 *Thermomechanical simulator Gleeble 3800c*

All experiments described in this paper were carried out using the thermomechanical simulator Gleeble 3800c (Dynamic Systems Inc., Figure 2). This machine provides conductive heating up to 3,000°C and heating rates with a maximum of 10,000°C per second. Quenching is provided using inert gas, air or water. Four thermocouple channels can be used for connecting thermocouple wires for the monitoring and the controlling of the temperature level during the joining process. Furthermore, different modular units enable mechanical load application like compression, tension, and torsion. The use of the software tool *Quicksim* allows controlling the heating process (via power level in electrical degrees), force and stroke (distance between the electrodes) as well as recording the parameters mentioned above. Moreover, program codes can be entered in *Gleeble Script Language*.

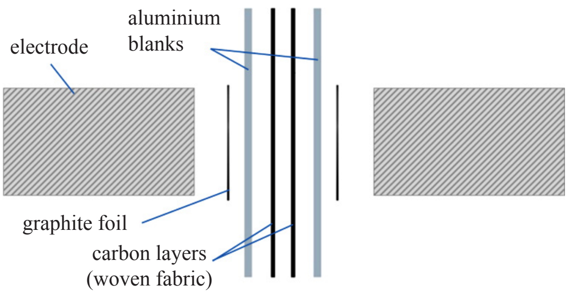

Figure 3: Experimental setup consisting of electrodes, aluminium sheets, carbon layers of woven fabric and graphite foils.

2.2 *Procedure*

In the context of the experimental work, a sandwich structure of two aluminium stripes and woven carbon fibres in between was joined by two cylindrical titanium electrodes (Ø 25 mm, Figure 3).

Using conduction these electrodes were heating the sandwich structure up to the bonding temperature level T_F = 590°C, which is just slightly above solidus temperature (585°C). Graphite foil was used as release agent to avoid any kind of welding of the electrode and the sheet metal. Once the material of the specimen has reached the semi-solid state, the applied compressive force caused a viscosity decrease of the semi-solid metal because of its material behaviour which depends on the shear rate. The carbon textile, which macroscopically forms an interface between the two metal sheets, was penetrated by the semi-solid metal and single fibre bundles were infiltrated. Thereby, the two sheet metals were joined with the intermediate fibre structure.

2.3 *Experimental design*

Experiments described in this paper pay attention to the joining process of aluminium (sheet thickness = 1.5 mm) with an increasing number of textile layers. In this way, the limit of the largest number of joinable carbon layers was determined as well. A varied setup without any carbon textile in between was used to determine any reinforcing or weakening effect of the carbon fibres on the aluminium-aluminium-joint. In order to assure reliability, each type of experiment was conducted three times.

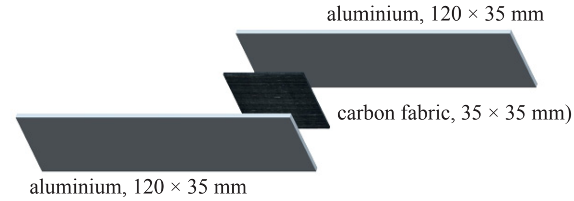

Figure 4: Dimension of sample made of carbon fabric (35 × 35 mm) and Al-sheets (120 × 35 mm).

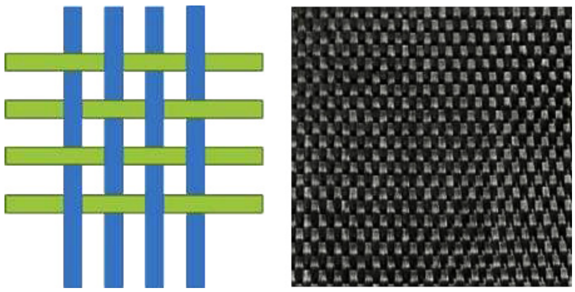

Figure 5: Carbon fibres in plain weave (WELA 43442-167-1000).

Furthermore, uniaxial tensile shear tests were carried out to investigate the strength of the joint. For that reason, aluminium sheet strips were used, whereas carbon fabric was cut correlating with aluminium sheet size and area of overlap (Figure 4).

2.4 *Material*

Woven fabric material WELA 43442-167-1000 having a thickness of approximately 0.3 mm was used (Figure 5). This texture was characterized by a small opening coefficient, which is why fibre bundles were woven very densely having small gaps in between.

The aluminium alloy EN AW-6082 (T6) was chosen as sheet material because of its good weldability and its widespread use in the automotive sector. The chemical composition is shown in Table 1.

Table 1: Chemical composition of EN AW-6082 (DIN EN 573-3)

Si	Fe	Cu	Mn	Mg
0.7–1.3	0.5	0.1	0.4–1.0	0.6–1.2
Cr	**Zn**	**Ti**	**others**	
0.25	0.2	0.1	0.15	

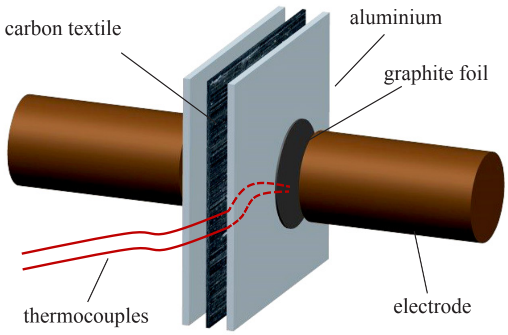

Figure 6: Experimental setup revealing welded thermocouples.

3 Results

3.1 *Development of heating control*

3.1.1 Heating control by temperature measurement

First experiments were put into effect by investigating temperature-controlled heating strategies. For this purpose, thermocouples were welded on the inward surface of one of the metal sheets (Figure 6).

By using the software tool *Quicksim*, the targeted temperature T_F (= 590°C) was preset and the Gleeble system started monitoring the current temperatures during the heating process. As soon as T_F was reached, the applied compressive force C_F (0.2 kN) caused the infiltration of fibre bundles with the semi-solid metal within the front surface of the electrodes.

Within this operating mode, the Gleeble system permanently balanced targeted and actual temperature and adjusted the heating power accordingly. Especially at the beginning of the heating process, the measurements showed significant fluctuations and aligning target and measured values as depicted in Figure 7 was time-consuming. Furthermore, the heating rate was reduced twice to support homogeneous heating in the area of contact zone of the electrode. Disadvantages of this heating control mode were the difficulty of welding thermowires on sheet surfaces and the associated time effort. Even if the welding procedure was performed successfully, mechanical load during the following experiment frequently caused the welded joint to detach. Finally, this method was proved to be unsuitable due to the preparatory welding time and measurement inaccuracies.

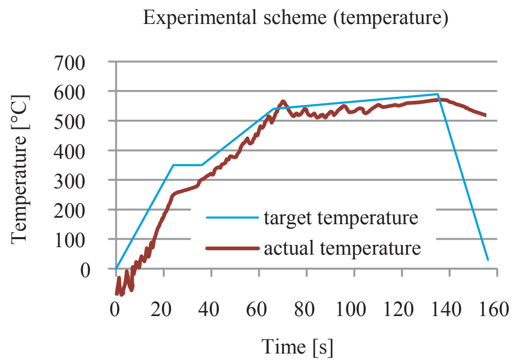

Figure 7: Time-Temperature-Diagram depicting targeted and measured temperature development [5].

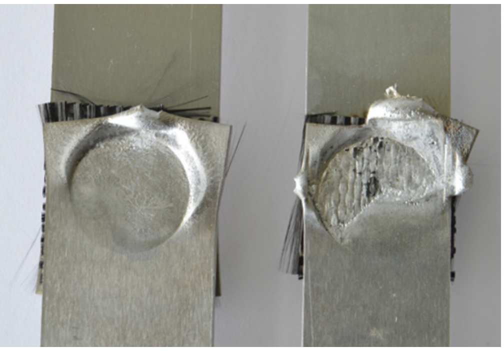

Figure 8: Samples indicating substantially different joining results despite of identical process parameters: successfully joined hybrid structure (left); failed sample due to overheating (right). Back sides look similar to front sides.

3.1.2 Heating control by power level

Due to power level measurements during the temperature-controlled heating process, a novel procedure was developed to power-control the heating transfer. Based on these recorded data, the power level of the Gleeble system was defined depending on time without performing further temperature measurements. This method generally helped achieving shorter process times, as a time-consuming alignment of targeted and actual temperature (Figure 7) was not necessary.

Furthermore, the cycle times were reduced because welding the thermocouples was redundant. However, experiments in which this heating method was used showed low reproducibility. Figure 8 presents two samples produced with identical process parameters.

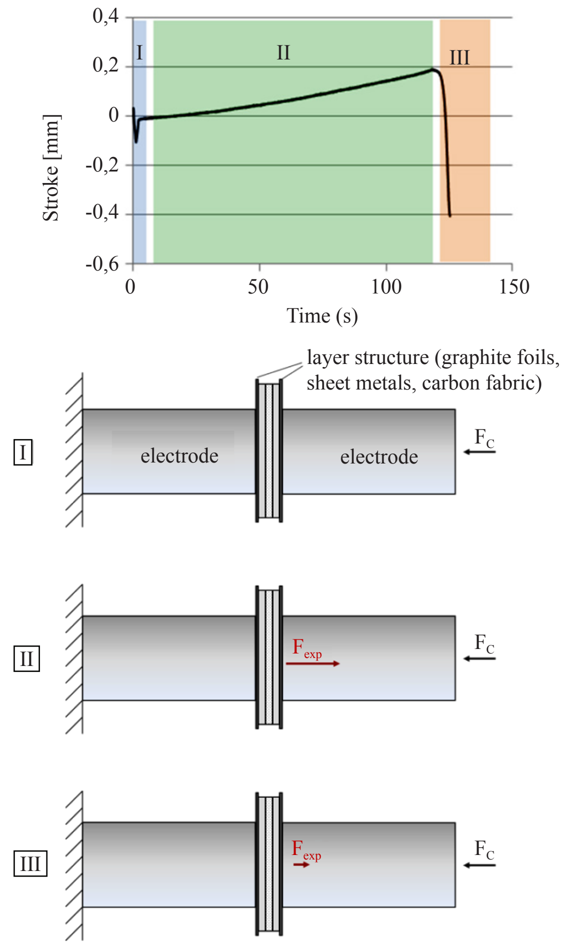

Figure 9: Stroke development during heating process and scheme of forces at work.

While the left sample showed a composite part indicating a homogenous, approximately circular joining zone, the sample on the right side clearly depicts overheating. Such scattering results can be explained by measuring the distance between the electrodes (stroke).

Figure 9 illustrates a stroke development, which is valid for all experiments regarding this heating control method. The curve shows a local minimum of the stroke during the first seconds (section I). This negative peak was caused by the time-limited increase of compression force, which supported homogeneous heating improving the contact between aluminium and fabric. Afterwards, the compression force was kept at $F_C = 0.2$ kN. During the heating process, stroke values

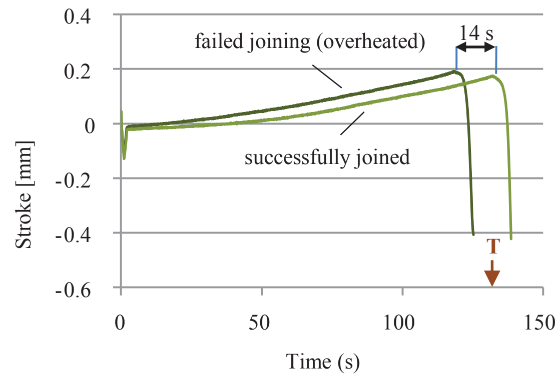

Figure 10: Divergent stroke development of two samples being manufactured by identical process parameters (process time T = 130 s).

rose constantly (II). This increase of the electrodes' distance was caused by the force F_{exp}, which arose from the thermal expansion of the sheet metals. The progression continued as far as the stroke curves significantly dropped (III), which was interpreted as solidus transition. First melt occurs and as a consequence F_{exp} extremely decreased and F_C drastically reduced the stroke.

However, Figure 10 compares the stroke curves of the samples shown in Figure 8. Despite the identical Gleeble system parameters, the melting onset of the two samples differed significantly from each other. If the Gleeble System was programmed to perform the heating process until reaching t = 130 s ('T'), one of the samples was overheated already.

Presumably, slight specimen variations (e.g. in sheet thickness or orientation of textile layers) resulted in altered electrical resistances and thus, required altered heating rates. As such batch fluctuations cannot be ruled out, the heating method control by power level was only suitable for single specimens. By contrast, serial processes require reliable process results, which is why a third control mode was developed.

3.1.3 Heating control by stroke

As the beginning of melting was considered as a convenient moment to perform the joining process, the Gleeble device was programmed to detect this drop of stroke and then stop heating and compressing when the stroke was smaller than 0.2 mm (Figure 11).

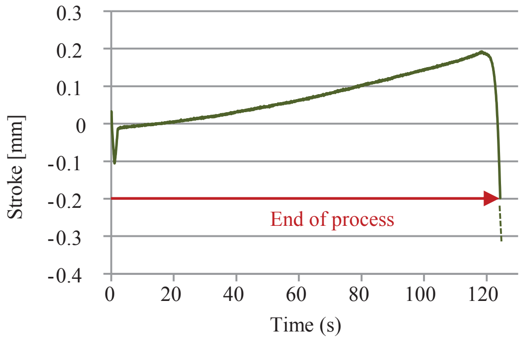

Figure 11: Stroke development versus time; Gleeble system was programmed to terminate heating as soon as stroke values fell below –0.2 mm.

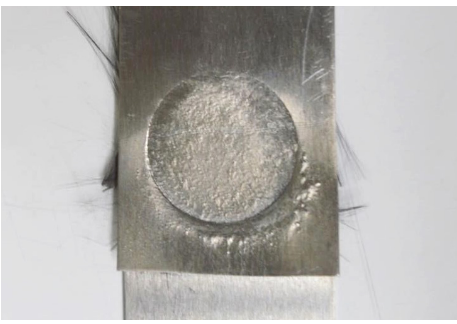

Figure 12: Successfully joined sample by stroke-dependent heating process.

This value was chosen with relation to the time-limited rise of compression force (Figure 9, section I) and the resulting stroke drop to values between –0.10 and –0.18.

Hence, the joining procedure presented here, occurs as a heating method being independent from the kind of alloy used. Also varying numbers of carbon layers as well as altered power levels could be used to produce hybrid components in a reproducible manner (Figure 12).

3.2 *Influence of additional carbon layers*

Joining experiments showed that a maximum number of four carbon layers were applicable (concerning sheets of 1.5 mm thickness). This textile package represented poorly penetrable boundaries for semi-solid aluminium and therefore, the major volume of liquid metal was squeezed out. As depicted in Figure 13, only the minor part infiltrated carbon textile and provided weak cohesion between the single components.

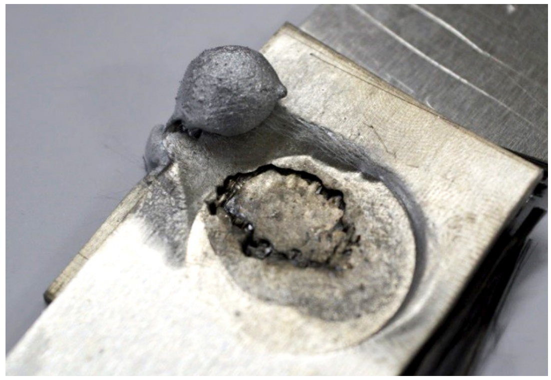

Figure 13: Sample with 4 carbon layers, while metal drop on sheet surface emerges as result of poorly penetrable carbon package.

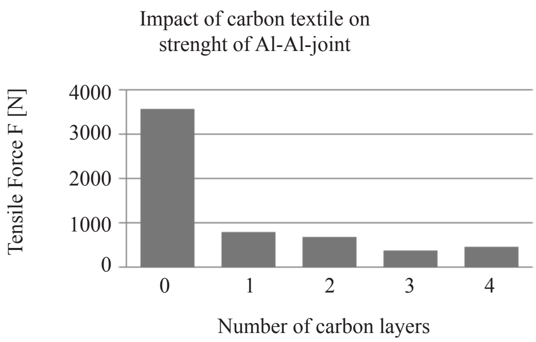

Figure 14: Weakening effect of carbon layers on aluminium-aluminium joint.

3.3 *Mechanical properties of joints*

Uniaxial tensile shear tests were performed to measure the strength of the joined samples. In this way the reinforcing effect of the carbon fibres on the metallic joint was investigated.

Figure 14 shows a weakening effect of the carbon fabric on the aluminium-aluminium joint. The reason for this unexpected effect was the setting of the tensile testing machine in combination with the sample's geometry.

As a consequence of the required sheets overlapping, the samples suffer bending stress as soon as they are clamped into the tensile testing machine. Hence, stress concentration occurred in a very small area (peeling effect, Figure 15). Therefore, future works will comprise a modified setting of tensile machine containing a specific amount of shims.

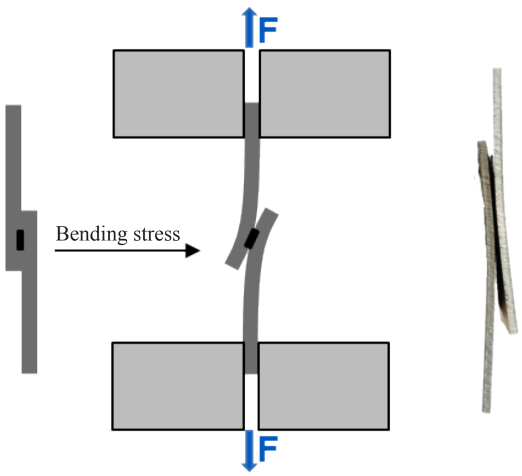

Figure 15: Peeling effect during tensile shear tests.

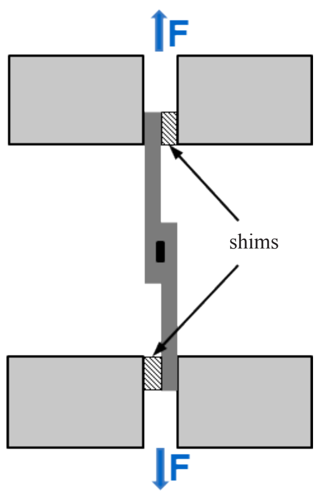

Figure 16: Projected setup of future tensile shear tests.

4 Conclusions and Outlook

This paper deals with an innovative joining method which was developed at the IFU Stuttgart/Germany. It was emphasized that this method requires a reliable heating process which was addressed in the investigations. The process control via stroke development represented a significant advancement compared to former procedures regulated in dependence of time. The new heating regulation is based on solidus transition detection and allows reproducible processes using varying numbers of carbon layers or different power levels. Experiments showed that the maximum number of carbon layers was limited to four. Therefore, textiles of other weaves should be investigated in future research. Supposedly, the textiles having a less dense weave (a greater opening coefficient) make it possible to join a larger number of carbon layers.

Concerning mechanical characterisation, samples with carbon textile in between showed lower strength than expected. As these results were influenced by bending and peeling effects, future investigations should eliminate these impacts.

Furthermore, the joining technique will be modelled by numerical simulation (finite element analysis). In a first step, optimal values for voltage and current will be determined. Process times which are adapted to industrial production and the homogeneous heating of the joining zone are boundary conditions of these simulations. Afterwards the infiltration of the carbon fabric by the semi-solid aluminium will be modelled to be able to predict the degree of infiltration.

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