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Combined Process of Ultrasonic Welding and Precipitation Hardening of Aluminium Alloy 2024/Carbon Fibre Reinforced Composites Structures

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The current demand for lightweight design leads to an increasing application of materials like aluminium, titanium, magnesium and fibre reinforced polymers and their combinations. However, efficient joining techniques are necessary to combine dissimilar material groups like metals and polymers in construction elements. Ultrasonic metal welding is one innovative method to realise sheet metal/carbon fibre reinforced polymer (CFRP)-joints. An important requirement for ultrasonic welding of these hybrid welds is a sufficient deformation capability of the light alloy. In contrast to traditional plastic joining techniques like induction welding or adhesive bonding, a direct contact to the load bearing C-fibres is possible by ultrasonic transverse waves without damaging the fibres. Until now only self-hardening aluminium alloys, primarily used in the automobile industry, were ultrasonically welded. A new idea to realise high-strength welds is to use precipitation hardening Al-Cu-Mg alloys for ultrasonic metal welding with CFRP. In this process at first the aluminium sheet is ultrasonically welded in the solution annealed condition to provide a sufficient deformation capability and to enable a direct contact between the load bearing fibres and the aluminium surface. After the ultrasonic welding process the precipitation hardening of the Al/CFRP-joint is performed. In contrast to non-precipitation hardened aluminium and Al-Mg alloys a significant increase of the tensile shear strength from 30 MPa to more than 40 MPa is possible by this procedure.

Keywords: *Ultrasonic Welding, Joining, Multi-Material-Design, Hybrid Joints, Precipitation Hardening, Al-Cu-Mg Alloys, AA2024, Composites, Carbon Fibre Reinforced Polymers (CFRP).*

1. Introduction and Motivation

Global markets lead to an increase of the volume of passenger traffic and transportation of cargo. Simultaneously the relevance of lightweight technologies increases by modified economical and ecological boundary conditions. Hence, the predominant aim of innovative products in the automotive and aircraft industry, but also in railway transportation and engineering in general, is the reduction of weight. The realisation of lightweight structures principles for the development of new products requires detailed knowledge of materials like aluminium or fibre reinforced polymers and their hybrids. For the fulfilment of these challenges appropriate joining techniques are necessary. At the Institute of Materials Science and Engineering (WKK) of the University of Kaiserslautern ultrasonic metal welding is one important research topic to realise innovative joints for lightweight structures.

The ultrasonic welding of similar materials e.g. copper wires for cable harnesses or plastics for packaging products is already established in industrial manufacturing [1]. At the WKK one research aim is to expand the application fields of ultrasonic metal welded joints out of dissimilar materials like glass or ceramics and metals [2].

In comparison to other joining techniques such as adhesive bonding, brazing or soldering ultrasonic welding is characterized by a low energy input and hence low temperatures in the welding zone as well as short welding times. For joining CFRP the ultrasonic plastic welding method is typically used [1], but this welding method only realises a joining between the polymer matrices of the CFRP. In this case the high-strength fibres of the CFRP are not used to transmit mechanical loads directly between the CFRP and the metal.

Recent investigations at WKK have shown that pure aluminium (e.g. AA1050) and also self-hardening Al alloys (e.g. AA5754) are well ultrasonically weldable with CFRP-sheets [3, 4]. These alloys are especially appropriate for automotive applications. To enlarge the application spectrum of ultrasonically welded hybrid joints it is necessary to increase the tensile shear strength simultaneously and to use aluminium alloys, which are common in the aircraft industry.

In this paper an innovative process to weld precipitation hardening aluminium alloys (AA2024) with CFRP sheets by ultrasonic welding is described. In the following the welding technology as well as selected monotonic properties of the realised hybrid joints are presented.

2. Ultrasonic Welding Technology

For joining AA2024 and CFRP with polyamide (PA66) matrix ultrasonic spot metal welding systems were used. One advantage of the ultrasonic metal welding system is the oscillation parallel to the surface of the joining partners. The relative movement between aluminium and CFRP sheets enable a direct contact between the metal surface and the load bearing fibres of the reinforced composite without damaging the fibres during the welding process. Scanning electron micrographs (SEM) of the welding zones have shown, that the ultrasonic metal welding process removes matrix material between the fibre reinforcement and the metal whereby the metallic surface gets into direct contact to the fibres [3, 4]. In comparison to ultrasonic plastic welding 60% higher tensile shear strength can be achieved. The operating mode of a spot welding system is described in figure 1.

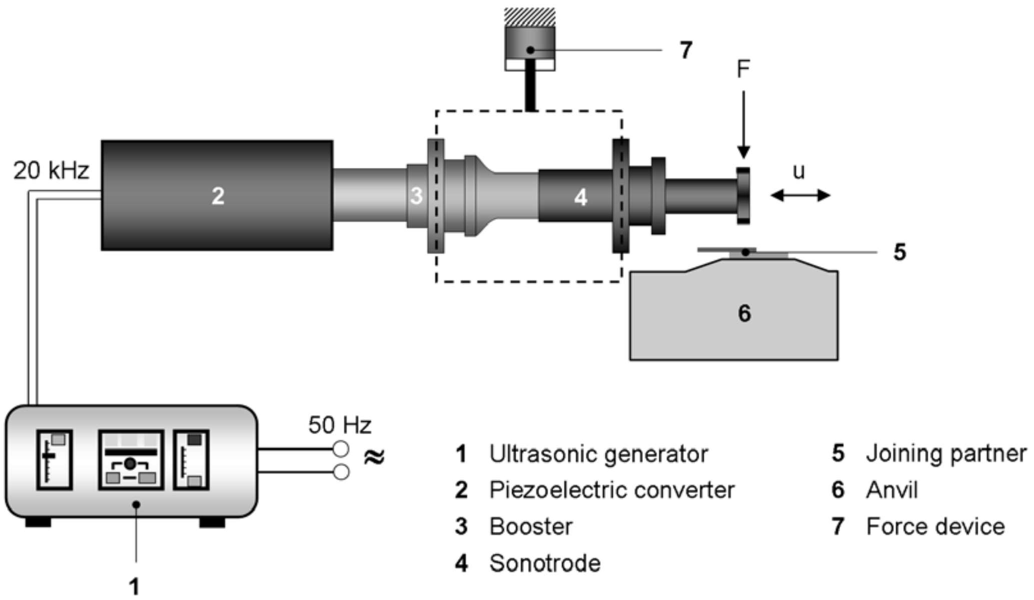

Fig. 1: Principle of ultrasonic metal welding

The main components of the welding system are an ultrasonic generator (1), a converter (2), a booster (3) and a welding tool, called sonotrode (4). The two materials (5) to be welded are pressed on an anvil (6) by the sonotrode with a static pressure perpendicular to the welding zone. This clamping force is one important process parameter. The ultrasonic generator converts the 50 Hz main voltage into a high frequency alternating voltage output of mostly 20 kHz. In the converter this oscillation is transformed into mechanical oscillations of the same frequency due to the inverse piezoelectric effect.

The necessary oscillation amplitude in the welding zone, the second important process parameter, is ensured by an appropriate design of the booster and the sonotrode. The amplitude typically ranges between 5 and 50 µm. Together with the third process parameter, the specific welding energy input, the welding process can be described completely. Moreover, there are several material parameters like surface microstructure or sheet thickness, which have an influence on the achievable mechanical properties of the joints [2-4].

3. Materials and Specimen Geometry

In the following selected results of welds between the investigated aluminium alloys and CFRP sheets are presented. For the aluminium sheet a thickness of 1 mm and for the CFRP 2 mm were chosen. The fibre reinforcement of CF-PA66 is a C-textile Satin 5H-fabric with a weight per unit area of 285 g/m². The fibre volume fraction of the 2 mm thick organic sheets is about 48 %. It was manufactured in an autoclave process by using six layers of CF-fabric. Selected mechanical properties of the investigated joining partners are summarized in table 1.

Table 1: Selected mechanical properties of the joining partners

	Young´s Modulus	0.2 % Yield Strength	Ultimate Tensile Strength	Ultimate Elongation	Martens Hardness
	E	$R_{p0.2}$	UTS	A	$HM_{0,05/10/5}$
	[GPa]	[MPa]	[MPa]	[%]	[MPa]
AA1050 H14	69	93	100	7.2	490
AA5754 H22	70	177	250	13.5	883
AA2024 T3	70	285	410	18.5	1496
CF-PA66	55	/	580	1.1	

The specimen geometry is shown in Figure 2a). The welding area of the sonotrode is 10 x 10 mm². Since it is not possible to determine the exact geometry of the joining area the tensile shear strength is calculated by the ratio of the achieved tensile shear force related to the sonotrode contact area. Besides a high reproducible clamping of the specimens on the anvil, it is necessary to control the welding force during the joining process precisely by an integrated force measuring device. Therefore a special clamping was developed at the WKK, see Figure 2b).

a) b)

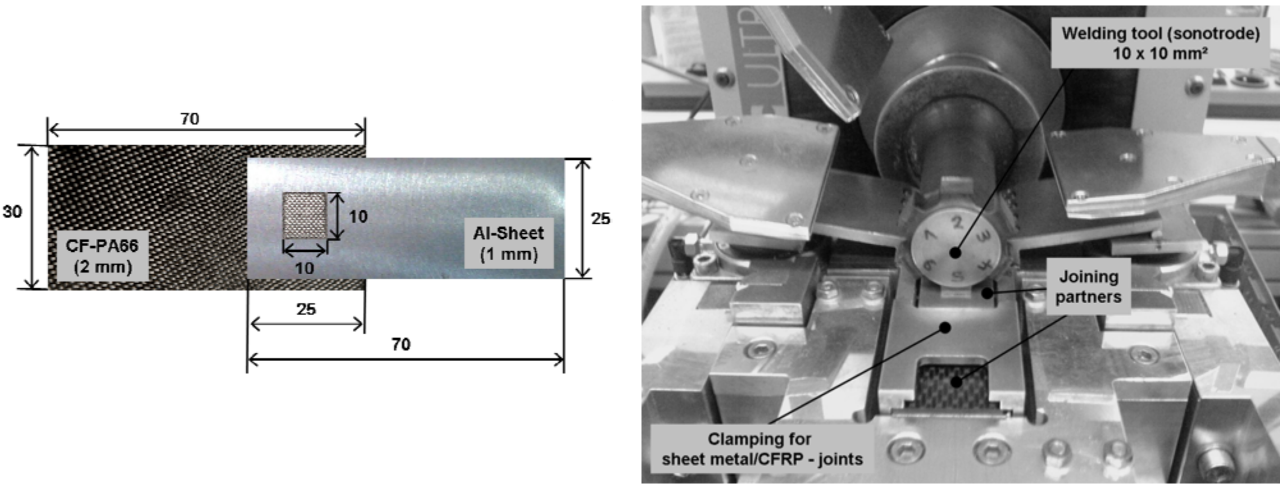

Fig. 2: a) Specimen geometry, b) ultrasonic spot welding system for hybrid joints

The statistical method named "central composite design circumscribed (CCC)" was used to investigate the weldability of the Al/CFRP-joints [3, 4]. In comparison to a stepwise variation of each welding parameter, this method for non-linear relationships allows to find the optimal parameters with considerably less welds. An important advantage of the CCC-model is the description of the mutual dependence of the three central welding parameters oscillation amplitude, welding force and energy in relation to the achievable tensile shear strength of the joints. The orthogonal structure of the statistical test plan guarantees a clear benchmark of the different parameters [5]. The design of the CCC-model is based on the three significant process parameters mentioned above with five different settings for each. The suitable ranges of the process parameters, which allow high strength joints, were estimated in preliminary investigations. This design of experiments reduced the number of welding tests by approximately a factor of 7 in comparison to a conventional procedure. At the same time the reproducibility of the joint strength was clearly improved [4]. Suitable combinations of the welding parameters were verified in tensile shear tests. For each parameter combination at least twelve welds were performed.

4. Combined annealing and welding of Al/CFRP-joints

The purpose of using a precipitation hardening aluminium alloy is to achieve a much higher joint strength than for self-hardening Al alloys like AA1050 and AA5754. But for joining Al sheets like AA2024 with CFRP by ultrasonic welding a sufficient deformation capability is necessary. For this reason an adapted coupled welding process has been developed. In a first step the AA2024 sheet was solution annealed at 500°C for 30 minutes. After water quenching, the ductile aluminium sheet was directly ultrasonically spot welded to the CFRP within 15 minutes, see figure 3. This fast process is necessary because of the rapid hardening of Al-Cu-Mg alloys [6].

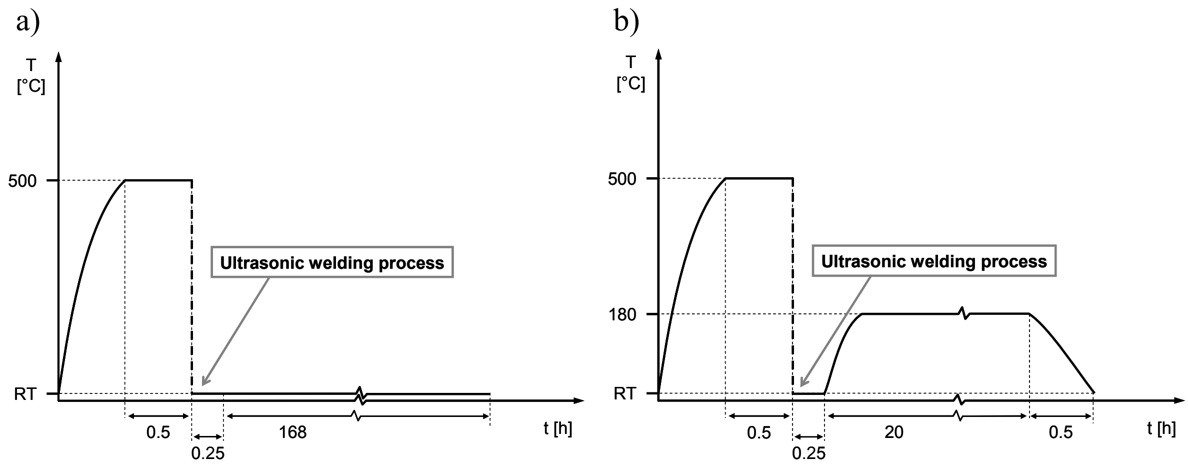

Fig. 3: Precipitation hardening of hybrid joints after ultrasonic welding
a) solution annealing, ultrasonic welding and natural ageing
b) solution annealing, ultrasonic welding and artificial ageing

After the welding process two further process steps were carried out. On the one hand a natural ageing of the welded hybrid joints was realised for 7 days under defined conditions (T =23°C, humidity = 50%), see figure 3a. On the other hand the ultrasonic welded joints were artificial aged for 20 hours at 180°C and finally air-quenched. After the ageing processes both AA2024/CFRP-joints types were proved in tensile shear tests and compared.

5. Monotonic properties of precipitation hardened hybrid joints

The results of the tensile shear tests for the three different Al alloys ultrasonically welded with CF-PA66 sheets are shown in figure 4. All mentioned hybrid joints were optimised with the

CCC-statistical test method. For each Al/CFRP-combination the best suitable process parameters (oscillation amplitude u, welding force F_{US} and welding energy W_{US}) are listed in figure 4.

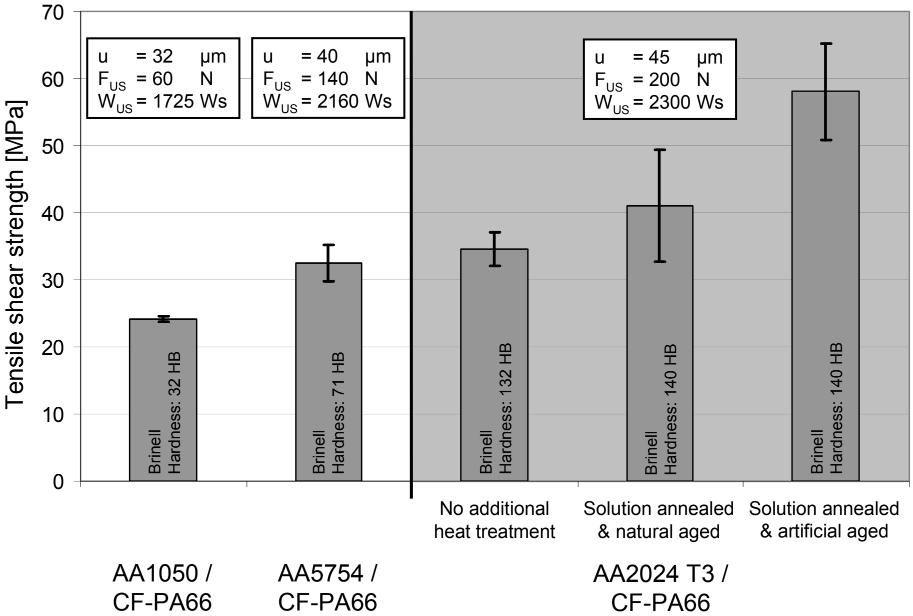

Fig. 4: Achievable tensile shear strength for different hybrid Al/CFRP-joints

For AA1050/CF-PA66-joints the appropriate parameters lead to tensile shear forces up to 2460 N corresponding to a tensile shear strength of 25 MPa [3]. By using AA5754 the tensile shear strength can be improved up to 32 MPa in average [4]. A similar strength was obtained for AA2024/CF-PA66-joints without additional heat treatment before and after ultrasonic welding. The highest tensile shear strengths were realised for solution annealed, ultrasonic welded and aged joints although the Brinell hardness is almost identical with about 132-140 HB. It has to be mentioned that in contrast to natural ageing, artificial ageing leads to a significant increase of the monotonic strength of more than 40% and more than 65% compared with the “no additionally heat-treated AA2024” version. The maximum improvement of the strength was realized with the process chain: ultrasonic welding after solution annealing followed by ageing. After annealing the AA2024 sheets have a Brinell hardness of only 93 HB combined with a high deformation capability. Both together lead to an improved ultrasonic weldability. Figure 5 shows three characteristic force-displacement- curves welded with the parameters listed in figure 4.

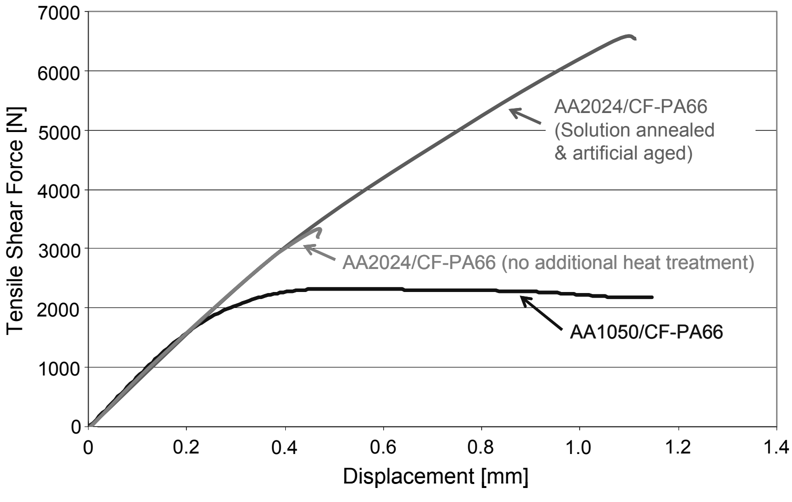

Fig. 5: Force-displacement-curves for ultrasonically welded hybrid joints with different metallic joining partners

For AA1050/CF-PA66-joints the ultimate tensile strength of the aluminium sheet limits the achievable strength of the joints [3]. In contrast to this behaviour for AA2024/CF-PA66 joints with and without additional heat treatment fracture occurs in the joining zone between aluminium and CFRP sheet.

6. Summary

The ultrasonic metal welding technique was successfully applied to join precipitation hardening Al alloys with CFRP. Therefore a new manufacturing process to realise high-strength welds was developed. After the solution annealing the AA2024 sheets were ultrasonically welded within 15 minutes after water quenching. Afterwards the welded hybrid joints were natural and artificial aged. By using this innovative procedure the average tensile shear strength was increased of more than 65% up to 58 MPa in contrast to AA2024/CFRP-joints without heat treatment. The possibility to join different aluminium alloys to CFRP with high strength extends the application fields for the ultrasonic metal welding technique. Regarding the efficiency, automation, ecological compatibility and the achievable mechanical and technological properties ultrasonic metal welding is an attractive alternative to existing polymer joining techniques. Application fields for ultrasonically welded hybrid joints can be seen in the automotive industry, e.g. to join different lightweight structures by using fibre reinforced materials or in the aircraft industry for construction elements of the fuselage, the aerofoil or the tail fin.
A further increase of the strength can be expected by using additional surface pre-treatments of the aluminium. Similar results are known for mechanical and chemical pre-treatment of self-hardening aluminium alloys but not yet for precipitation-hardening alloys [7].

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