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Fatigue behaviour of material-adapted fibre-reinforced polymer/metal joints

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Keywords

Fatigue, Flow Drill Joining Concept (FDJ), Joining Technology, Joint, Multi Material Design

Abstract

By regarding the needs and requirements in modern multi-material joining, the Flow Drill Joining Concept (FDJ) was developed at the Chemnitz University of Technology. The technology allows an efficient and material-adapted joining of thin metal sheets with continuous fibre-reinforced thermoplastics, as required in modern lightweight engineering. For a better understanding of their fatigue behaviour, single-lap FDJ joints were examined in quasi-static and dynamic tests regarding shear loads, cross tension and superimposed shear/cross tension loads. By way of example, joints between micro-alloyed steel with high yield strength for cold forming and a continuous glass/carbon fibre-reinforced polyamide 6 were investigated. The fatigue curves show inclinations between $k = 8.01$ (shear loads) and $k = 5.17$ (cross tension loads), depending on the applied load angle. The results of the fatigue testings represent a basis for the enhancement of a failure criterion for FRP/metal joints in highly stressed multi-material designs.

1 Introduction

In many industry sectors, there is a growing interest in the large-scale integration of fibre-reinforced plastics (FRP) into complex multi-material structures [1]. Cause for this trend is the possibility of resource and cost-efficient weight savings, which can be reached by a targeted use of the anisotropic lightweight materials. In this regard, the combination of continuous fibre-reinforced thermoplastics with metallic thin sheets has a particularly high potential.

Due to the lack of alternatives, the production of such FRP/metal-structures is currently predominantly based on established joining methods, such as bonding or screws, rivets and bolts, known from metallic construction [2–3]. However, this procedure is associated with a poor exhaustion of the material's lightweight potential and high demands on the surface condition. Problems emerge, for example, through:

- the reduction of load-bearing fibres due to drilled holes
- delaminations and fibre damages, induced by machining or joining elements with cutting edges
- failure-critical stress concentrations in the joining area due to the anisotropy of the composite
- additional weights due to joining elements and reinforcements of the joining zone, e.g. inserts and moulded tubes
- cost-intensive pre-treatments, such as surface preparation or drilling
- polymer-creep and relaxation phenomena in force-fitted joints

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By regarding the aforementioned needs and requirements in multi-material-joining, the Flow Drill Joining Concept (FDJ) was developed at the Institute of Lightweight Structures, located at Chemnitz University of Technology [4]. The technology allows the material-adapted manufacturing of high-strength FRP/metal-joints without auxiliary joining elements. In addition to the qualification of the joining process by parameter studies and the analysis of the mechanical joining properties, the development of a suitable design strategy is currently being investigated at the Institute of Lightweight Structures [5–6]. For the development of an engineering failure criterion, which takes into account the effects of cyclic loading on FDJ joints, the following investigations on their fatigue behaviour were carried out.

2 Flow Drill Joining Concept

2.1 Description

The automated FDJ joining process can be described by the three main steps:

1. Plasticising of the thermoplastic matrix
2. Forming of a metallic bushing with a flow drill
3. Forming of a closing head to realise a form lock between FRP and metal sheet

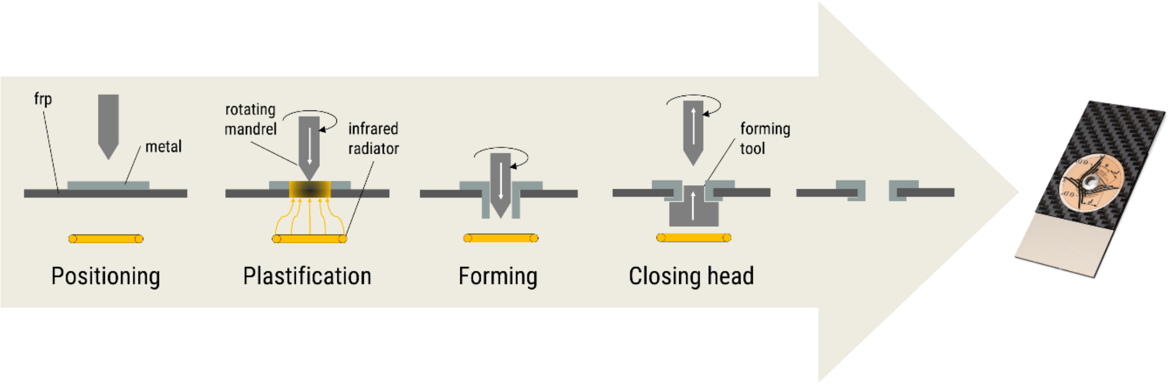


Figure 1: Process sequence of the Flow Drill Joining Concept

A rotating mandrel is first applied to the upper side of the metallic sheet and then forms the required bushing throughout the plasticised FRP, in two phases. The first phase, with a comparably low feed rate, serves the heat influx to increase the plasticity of the metal sheet. The second phase completes the forming process, with a higher feed rate. By forming the bushing through the previously plasticised FRP, the contained reinforcing fibres are redirected tangentially and unharmed around the punctiform joint. The sectioning of the feed rate allows a defined energy input into the metallic part, to guarantee a high quality of the bushing for every material. In a final step, the bushing is folded by a forming tool to obtain traction and form a lock between the two basic materials. As a result of the process-induced fibre realignment and the displacement of the thermoplastic matrix, a local accumulation of material occurs in the fringe of the joining area. Accordingly, FDJ joints contain, in contrast to established technologies, a process-related reinforcement in the critical areas next to the joint [7]. Further investigations and findings on the FDJ joining concept are described in [8–10].

3 Materials, parameters and methods

3.1 Materials

HX420LAD+Z100

According to DIN EN 10346 [11] and DIN EN ISO 10027-1 [12], HX420LAD (material no. 1.0935) is a micro-alloyed steel with high yield strength (HSLA) for cold metal forming. The appendix +Z100 points to a surface refinement by hot-dip galvanising with a minimum coating mass of 100 g/m² (both sides) and a typical coating thickness of 7 µm (per side) [11]. The material is primarily used in the production of structural, chassis and reinforcing parts.

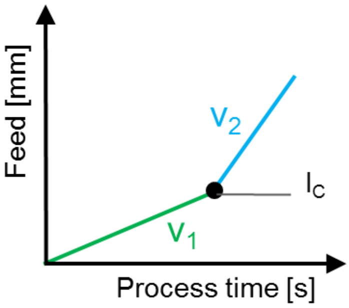
Continuous fibre-reinforced Polyamide 6

The thermoplastic FRP was made of unidirectional prepreg tapes (Celstran® CFR-TP PA6 GF60 and CF60), stacked and formed to a symmetric $[(0/90)^C/(0/90)^G]_s$-composite with a thickness of 1.7 mm and a fibre volume content of approx. 44 %. Comparable laminates are suitable for CDP-treatment [13] and will be used in industrial, automotive, and sporting goods applications with demand for high strength and toughness in future.

3.2 Process parameters

The process parameters of the FDJ joints used in this study are summarised in Table 1. To introduce a precise heat input into the metal sheet and thus obtain a high quality of the metallic bushing, the forming process is carried out with two feed rates (v_1 and v_2) that are changed at a defined changeover point (l_c). The diameter of the joint (d_p) requires a melting area (d_m) of 26 mm due to the permissible elongation of the material-inherent carbon fibres. In case of a smaller melting area, the maximum yieldable fibre elongation would be exceeded, which would lead to fibre breakage and thus to material damage [7,14].

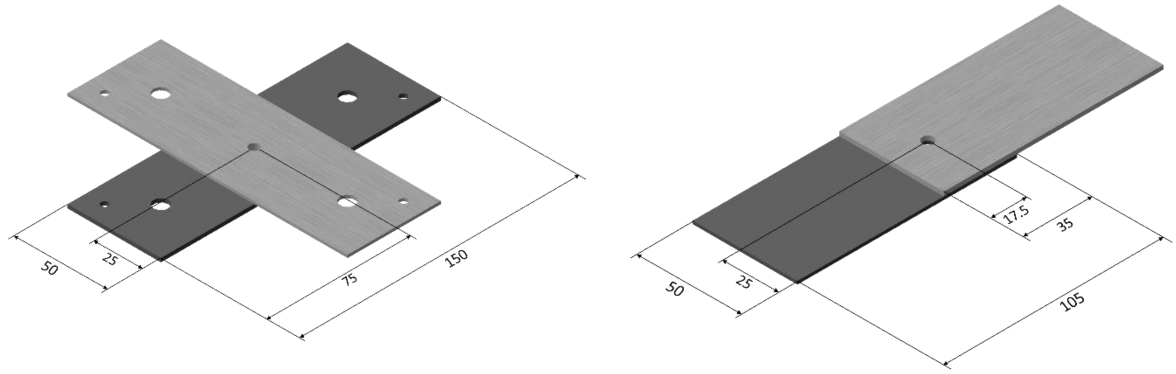
Table 1: Process parameters of the FDJ joints in this study

Parameter	Value	Unit	Visualisation
Diameter of the joint d_p	5.3	mm	
Diameter of the melting area d_m	26	mm	
Rotational speed n	3000	U/min	
Feed rate 1 v_1	300	mm/min	
Feed rate 2 v_2	1300	mm/min	
Change-over point l_C	1.0	mm	
Forming force F_U	18	kN	

3.3 Methods

3.3.1 Specimens and test device

The assessment of punctiform joints is mainly based on test specifications for the analysis of resistance spot welds, in particular on shear tensile tests according to DIN EN ISO 14273 [15] and cross tensile tests according to DIN EN ISO 14272 [16]. For a more detailed description, the resistance of FDJ joints against superimposed shear and cross tension loads were examined, too [17]. The associated sample shapes are shown in Figure 2 and were derived from the standards mentioned above.



Cross tension & superimposed loads
DIN EN ISO 14272

Shear tension
DIN EN ISO 14273

Figure 2: Specimens according to DIN EN ISO 14272 and 14273

The cross tension and superimposed shear/cross tension tests were carried out with a particular test device, as shown in Figure 3. The mount enabled the testing with load angles of 30, 45, 60 and 90 degrees.

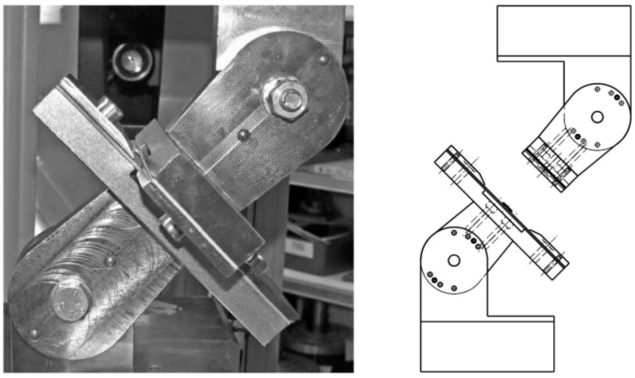


Figure 3: Test device for cross tension and superimposed shear/cross tension loads

3.3.2 Static tensile tests

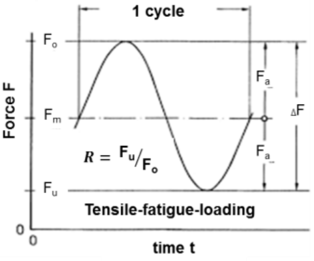
All tests were performed on a Zwick/Roell Z010 TN ProLine according to DIN 51220 [18], with force measurement electronics according to DIN EN ISO 7500-1 [19]. The room climate was at 23 °C with 38 % relative humidity. The specimens were pneumatically clamped with a preload of 30 N and conditioned beforehand following DIN EN ISO 1110 [20]. The applied load was measured by the use of a 10 kN load cell with a test speed of 2 mm/min. Each test series contained five samples.

3.3.3 Dynamic tensile tests

The dynamic tensile tests were carried out on a servo-hydraulic Instron 8501 fatigue test machine with a 10 kN load cell using the pearl string method according to DIN 50100 [21]. Based on the results of the quasi-static tests, the load levels were gradually reduced until one specimen reached more than 10^6 cycles. Because the test requires only one specimen per load level, Woehler curves can be determined with comparatively little effort. Concerning the generally high dispersion of fatigue tests, the statistical significance of the method is rather low. Nevertheless, it has a high relevance and offers the possibility of an investigation of the fatigue strength with the aid of a small number of samples [21–23].

The test parameters are shown in table 2. As mentioned in [24], the fatigue behaviour of polymers is strongly influenced by the test frequency due to their viscoelastic behaviour. Due to inner polymer damping, high test frequencies lead to thermal-induced fatigue. As a result, the test frequency was chosen relatively low to avoid a significant impact of sample heating.

Table 2: Testing parameters for the dynamic tensile tests

Parameter	Value	Visualisation
Load profile	sinusoidal	
Load ratio	R = 0.1 (tensile fatigue loading)	
Test frequency	F = 5-10 Hz (to keep sample heating < 2 °C)	
Test method	pearl string method	
Abort criterion	sample failure	

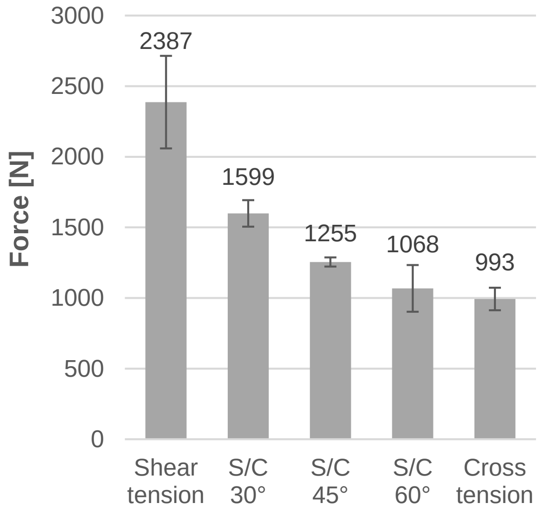
3.3.4 Statistical evaluation

The chosen evaluation of the fatigue strength tests is based on the Basquin equation [25]. Test results << 10^4, as well as > 10^6 cycles, were not taken into account for the calculation. The regression of the Woehler curve was performed by the "method of ordinary least squares" in the range of 10^4 to 10^6 oscillation cycles. The survival probability for the 10 % and 90 % quantiles of the normal distribution was calculated by normalisation of the results and imposed on the Woehler curve as a parallel scatter band [25]. Since the variation of fatigue strength tests typically increases with lower forces, this method can only be regarded as an approximation [26].

4 Results

4.1 Static tensile tests

Shear tensile loads represent the preferred load case for FDJ joints, as this is standard for punctiform joints. This can also be seen in the experimentally determined results, where the maximum bearable shear tensile force of the investigated material pairing is 2387 N on average (Figure 4). Pure shear tensile loads lead to polymer-sided bearing stresses and a partial deformation of the metallic bushing, whereby the formed hole expands and thus allows the metallic sleeve to slide out of the joint.



Materials	
Material 1	HX420LAD+Z100 1.5 mm
Material 2	Celstran CFR-TP PA6 GF/CF60 1.7 mm / $[(0/90)^C/(0/90)^G]_s$
Joining concept	
Flow Drill Joining	
$Ø_{FDJ}$ = 5.3 mm / n = 3000 U/min / v_1 = 300 mm/min / v_2 = 1300 mm/min / l_U = 1.0 mm	
Test method, standards and machine	
DIN EN ISO 14272 / 14273 (static, n = 5) Zwick/Roell Z010 TN ProLine	

Figure 4: Results of the static tensile tests

In comparison, cross tension loads represent a more critical load case. At 993 N, the maximum cross tension forces lie considerably lower than the maximum forces bearable in the shear tensile tests. The joint failure is initiated by the yield of the metal sleeve whereby the required undercut of the joint is eliminated. On the other hand, the fibre-reinforced polymer does not suffer any macroscopically detectable damage. In contrast to shear tensile stress, failures due to cross tension loads occur abruptly and should therefore be avoided as far as possible in application cases by suitable design measures. The results of the superimposed shear and cross tensile tests show that even a small amount of cross tension loads has a huge influence on the bearable forces. However, with a further increase in the load angle, the decrease in the joint strength weakens considerably.

4.2 Dynamic tensile tests

As expected, the dynamic experiments confirm the tendencies already discernible in the static experiments. FDJ joints subjected to shear tensile loads show the highest resistance to vibrating loads with a k-factor of 8.01. The fatigue rate rises significantly when (shares of) cross tension loads are applied (Figure 5).

Material 1	Material 2	Joining concept	Methods and standards	Test parameters	Test machine
HX420LAD+Z100 (1.5 mm)	CFR-TP PA6 GF/CF60 $[(0/90)^{C}/(0/90)^{G}]_{s}$	Flow Drill Joining	DIN EN ISO 14272 / 14273	R = 0,1 f = 5 Hz	Instron 8501

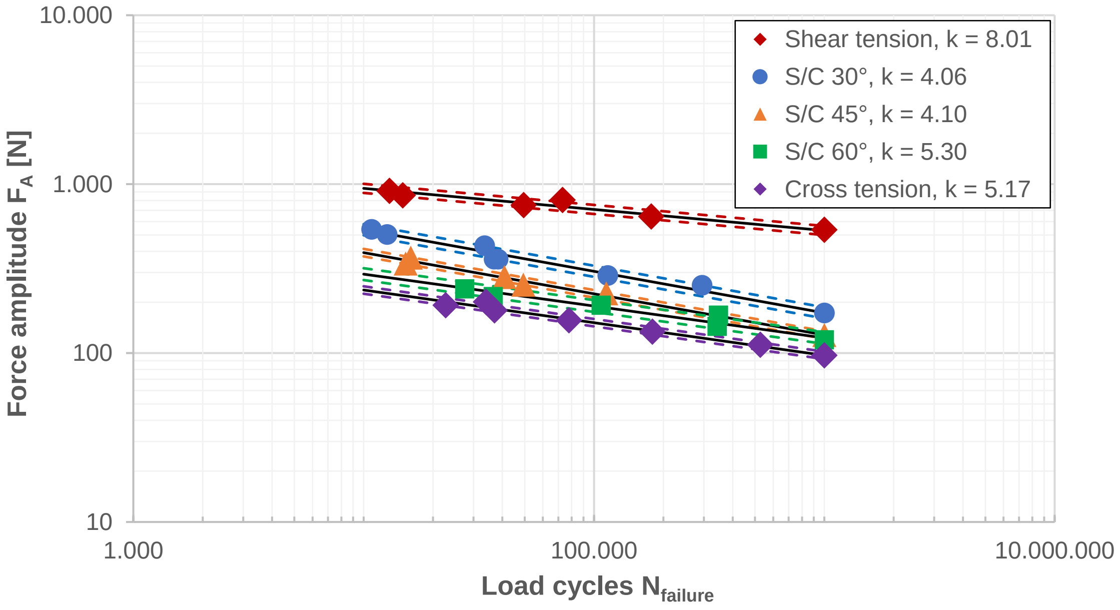


Figure 5: Results of the dynamic tensile tests (Woehler diagram)

5 Discussion and outlook

The characteristic values determined in the static and dynamic tests allow the derivation of dimensioning principles for FDJ joints. In general, as for all punctiform joining techniques, the following principle applies to thermomechanical forming as well: cross tensile loads should be avoided by design matters to achieve optimum utilisation of the joint potential. In quantitative terms, this is reflected in the significantly lower bearable tensile forces of 993 N and a higher fatigue rate (k = 5.17) for cross tensile loads, compared with 2387 N (k = 8.01) for shear tensile loads. In addition, it could be shown that even a small percentage of cross tension loads has a huge influence on the reduction of the tolerable tensile forces under both static and dynamic loads, which requires a correspondingly consistent design of the joining area.

At first glance, the macroscopic failure profile of the joints shows no apparent difference between static and dynamic loads. Pure shear tensile loads lead to a polymer-side failure due to bearing stresses, whereas the failure of cross tension loaded FDJ joints is due to a metal-side deformation of the bushing (Figure 6). Superimposed loads show a mixture of the failure profile depending on the load ratio. However, a different picture seems to emerge at higher load cycles (> $5 \cdot 10^5$). The available test results show that, in addition to the hole embrasure in the fibre reinforced polymer, shear tensile specimens also show a failure of the metallic sleeve due to tearing. Since the number of samples in this area is low, further investigations must be carried out in this respect.

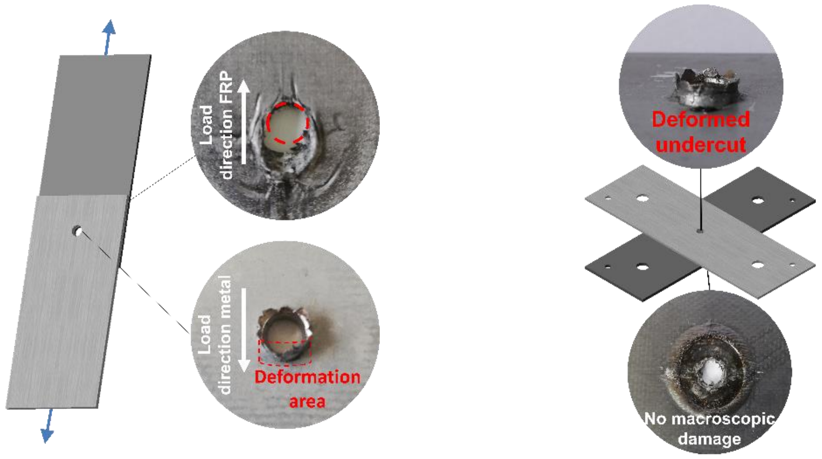


Figure 6: Macroscopic failure profile of tested FDJ joints due to shear (l) and cross tension (r) loads

The overall findings of this study can be used to extend a section-force related failure criterion for punctiform FRP/metal-joints, as described in [5–6]. For this purpose, however, further investigations must be carried out with regard to dynamic torsional tensile and peel loads, which complement the previous studies to enable a complete representation of the three-dimensional failure space of the joints. In a further step, the influence of corrosion on the fatigue behaviour of FDJ joints is to be determined and subsequently implemented into the failure equation [6].

Acknowledgements

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