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Original scientific paper*

TENSILE-SHEAR TESTING OF RESISTANCE ELEMENT WELDED JOINT OF CARBON FIBER-REINFORCED POLYMER AND DP500 STEEL

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Abstract. *The aim of the research presented in this paper is to analyze the possibility of joining Carbon Fiber-Reinforced Polymer (CFRP) and DP500 steel using novel joining technology called resistance element welding (REW). These two materials are representatives of the multi-material structure, and in this research 1.0 mm thick CFRP and 1.5 mm thick DP500 steel were used. A S355JR steel rivet was used as the auxiliary element. The specimens were assembled with an overlap distance of 35 mm. The REW joining procedure began by drilling a hole in the CFRP and inserting the 4 mm diameter steel element (S355JR) in the CFRP, after which classical resistance spot welding (RSW) was performed. The tensile-shear tests were done on a Beta 50-7 / 6×14 testing machine at a cross head speed of 2 mm/min. Macrostructural analysis was conducted by using a Keyence VHX-6000 microscope. The results presented in this paper show that resistance element welding can be used for joining CFRP and DP steel.*

Key words: *Resistance element welding, Dissimilar materials joints, CFRP, DP steel.*

1. . INTRODUCTION

Currently, there are three main trends in automotive lightweight construction: the use of high-strength metal alloys, substituting metals by composites, and the combination of dissimilar materials in one structure (multi-material design) [1]. Steel DP500 is advanced-high-strength-steel (AHSS) composed of a ferrite matrix with martensite as a second phase [2]. This material possesses good formability and weldability and is suitable for car-safety components such as reinforcements, which is very attractive in order to reduce the weight of automobiles [3]. Replacing conventional carbon steels with AHSS steels such as DP500 resulted in a 15-20% reduction in car weight [4]. Substituting conventional steel with CFRP leads to a significant weight saving of vehicles, around 60% [5]. Complete replacement of

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steel with CFRP is not possible primarily due to high prices, so there is a compromise in the application, in the form of a combination of these two materials in one structure, which gives a multi-material structure.

The combination of steel and CFRP in one structure is very promising for application in the automotive and aerospace industry, but the joining of these two materials is a big problem, which is why it has been the subject of interest of many researchers lately. There are different joining technologies that can be used for joining CFRP and steel such as adhesive joining [6, 7], mechanical joining [8], laser joining [9, 10] and resistance spot welding (RSW) [11, 12]. Y. Lim et al. [13] researched the joining of carbon fiber composites and DP980 using FBJ (friction bit joining), adhesive bonding and weld bonding. Average lap shear failure peak loads were found to be 6.0, 14.8, and 13.3 kN for FBJ, adhesive-bonded, and weld-bonded specimens, respectively. The obtained lap shear failure load for each joining process was higher than or comparable to the joint strengths found in the open literature.

RSW is one of the most used joining technologies in the automotive industry but joining steel and CFRP is very difficult, primarily in the view of the fact that CFRP is not conductive and RSW technology is based on conductive materials. As explained in the two studies by N. Kimiaki et al. [11, 12], RSW joining of steel and CFRP can be done by the current that flows solely in the metal side and since the metal is heated near the electrode by resistance heating, joining can be performed by the CFRP being melted by thermal conduction and then solidified.

This study will analyze the possibility of joining Carbon Fiber-Reinforced Polymer (CFRP) and DP500 steel using a novel jointing technology called resistance element welding (REW) as an alternative to RSW. REW is a process that begins with the insertion of the steel element into a lightweight material, in this case CFRP. After the element is inserted into CFRP, the procedure of classic resistance spot welding follows. Fig. 1 shows the procedure of REW joining.

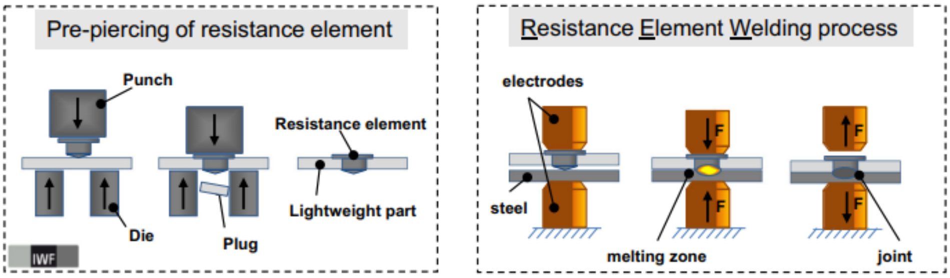

Fig. 1 The procedure of resistance element welding [14]

The published studies about the REW joining technology are mainly focused on joining steel/aluminum alloys [15-19] and steel/magnesium alloys [20, 21] and their comparison with other technologies. The REW joining technology is also very suitable for combining with adhesives [22, 23]. J. Troschitz et al. [24] analyzed the possibility of welding 2 mm thick thermoplastic composites (TPC) and a 1.5 mm thick HC340LA steel sheet . They conclude that TPC components can be welded to steel sheets by using resistance element welding. The steel element can be embedded in TPC during compression molding with high quality and without fiber damage. The ultimate shear load of the welded joints was 3.7 kN on average with a maximum displacement of 13 mm to 15 mm. This paper will also present the tensile-shear testing and macrostructure analysis of a REW joint of CFRP and DP500 steel.

2. EXPERIMENT SETUP

As representatives of multi-material structure, for this research 1.0 mm thick Carbon Fiber-Reinforced Polymer and 1.5 mm thick DP500 steel were used. A S355JR steel rivet was used as the auxiliary element. The chemical compositions and basic mechanical properties of DP500 and S355JR steel are shown in Table 1.

Carbon Fiber-Reinforced Polymer was manufactured from heat-treated prepreg (factory impregnated material). The thickness of 1.0 mm is constructed in two directions (fiber position 0° / 90°).

Table 1 The chemical compositions and basic mechanical properties of DP500 and S355JR steel

Material	Chemical composition (%)									
	C	Cr	Si	Mn	P	Fe	S	N	Al	Cu
DP 500	0.1	/	0.5	1	0.025	Bal.	0.01	/	0.015	/
S355JR	0.24	/	0.55	1.6	0.04	Bal.	0.04	0.012	/	0.4
	Mechanical properties									
	Yield strength $R_{p0,2}$ (MPa)			Tensile strength R_m (MPa)			Elongation A_{80} (min %)			
DP 500	330			550			20			
S355JR	355			550			22			

The specimens for tensile-shear testing were 30 × 100 mm with an overlap of 35 mm (Fig. 2a). Fig. 2b shows the test specimens after welding prepared for testing.

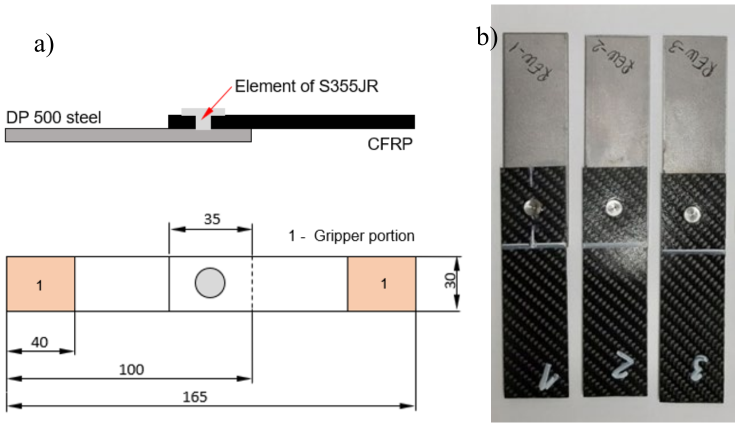

Fig. 2 a) Dimensions of specimens; b) Specimens after welding prepared for testing

The REW joining procedure began by drilling a hole in CFRP and inserting a 4 mm diameter steel element (S355JR) in it (Fig. 3). Dimensions of the steel element are shown in Fig. 4a. After inserting the steel element into CFRP, classical resistance spot welding (RSW) was done using the RSW machine manufactured by Kocevar & sinovi, which is managed by using the BOSH 6000 software. Welding was carried out using a type F1 electrode with parameters: welding current I=5 kA, electrode force F=3.68 kN, and welding time T=80 ms. Welding parameters were chosen after a set of experiments that involved hand tensile-shear tests and visual testing of joints. Dimensions of the F1electrode are shown in Fig. 4b. Before welding, alcohol was used to clean the steel site of specimens.

Fig. 3 Inserting a steel element in CFRP

a) b)

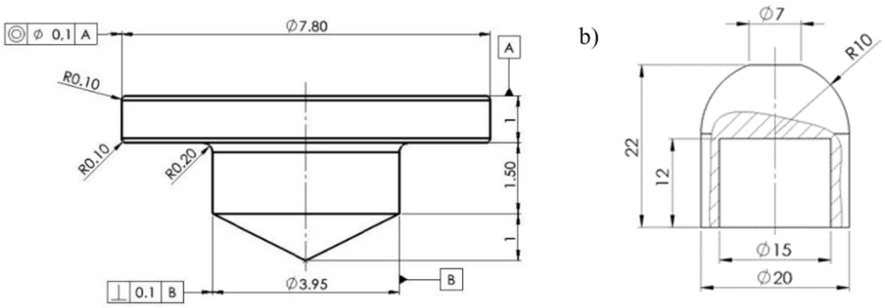

Fig. 4 a) Dimensions of the steel element; b) Dimensions of the F1electrode

The tensile-shear tests were done on a Beta 50-7 / 6×14 testing machine at a cross head speed of 2 mm/min. The failure energy was calculated by measuring the area under the load-displacement curve up to the maximum load point. Metallographic samples were cut from the center of the joints. The samples were ground and polished based on standard metallography procedures and were etched using 4% nital solution (for 5 seconds). Macrostructural analysis was done by using a Keyence VHX-6000 microscope.

3. Results and discussion

Fig. 5 shows the typical force-displacement curve for the REW joint of DP500 steel and CFRP. The maximum failure load for the REW joint was 2411.5 N with the displacement of 0.73 mm and the failure energy of 1.2 J. A comparison of the obtained results with the results presented in the available studies is shown in Table 2. The maximum failure load presented in study [24] is slightly higher than the maximum failure load obtained in this study, but the material thicknesses selected for this study are significantly less than the material thicknesses of the presented study. However, the REW joint of steel/aluminum alloys or steel/magnesium alloys has significantly better mechanical characteristics than the REW joint of steel/CFRP.

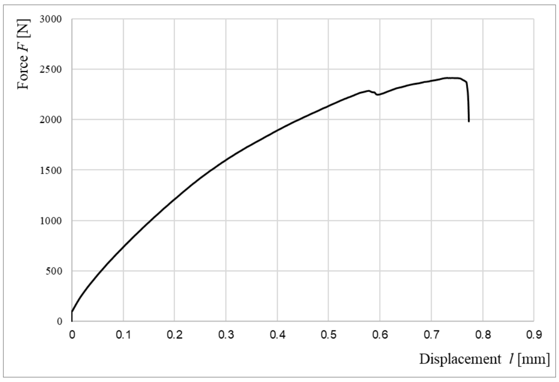

Fig. 5 Force-displacement curve for the REW joint of DP500 steel and CFRP

Table 2 The comparison of the tensile-shear mechanical characteristics of REW joints

Refer.	Materials	The maximum failure load F_{max} [kN]	Displacement at the maximum failure load l_{max} [mm]	Failure energy E_{max} [J]
This study	DP500 steel (1,5 mm) / CFRP (1 mm)	2,41	0,73	1,2
[24]	HC340LA steel (1,5 mm) / CFR-TP PP-GF70 (2 mm)	3,7	≈1,5	-
[15]	22MnMoB steel (1,8 mm) / AA 6061-T6 (2 mm)	7,08	-	11,38
[21]	AISI 316L steel (0,7 mm) / AZ31 Mg alloy (1,5 mm)	3,71		10,19

The failure mode during the tensile-shear test is also an important parameter of joint quality. The joint obtained by resistance element welding failed through the weld in the interfacial mode (IF) due to the very small weld area (Fig. 6). This explains the very low failure load of this joint.

The macrostructure of the REW joint is shown in Fig. 7. One can notice that the weld has numerous shortcomings. Numerous air inclusions are visible on the element side of the nugget. Near the nugget, between CFRP and DP, the metal splash is also visible. The larger part of the nugget is in the S235JR steel element. This formation of the asymmetrical nuggets can be attributed to the differences in electrical resistivity and thermal conductivity. This macrostructure explains the small failure load of the joint as well as the fracture in the IF (interfacial) mode.

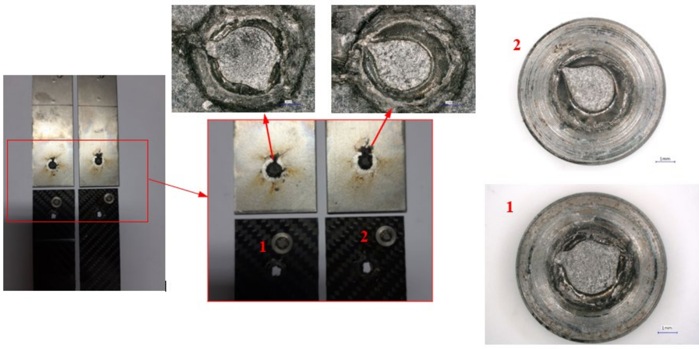

Fig. 6 Failure modes and fractography of the REW joint of DP500 steel and CFRP

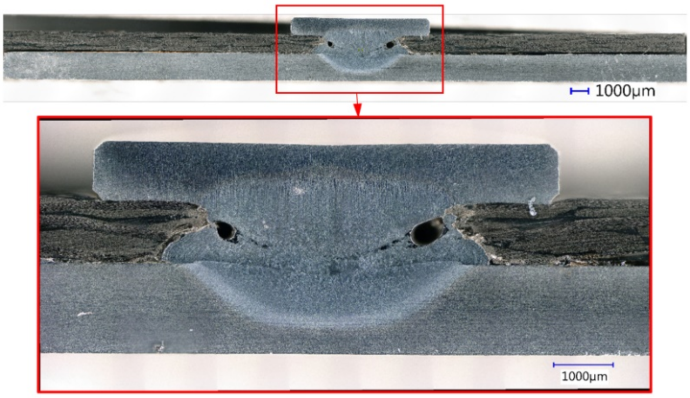

Fig. 7 The macrostructure of the REW joint of DP500 steel and CFRP

4. Conclusion

This research has presented the possibility of joining Carbon Fiber-Reinforced Polymer (CFRP) and DP500 steel using resistance element welding. After the research, the following conclusions were reached:

1. DP Steel and CFRP can be joined by resistance element welding with the maximum failure load of 2411.5 N and the failure energy of 1.2 J, but the joint failed through the weld in the interfacial mode (IF).
2. Compared to the RSW joint of steel and light metal alloys such as aluminum and magnesium alloys, the REW joint with CFRP has significantly poorer mechanical properties.
3. The analysis of the macrostructure of the REW joint showed that during welding air inclusions and metal splash occur, which affects the load capacity of the joint, so the focus of further research should be on finding the optimal geometry of elements and welding parameters to remedy these shortcomings.

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