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Abrasive Waterjet texturing as a method to enhance the embedment of metallic inserts in composite materials

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Abstract

This research work arises from the need of embedding metals in composite materials to improve mechanical performance of adapted metal inserts for the union of rotor blades by improving the inertia, while strengthening and decreasing the total weight of the structure. The resin union itself or with adhesives is not enough to achieve the high requirements demanded by industries like boat industry, civil engineering, aerospace industry or wind sector, where high loads are commonly employed.

This work proposes an innovative method to assure a rigid and secure embedment of the metallic insert, thus, avoiding problems related to the decoupling of the metal-composite interface. This method consists on generating a "mechanical restraint" by texturing the metallic surface by abrasive waterjet (AWJ) technology, which has demonstrated to be a flexible method to generate different textures in metallic surfaces. This paper presents the experimental work done in steel and fiberglass/epoxy laminate.

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Keywords: waterjet, texturing, inserts, composites, bonding

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1. Introduction

The use of light and strong composite materials has grown drastically in structural components, where high weight to strength ratio is demanded. Anyway, the use of composite materials involves many technical challenges, related to the processes for bonding metals to composites and to the reinforcement of these joints for producing structures with high structural integrity.

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Structural joints between composites and metallic parts are commonly carried out by chemical means (adhesives) and by placing fastening elements in the form of bushings. Examples of these kinds of mechanical joints can be found in aircraft [1] and boat structures [2]. However, these joining methods are not enough when large tractive or compressive loads are produced in the components, especially when long and heavy components are used. This problem could be solved by reinforcing the module walls with more fiber and larger fastenings, but this leads to a higher weight, which would unacceptably increase loads.

The texturing of the metallic surface can promote mechanical bonding between the composite and the metallic part [3]. Thus, the surface preparation of the metallic part is essential prior to bonding. Grit-blasting, which usually generates a texture in the micrometer-range, is the standard method for mechanical surface preparation.

In this work, Abrasive Waterjet (AWJ) technology is proposed as a method for generating a "mechanical restraint" in the metallic surface by texturing it. Parameters and tool paths for the tests corresponding roughed surface are fixed based on the previous experience in roughing titanium and steel alloy [8]. The main objective of this work is to compare the bonding quality of a structural steel and a fiberglass/epoxy composite using two texturing patterns for the metallic surface (roughed and knurled-like) and three manufacturing methods for composite-metal components (infusion lamination, pre-preg lamination and using a structural adhesive).

First, an experimental study has been carried out in order to find process parameters and tool paths which lead to the required surface properties. Besides, the AWJ texturing generates compressive residual stresses in the treated surface, together with a rough pattern [4, 5]. The parameters and tool paths for the tests corresponding to a knurled-like surface were fixed based on the AWJ milling model developed by the authors, which predicts the achieved depth and kerf width as a function of the pressure, the stand-off distance, the abrasive mass flow rate and the traverse feed rate [6], and studies the tool path effect over the whole machined area [7]. After the selection of the process parameters for the texturing of the metallic surface by AWJ, the bonding of metal and composite materials using this method has been evaluated through tensile and fatigue testing.

2. AWJ texturing parameters selection

AWJ technology has demonstrated to be a flexible method for obtaining different surface textures, by adjusting both process parameters and tool path strategies. For the target application, its main advantage over other techniques is its capability of treating surfaces with complex geometries. Despite the compressive residual stresses and the rough pattern generated by AWJ texturing, it provides to the manufactured components both fatigue strength and rough surface texture which are usually required for coatings in automotive and aircraft industries.

The objective of this experimental work consisted on determining the AWJ process parameters in order to obtain two different texture patterns in the metallic material surface:

1) Roughed surface, with an Rz of 100 μm.
2) Knurled-like surface, with a depth between 0.5 and 0.8 mm and a lateral feed of 1 mm.

These types of patterns were specified by the end-user of the application thanks to its previous experience regarding this type of bonding according to DIN 82 standard. The material used in this case-study was a non-alloy structural steel (S235) with an average hardness of 350 HV.

2.1. Experimental set-up

Experimental tests to define the parameters for obtaining the two patterns described above, consisted on texturing rectangular areas of structural steel using different parameters and tool paths.

As mentioned before, parameters and tool paths for the tests corresponding to a knurled-like surface were fixed based on an AWJ milling model which predicts the achieved depth and kerf width as a function of the pressure, the stand-off distance, the abrasive mass flow rate and the traverse feed rate, and studies the tool path effect over the whole machined area. From the 7 patterns of knurl defined in DIN 82 standard, only two types were selected: RKE cross knurl and RGE diamond knurl.

On the other hand, the parameters and the tool paths for the tests corresponding roughed surface were fixed based on the previous experience in roughing titanium and steel alloy.

The tool paths used for producing the aforementioned patterns are shown in Fig. 1.

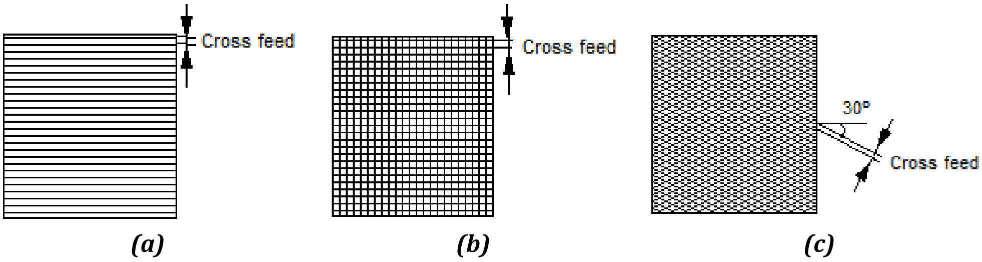


Fig. 1. Tool path strategies: (a) roughing tests; (b) RKE type knurl; (c) RGE type knurl.

All tests were carried out in a 3 axis Byjet L2030 waterjet machine, equipped with a high pressure pump up to 360 MPa. An orifice diameter of 0.25 mm and a focusing tube diameter of 0.91 mm were used for all tests. The rest of the parameters used for the experimental tests are stated in Table 1.

Table 1. Experimental tests for AWJ texturing

Pattern	Target	Pressure (MPa)	Stand-off distance (mm)	Abrasive mass flow rate (g/min)	Traverse feed rate (mm/min)	Cross feed (mm)
Roughed	Rz=100 μm	110 and 160	2	100	1500	0.35- 0.60
Knurled-like (RKE and RGE)	Depth=0.5 mm	110	2	250	800	1

The obtained surfaces were measured with a LEICA DCM 3D confocal microscope.

2.2. Results and discussion

2.2.1. Roughed surface

The surfaces obtained in the roughing tests are shown in Fig. 2.

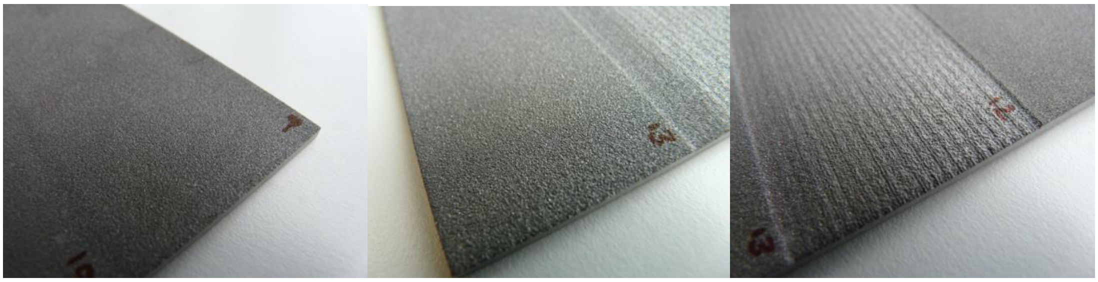


Fig. 2. Roughing tests.

The surface topography in AWJ texturing process is very similar to the one obtained in AWJ milling process, which can be divided in three main components:

- Roughness: having wavelengths shorter than cross-feed increment
- Cross-feed waviness: typically of a wavelength equal to the cross-feed increment
- Process waviness: with a wavelength of several millimeters

Often, the waviness and roughness components are overlapped, since there is not a clear barrier between them, and, moreover, they depend on the process parameters. The cut-off length is the wavelength at which roughness and waviness are distinguished.

In this case-study, the surfaces were evaluated through the Sz parameter, which was evaluated using a Gaussian filter with a cut-off length of 0.8 mm. Thus, the cross feed waviness has been taken into account in the evaluated Sz parameter, since the cross feeds are lower than the cut-off length. The measured surfaces and Sz values are shown in Fig. 3. These results show that the increase in the pressure produces a higher roughness, due to the greater impingement impact of abrasive particles. On the other hand, similar trends of Sz were obtained with the cross feed. The minimum roughness value for the two tested pressures was obtained for a lateral feed of 0.45 mm, which is a half of the focusing tube diameter.

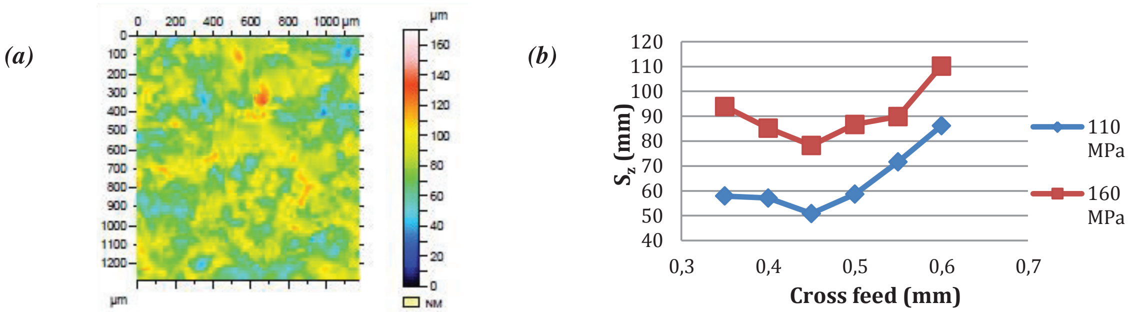


Fig. 3. Roughness results: (a) measured surface; (b) Rz results for different tests

The selected parameters for the fabrication of test specimens in order to evaluate the bonding between the steel and the laminated fiberglass/epoxy composite have been a pressure of 160 MPa, and a lateral feed of 0.6 mm.

2.2.2. Knurled-like surface

The surfaces and profiles obtained in the knurled-like surfaces are shown in Fig. 4.

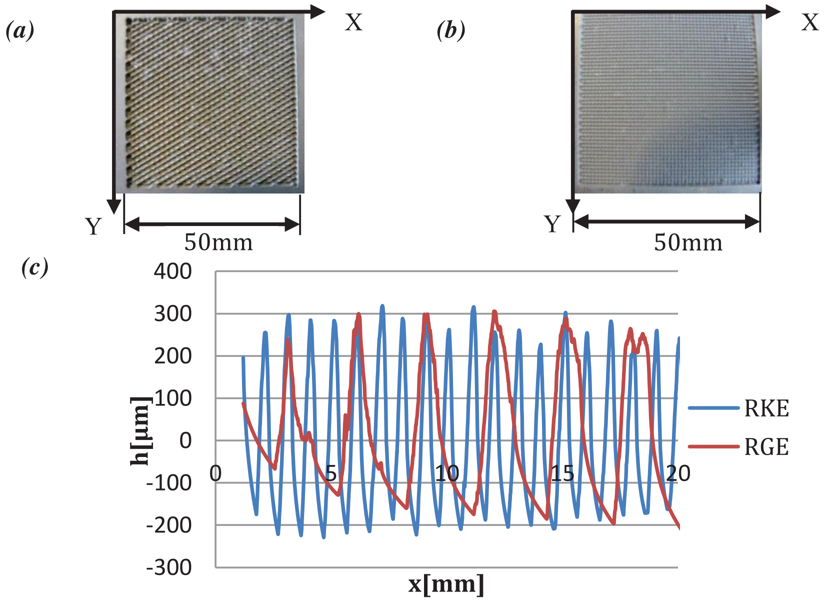


Fig. 4. Knurled-like tests results: (a) RGE knurl-like surface; (b) RKE knurl-like surface; (d) profile of RGE and RKE knurl-like surfaces

The average depths obtained in the RGE and the RKE knurl-like surfaces are 473 and 485 µm respectively, which are near the objective depth of 0,5mm. The RGE knurl-like surface was selected by the end-user for metal-composite bonding tests due to its specific characteristics in the peaks of the profile.

3. Metal-composite bonding strength evaluation

The objective of this part of the work consisted on evaluating the metal-composite bonding combining the two different patterns of metal surface obtained by AWJ selected in the previous section (the roughed and the RGE knurled-like), and three different manufacturing processes of fiberglass and epoxy resin (infusion lamination, pre-preg lamination, and structural adhesive bonding) through tensile and fatigue testing. All tests were based on DIN EN 6060 standard.

3.1. Test specimen fabrication

The geometry of the test specimen is shown in Fig. 5.

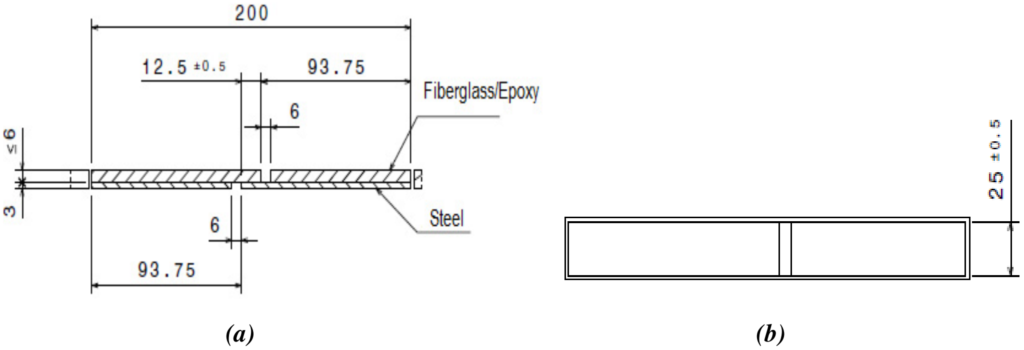


Fig. 5. Test specimen geometry according to DIN EN 6060 (dimensions on mm): (a) Lateral view; (b) Front view

For test specimen fabrication a total of 6 steel sheets of a dimension of 500mm x 240mm x 3mm were textured, 3 of them with roughed pattern and the other 3 with the RGE knurl-like pattern (see Table 2).

Table 2. AWJ parameters for steel sheets texturing

Pattern	Pressure (MPa)	Stand-off distance (mm)	Abrasive mass flow rate (g/min)	Traverse feed rate (mm/min)	Cross feed (mm)
Roughed	160	2	100	1500	0.60
RGE Knurled-like	110	2	250	800	1

The textured surfaces were cleaned by brushing, and the fiberglass/epoxy composite was laminated in the textured steel sheets using three manufacturing techniques: infusion lamination, pre-preg lamination and structural adhesive boundary.

After lamination, 6 mm width slots were machined by conventional milling (see Fig. 6), and the specimen profiles were cut by AWJ (18 specimens were obtained from the steel sheets with the laminated fiberglass/epoxy composites), which can cut dissimilar materials obtaining a good cutting quality.

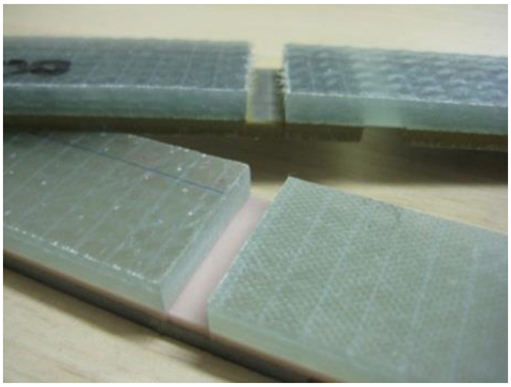
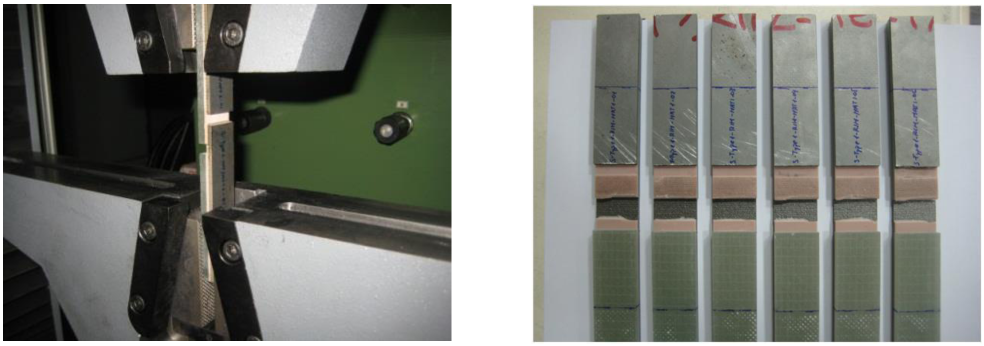


Fig. 6. Test specimens for tensile tests.

3.2. Tensile testing

To obtain the shear strength of the steel-composite bonding, a total of 6 combinations (2 metal surface patterns and 3 types of composites manufacturing methods) were evaluated through tensile tests. For each combination, 6 specimens were tested on tensile strength testing machine E1/044.



(a) ***(b)***

Fig. 7. (a) Tensile testing equipment; (b) Failure of specimens using the structural adhesive

The obtained average shear strengths and its standard deviations are stated in Table 3. The infusion lamination provides slightly lower shear strength than when using structural adhesive or pre-preg lamination. This is thought to occur due to an air entrance during the manufacturing process, causing a bad adherence between the composite and the steel surfaces. Thus, infusion lamination method has been discarded as a manufacturing method due to the low values of shear strength presented by the bonding. In the pre-preg lamination, the roughed pattern improves in a 50% the shear strength obtained by the knurled-like pattern. In addition, the knurled-like pattern provides slightly lower shear strengths than the roughed surface. Thus, the knurled like pattern was also discarded.

Table 3. Results of the obtained average and standard deviation of the shear strength.

	Shear Strenght (MPa)		
Texturing pattern	Structural adhesive	Infusion lamination	Pre-preg lamination
Knurled-like pattern	21.14 ± 1.53	6.11 ± 1.47	20.33 ± 1.45
Roughed pattern	22.54 ± 1.38	4.31 ± 0.88	30.48 ± 1.65

3.3. Fatigue testing

After the evaluation of the metal-composite bonding through tensile tests, fatigue tests were carried out only for the roughed texture and two composite manufacturing methods (adhesive bonding and pre-preg lamination), since the knurled-like surface and the infusion lamination method were discarded in the previous stage. Fatigue tests were carried out in a fatigue testing machine INSTRON 8032 (Fig. 8-a).

Fig. 8. (a) Fatigue testing equipment; (b) adhesive bonding specimens after fatigue testing; (c) pre-preg specimens after fatigue testing.

The number of cycles until failure depending on the applied load for each specimen is shown in Fig. 9. The pre-preg lamination manufacturing method presents a higher endurance to fatigue failure than adhesive bonding, which provides a maximum number of cycles about 5 times lower. Moreover, the number of cycles achieved with the pre-preg manufacturing method using a higher load is near the ones obtained with the adhesive bonding using a lower load, meaning that if the same load is applied to both pre-preg lamination and adhesive bonding, a higher number of cycles would be reached with the pre-preg lamination.

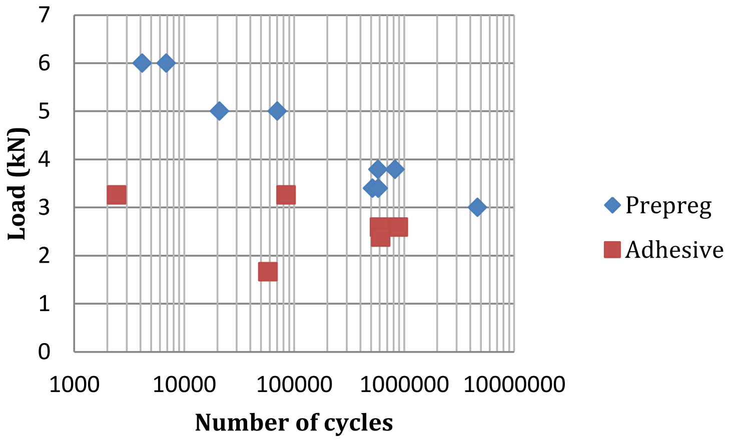


Fig. 9. Fatigue tests results for adhesive bonding and pre-preg lamination.

4. Conclusions and future work

The results show that AWJ texturing is a promising alternative to improve the bonding between metallic and composite materials. Roughed pattern combined with pre-preg lamination results to be the combination that presented the highest shear strength (30.57 MPa) and the higher number of cycles during fatigue testing (4674152 cycles with a 3KN load).

Future works are addressed to improve tool paths and process parameters in order to obtain a random roughed pattern, where the waviness related to the cross-feed is deleted.

5. Acknowledgements

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