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Experimental study of laser dissimilar joining for Usibor 2000 and Al-T7075 with Tepex 102

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Abstract

Due to the needs of weight reduction in the automobile structures and of time reduction in the Body-In-White (BIW) manufacturing stage, effective and accurate dissimilar joining is demanded to take advantage of metal-polymer structures. Automotive industry is highly interested in the combination of metal alloys and composite materials; however, dissimilar joining of this type of materials without using mechanic or adhesive joining is a challenge. As an alternative to the classical joining techniques, laser technology can be used to join dissimilar materials. In laser direct joining, a laser beam is used to heat the metal and by conduction to heat the polymer up to melting temperature in the interface without reaching degradation temperature. In this work, an experimental procedure is proposed to set the basis of dissimilar joining between metal and composite parts for the automobile industry. To do that, laser texturing on metallic parts was studied and a wide battery of experimental test were performed to obtain the proper joining process parameters for dissimilar joining between Usibor 2000 and Al-T7075 with Tepex 102. Results show that is possible to reach over 17 MPa in lap shear adhesion test which is similar to the performance of typical adhesives used in automotive industry.

Keywords: Laser; dissimilar; texturing; direct joining

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1. Introduction

The laser dissimilar joining approach for metals and polymers was first demonstrated in 2006 [1,2]. In these early works, unions of stainless steel to polyethylene terephthalate, polyamide, polycarbonate and polypropylene were performed, and good results were found in terms of mechanical integrity. Since then, this technique has been extended to other materials combinations. In the last years, it has been observed that the generation of micro-textures in the metallic part gives better results in mechanical response of the joints [3–5], this enhances the performance of the dissimilar joints between metals and polymers, but the final resistance shows great dispersion if surface texturing is slightly changed. To get good adhesion the polymer melts must flow inside the pre-textured cavities, and depending on material flowability, textured structures and applied pressure, the wetting area is modified so resulting joint can present different behavior. Thus, it is critical to have an accurate control on removed material in order to reach same textured structure, furthermore, to guarantee the optimal flow, it is necessary to develop a specific pressure element to reach same joint integrity in all experiments [6].

Texturing must guarantee the penetration of the polymer once the melting temperature has been reached as a result of the heating induced by the laser through the metal surface. One of the critical aspects of the process is the lack of repetitiveness due to the influence of both the texturing variables and the joining parameters in combination with the motion strategy used. The objective of the texturing is the modification of the surface to maximize the contact area and allow an optimal adhesion. Techniques such as sand blasting allow to increase surface roughness in a simple and fast way, however, it is difficult to achieve good repeatability due to the influence of aspects such as distance, time and trajectory during the blasting process. Other alternatives such as knurling have limitations in the processing of ultra-high elastic limit steels and are not capable of generating micro-cavities or surface-roughness that allow adhesion in an intimate way.

Previous studies [7] have shown that laser texturing allows a selective removal of material with a high degree of repetitiveness and minimal heat affected zone (HAZ) when using ultra-short pulse lasers with picosecond order durations (10^{-12} s) or femtoseconds (10^{-15} s). As a disadvantage, ultra-short pulse equipment has a cost significantly higher than nanosecond laser which is used in laser marking and some engraving operations [8] (10^{-9} s). This type of equipment allows selective removal of material, but, unlike ultra-short pulse lasers, in combination with ablation there is some melted and then solidified material as a surface layer, resulting in less defined geometries and burrs than sometimes they may not be acceptable [9]. In dissimilar joining applications, an irregular surface should not have to give a bad result, it is more, the generation of burrs in the surface area as a consequence of the re-solidified material, can be beneficial, since, it increases the available contact area. However, the final strength of the joint depends directly on the surface finally generated and usually, inadequate parameters with excessive melting result in variations in the surface that affect the final strength causing two equally processed surfaces to reach different levels of resistance.

Another key aspect affecting the joining strength is the texturing pattern used. An inadequate texturing results in an insufficient contact area, while if the texturing is adequate there will also be a limit from which an increase in the contact area does not cause an increase in the resistance, because the failure will be by shearing the polymer and not by lack of adhesion to the metal. In order to facilitate the extraction of conclusions, it has been chosen to work with flat test specimens of 105 x 25 mm and a texture based on grooves transverse to the direction of application of shear stress. This type of geometry makes possible to systematically evaluate the influence of the texturing parameters on two critical points, such as the width and depth of the grooves, which are key when determining performance and allow to check in a simple way if the selected parameters provide the degree of repeatability required.

Thus, in the present work the feasibility of using nanoseconds short pulse lasers for the texturing of materials for applications of dissimilar metal-polymer joints was analyzed. For this, two combinations of interest have been selected by the automotive industry, such as Aluminum 7075 T6 and second generation of ultra-high strength steel (UHSS) Usibor 2000 in combination with the composite material Tepex 102 manufactured from Polyamide 6 reinforced with fiberglass. In the present study the influence of the contact area and joining parameters was analyzed in terms of resistance to lap shear strength test.

2. Laser texturing experimental test

The experimental texturing tests were carried out using a pulsed Nd: YAG fiber laser with 50 W of mean power, working in pulsed mode. The equipment used allows a pulse frequency of 1 to 1,000 kHz with a minimum pulse duration of 7 ns and a beam quality of 1.6 M^2. For laser guidance, a 2D galvanometric head with a focal length of 160 mm was used providing a maximum workspace of 110 x 110 mm^2 and 50 µm focused beam diameter with a maximum scanning speed at the surface of 10,000 mm/s.

To avoid variations in the absorption of energy, a first cleaning sweep was carried out to homogenize the laser incidence surface. For this, a surface swept motion was programmed with a zigzag strategy at 45º in combination with radial step of 0.05 mm to process an area of 45 x 25 mm^2 at 100% power with scanning feed rate of 7,000 mm/s, a frequency of 190 kHz and pulse duration of 40 ns.

In order to be able to characterize the material removal and the contact area in a simple way, a texturing geometry based on parallel grooves was considered. Figure 1(a) shows schematically the target texture. The texture was evaluated measuring the width and depth of each groove as it is schematically represented in Figure 1(b) and Figure 1(c) shows a sample of textured specimen of Al 7075.

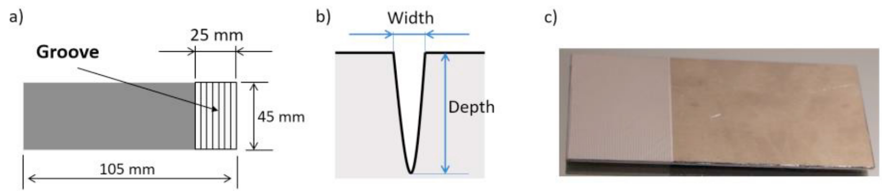

Fig. 1. (a) texturing grooves; (b) considered groove width and depth for evaluation (c) laser textured specimen sample on Al 7075.

The ranges of the tested parameters were defined taken as reference the maximum power delivery of the equipment used because a high material removal rate is needed to generate the texturing with minimal cycle time. The laser equipment used for texturing generates a maximum power output for a pulse duration of 250 ns at 50 kHz providing a power peak of just over 10 kW in the first 20 ns of the cycle to then fall exponentially to 2 kW in the remaining cycle 230 ns. These operating conditions allows maximum removal rate, however, since the absorption of the radiation and the melting temperature are not the same in aluminum and Usibor, different ranges of pulse frequency, feed rate, scanning feed rate and number of passes for each material were defined. Table 1 shows the parameters analyzed in each material.

Table 1. Tested Process parameter

Parameter	Al 7075T6	Usibor 2000
Pulse Frequency (kHz)	40-50-70	40-50-60
Feed rate (m/s)	750-800-900	450-500-550
Passes	3-5-7-10	3-5-7-10

The study was carried with two fixed variables, the power, fixed at 100 % and the pulse duration set at 250 ns. The result was evaluated measuring the 3D topography with a LEICA DCM 3D confocal profilometer. Using a program specifically developed in Matlab©, the different profiles perpendicular to the direction of the grooves were extracted and the average of all is finally considered as result.

As it was expected due to different radiation absorption ratio for each material at 1060 nm, which is the Nd:YAG fiber laser wavelength emission, the most effective pulse frequency for material removal varies depending on the type of material. In this case, for aluminum, the best results were obtained at 50 kHz, while, in the case of steel, the best results were obtained at a frequency of 40 kHz. Comparing the evolution of the dimensions of the grooves obtained, both in width and depth, in both materials a similar trend was observed. In both materials, the depth obtained follows an almost linear evolution, with slight differences depending on the scanning feed rate. Thus, for slower feed rate, which correspond to an increase in energy density, the depth obtained is greater with same number of passes, so, higher energy density provides higher material removal rate. This material removal rate is different in each material but in both of them this rate is constant and the reached depth increases with number of passes following a linear behavior. In the case of aluminum, the maximum depth reached is 160 µm with 10 passes, while in the case of steel a maximum of 110 µm for speeds of 450 mm/s is reached as it can be appreciated in Figure 2(a).

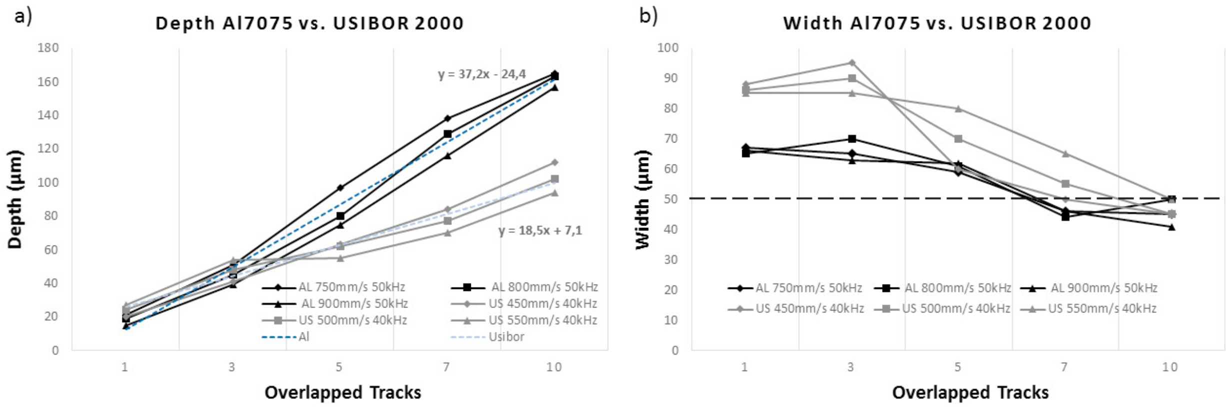

Fig. 2. (a) depth study and (b) width study for Al7075 and Usibor2000.

Unlike what happens with the maximum depth of the grooves, the width of the grooves follows a different evolution. Considering that the optic used has a minimum diameter of 50 µm, and additionally to vaporization there is also material melting, grooves wider than 50 µm are expected, moreover, with several passes the grooves should become wider because of accumulated material melting. However, although when the number of passes is less than three, the evolution corresponds to this approach, from 5 passes overlapping there is a clear decrease in width in both materials as it can be appreciated in Figure 2(b). In the case of the Usibor, a greater sensitivity is observed as a function of the feed rate, so, the greater is energy density then width becomes also greater.

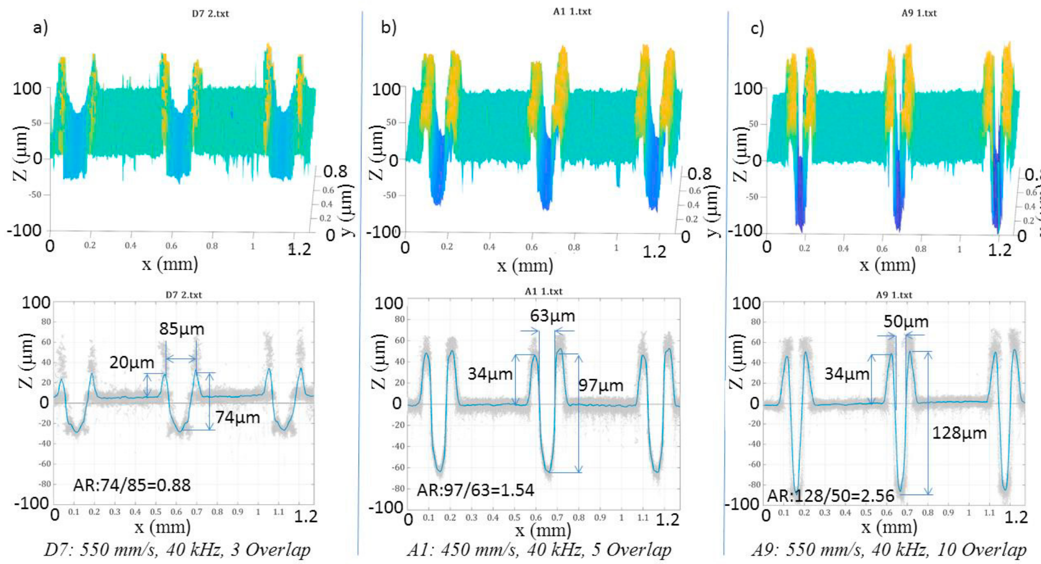

Fig. 3. (a) low aspect ratio; (b) medium aspect ratio and (c) high aspect ratio textures in Usibor 2000.

In the case of aluminum, said sensitivity is lower, and the width obtained is practically the same for the entire range of feed rates studied. On the other hand, both in the case of steel, and more notably in the case of aluminum, over 7 passes overlap the diameter of the groove decreases to values lower than the own beam diameter.

This phenomenon is explained by the mixed mechanism of material removal that involves part of vaporization of material and part of fusion. When there are few passes, the molten material is expelled from the cavity by the recoil pressure and solidifies in the form of burr [10]. As the groove is deeper, the molten material is not expelled from the cavity and ends up solidifying in the walls making the groove narrower, reaching in the most extreme case to be the groove even of smaller diameter than that for focused laser beam.

Once the tests were performed, slots of different depths were selected and the first dissimilar joining tests were carried out with 105 x 45 mm rectangular Tepex 102 test parts of 2.5 mm thick. The first joining tests were performed using specimens with different depth and width of grooves previously selected that present appropriate aspect ratio. Figure 3(a) shows low aspect ratio sample texture (D7) and Figure 3(b) and Figure 3(c) show medium and high aspect ratio textures (A1 and A9), however, the results obtained in lap shear testing show that the relationship is more complex, moreover, topographies that initially are very similar provide values of resistance significantly different.

3. Dissimilar joining and result discussion

3.1. Surface texturing influence

Experimental joining was carried out in the laser cell developed by Tecnalia Research & Innovation technology center shown in Figure 4(a), which uses a high-power direct diode laser 3.1 kW from Rofin fiber-guided that provides spot beam of 10mm in diameter with Gaussian energy distribution. The laser spot is moved by Fanuc S-10 robot manipulator and the test part is fixed in a pressure jig, shown in Figure 4(b) while laser energy output during process is controlled by PID controller fed by temperature signal registered via pyrometry. Figure 4(c) shows three samples of dissimilar joints Al 7075-Tepex102. In all tests, the scanning strategy followed during joining was a zigzag trajectory.

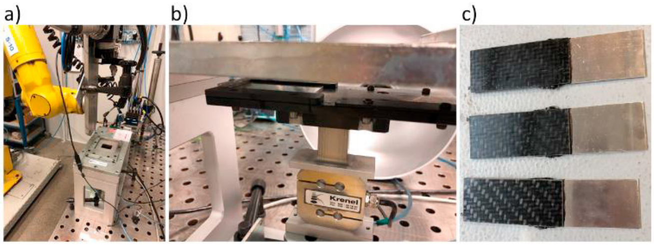

Fig. 4. (a) joining cell; (b) pressure jig detail; (c) samples of Al 7075 – Tepex 102 joints.

The power of the laser is regulated with a PID controller that has as input the temperature measured on the beam incidence face. The controller acts modifying the energy output in order to keep the temperature constant. In both materials the closing pressure of the pressure tooling was 3 bars and 2 zigzag sweeps were performed at 50 mm/s. The threshold temperature for PID controller was set at 360 °C for steel and at 430 °C for aluminum. In both cases an emissivity of 0.9 was considered for the pyrometry temperature measurement. After joining the specimens were tested for Lap Shear Adhesion following ASTM D5868 standard. The specimens were identified using a combination of letter and number depending on frequency, feed rate and number of overlapped tracks. In Figure 5 are represented the most relevant combinations. Results show a maximum lap shear strength of 13.8 MPa for Usibor 2000 steel in Figure 5(b) and maximum of 13.9 MPa in Aluminum 7075 T6 in Figure 5(a), in both cases with a standard deviation lower than ±0.3 MPa in the three measurements carried out with each material specimen. The texturing parameters that provide best results in lap shear test for each material are shown in Table 2. Initially, it was expected that the strength of the joint should be proportional to the contact area between both materials, moreover the contact is proportional to the aspect ratio (AR) defined as relation between depth and width. In case of Usibor, considering shear test results of Figure 5(b) this point is confirmed since D7 texture presents the lowest resistance with AR:0.88 while A1 presents medium aspect ratio and medium resistance with AR:1.54 and A9 presents the maximum resistance with AR:2.56.

However, this relation is more complex because D1, D3 and D2 which have very similar aspect ratio of AR:0.5, present a significantly different resistance in the test performed. Similar trend was also noticed in aluminum specimens in Figure 5(a), where A4 specimens, with AR:2.2 have much more aspect ratio than A2 specimens with AR:0.56 but the shear strength is higher for A2. So, small variations in topography have high impact in final resistance as well as in repeatability.

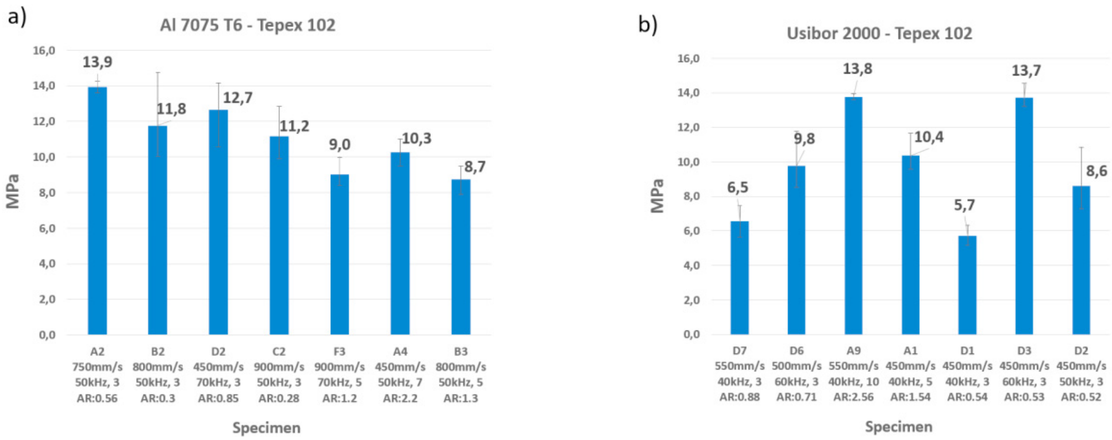

Fig. 5. (a) lap shear test in Al 7075; (b) lap shear test in Usibor 2000.

Table 2. Laser texturing parameters that provide highest resistance in lap shear test.

Material	Power (W)	Feed (mm/s)	Freq.(kHz)	Passes	Pulse (ns)
Al 7075 T6	50 (100%)	750	50	3	250
Usibor 2000	50 (100%)	550	40	10	250

3.2. Joining parameter influence

Once the textures that provide maximum lap shear resistance with satisfactory repeatability were identified, the joining parameters were studied for each material. Table 3 shows the parameters and values for each one tested in this second step. In order to analyze also the influence of the thickness in the joint strength, the 32 tests for each material were repeated 4 times in two different thicknesses, which gives a total of 256 tests in each material. The tested thicknesses were 2 and 3 mm in the case of 7075 aluminum and 0.8 and 1.5 mm in the case of Usibor 2000. In all cases the Tepex 102 thickness was 2.5 mm. In Figure 6 the results obtained in Al 7075 are shown and in Figure 7 the results in Usibor 2000 are shown.

Table 3. Tested joining parameters

Material	Temp (ºC)	Pressure (bar)	Feed (mm/s)	Passes (vlt)	Thickness (mm)
Al 7075 T6	340 – 370 – 400 – 430	3.5 – 5	30 – 50	1 – 2	2 – 3
Usibor 2000	330 – 360 – 390 – 420	3.5 – 5	30 – 50	2 – 3	0.8 – 1.5

In the case of aluminum, a maximum average lap shear strength above 18.5 MPa with a deviation of ± 1 MPa was obtained for 2 mm thick specimens processed with 370 °C threshold temperature, 3 bar pressure, 50 mm/s feed rate and two swept passes. However, with the same parameters, for specimens of 3 mm, a maximum resistance of 14 MPa was obtained. Since texturing geometry was almost the same in both thicknesses, the main difference in the test is the resulting thermal field in each case. This result shows the high sensitivity in the resistance achieved as a function of the temperature distribution reached during the process. In results shown in Figure 6 it is observed that the window of joining parameters that provide resistance levels between 10 and 14 MPa is relatively broad, thus, different combinations of parameters provide acceptable results. On the other hand, an excessive heating associated with high threshold temperatures with low feed rate, cause an over-melting of the polymeric resin resulting in low strength joints.

In the case of Usibor 2000 steel, the results shown in Figure 7 present higher average resistance level than in aluminum. Also, the influence of the thickness on the final strength for given parameters is also appreciable, however, in this case the highest resistance levels are given for the thickness of 1.5 mm compared to 0.8 mm. As in the case of aluminum, there is a relatively large parameter window that provides high resistance levels, around 17 MPa, and in general it is a joint that has a more stable behavior and with better repeatability. The difference in strength is directly related to the flow of the material and the way in which it fills the textured cavities. Taking into account that the textured topography in both cases is similar, the detected variations can be associated to the influence of the thermal conductivity of the material in the heating and cooling process of the polymeric matrix of the Tepex 102. This point requires a deeper study and that exceeds the scope of the present study but will be taken into account in future work.

Among the parameters of steel joining, it should be noted that with a thresjold temperature of 390 °C, 3.5 bar pressure, feed rate of 50 mm/s and 3 swept passes (vlt), a final resistance of 17 MPa was obtained in both 0.8 as 1.5 mm thick with a deviation less than ± 1 MPa, which is a remarkable good result.

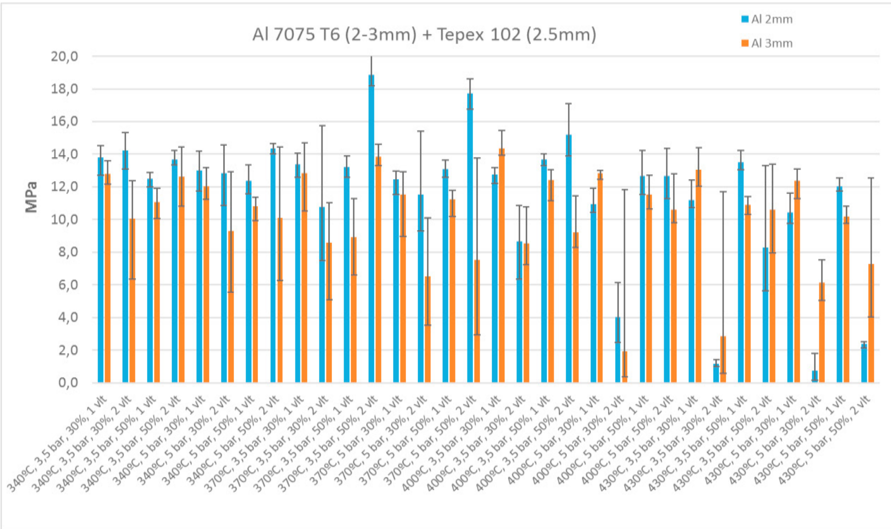

Fig. 6. Joining parameters in Al 7075T6 – Tepex 102

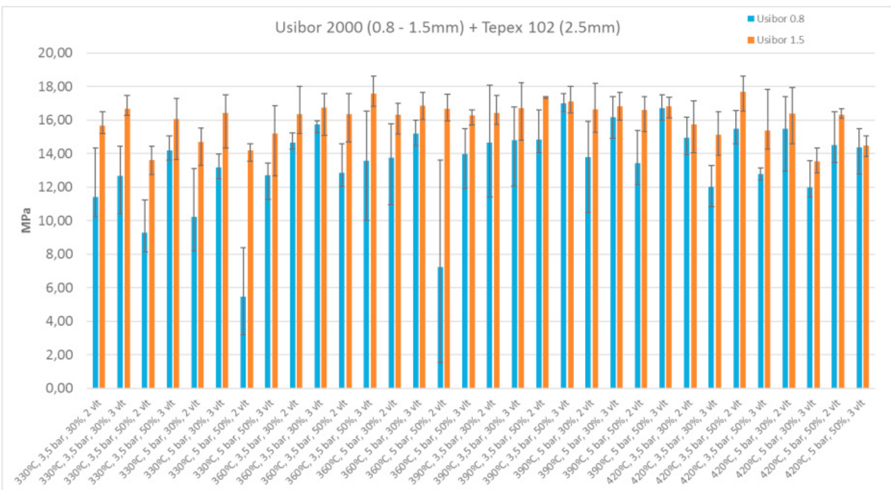

Fig. 7. Joining parameters in Usibor 2000 – Tepex 102

4. Conclusions

In this study laser texturing on metallic parts was studied and experimental tests were performed to obtain the proper joining process parameters for dissimilar joining between Usibor 2000 and Al-T7075 with Tepex 102. Results show that fusion mechanism has a noticeable effect on the material removal process and texturing process. Both, aluminum and Usibor present similar behaviors but aluminum presents higher removal rates. The removal rate is also associated with the energy density used. The higher the energy density, the higher the removal rate achieved.

The strength of the joint does not depend only on the contact area. Similar textures result in large variations in lap shear strength. Burr formation plays an important role in the resistance and its impact should be studied more in deep. Different joining parameters were tested in both, steel and aluminum, where shear strength values above 17 MPa were achieved with standard deviation below ±1 MPa. Same texturing and joining parameters were studied in different thickness specimens, and results show a clear influence of the thickness of the sample on the final resistance reached.

There is a relatively wide parameter window that provides good resistance, however, obtaining good results with good repeatability is complex and small variations in texturing and joining parameters lead to significant shear strength variations. Failed joints are given as much by a lack of fusion as by excess heating of the composite material. In comparison with Al 7075, Usibor 2000 has a more uniform behavior and less deviation in the results when same conditions are repeated. Finally, can be concluded that determination of the optimal joining parameters requires an extensive campaign of experiments and suitable simulation tool can be helpful.

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