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Transmission laser welding of thermoplastics: Influence of welding parameters and rib dimensions on the strength of welded joints

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ABSTRACT

Laser transmission welding of injection moulded thermoplastics is commonly used in industrial applications such as electronic packaging, textiles, biomedical devices, windows, signs, food and medical packaging, visual displays and automotive components due to very precise control of the process parameters, including the amount of energy delivered and its location, which results in high joint quality. In this article, the influence of laser transmission contour welding parameters and geometry of welding rib on joint force is investigated. Velocity with which the laser beam moves on the sample, temperature applied, clamp force, laser beam size and number of laser passes were studied for various dimensions of the rib with rectangular and triangular cross section. Samples of different thermoplastic materials, PMMA and PC/ABS, were produced and then joined by transmission laser welding and after that were subjected to tensile tests, in order to measure strength of the joint between the plastic parts. Initially, optimal welding conditions were found for each studied rib and their influence on the force of the joint was analysed. Afterwards, a comparison between the best results obtained for each rib was performed, in order to define the dimensions of the rib that result in the highest joint force. It was observed that samples with triangular ribs achieved higher joint strength. For both studied geometries of rib cross section, an increase of the width of the ribs improves the joint strength, while an increase of the height worsens it.

Introduction

Laser transmission welding of thermoplastics is a technique widely used for joining plastic components due to its several advantages, such as high-speed welding, ease of joint fabrication, higher joint quality, minimal resulting flash, relatively low residual stress to thermoplastic parts, well defined heat affected zone (HAZ), no part marking from tooling and fixture and the ability to weld complex shapes (Acherjee et al., 2009). It finds its application in several areas, such as biomedical devices, automotive components, visual displays, electronic packages, textiles, windows and signs, food and medical packaging.

Usually, laser transmission welding is used for minimal visual cues for the weld (Acherjee et al., 2009; Extol Inc n.d.), by minimizing the resulting flash and by focusing the weld to a small area. Adding a rib might be counterproductive if it is important to have a rib that is almost unnoticeable, but the rib might enhance the mechanical behaviour if visual appearance is not that important.

In laser transmission welding one of the components has to be transparent to the laser radiation and the other has to absorb it. In that way, the laser energy passes through the first component and is absorbed and converted into thermal energy by the second component. Part of the generated thermal energy is transferred by heat conduction from the second component to the first through the interface between both of them. The polymers melt at the interface and finally, by molecular diffusion of the polymer chains, the weld is formed upon cooling.

Regarding the use of ribs for the joining of thermoplastics using welding processes, ribs are frequently used/required for conventional welding technics, such as Hot Plate Welding, Vibration Welding and Infrared Welding (Extol Inc n.d.; Sieben and Brunnecker, 2010; Reed, 2015). In these technologies, the welding rib is used since it is crucial for achieving high-bond strength and a tight, hermetic seal (Reed, 2015; Iyer et al., 2014) and also to focus the welding to a specific area and consequently minimize weld seam visibility.

Regarding the use of laser transmission welding for injection

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moulded thermoplastics, some extensive literature reviews were found on the topic (Acherjee, 2021; Gonçalves et al., 2021; Dave et al., 2021; Hu et al., 2023; Wu et al., 2021) but none mentioned the analysis or use of ribs. On the topic of welding ribs in laser transmission welding, the works of Brown (2011), Humbe et al. (2014) and Gillespie (2017) briefly mention that if two flat pieces are to be joined it is recommended that a raised rib be designed into the bottom piece. This rib will allow for melt collapse to take place without the need for extreme clamping pressure.

Welding process parameters have an influence on the quality of the joint between the components. The most critical are temperature, time and pressure. They are controlled by laser power, beam size, irradiation time, presence of the laser absorber materials and clamp force (Troughton, 2008). The process parameters of temperature and time can be combined as energy density used during welding.

Low energy density means there is not enough heat in the process resulting in weak welds, while high energy density means excess of heating that leads to degradation of the polymer and again weak welds.

There are several studies focused on influence of welding process parameters on the weld quality. Van De Ven and Erdman (2007) found that high laser power and small welding velocity result in material decomposition, while low laser power and high velocity result in thin welds. The weld strength generally increased with increasing line energy, which is defined as a laser power divided by the laser velocity. Clamping force was found to provide a small, but not statistically significant, influence on the visual appearance, weld width, and weld strength, similarly to what is reported by Acherjee et al. (2015).

Acherjee et al. (2009) found that increasing laser power increases the lap-shear strength and the weld-seam width, whereas, increasing welding speed decreases both the responses. Clamp force has slight positive effect on the lap-shear strength.

Acherjee et al. (2012) also observed that laser power, welding speed and stand-off distance, i.e. the distance between laser optic and work material which defines beam spot area, have a strong interaction effect on weld strength and weld width. As described in the literature (Troughton, 2008), these parameters control the heat input to the weld zone and thus the quality of the weld. The weld strength is limited by very high heat input, which causes overheating and partial decomposition of the material. A very low heat input, on the other hand results in lack of fusion.

Acherjee et al. (2015) concluded that laser power is the most important factor affecting the weld strength, followed by stand-off distance and welding speed.

Bhattacharya et al. (2018) also confirmed that increasing laser power up to a certain limit gives more heat energy, which results in good weld width and in a stronger weld. After that, it starts decreasing due to material decomposition. With the increase of laser velocity up to a certain limit the weld width decreases, producing a smaller HAZ. Further increase of velocity results in insufficient melting of material to bond, thus weaker weld.

Pereira et al. (2019) focused more on joint type and number of weld passes. He found that adding one weld pass to a lap joint nearly doubled the joint strength.

All these studies analyse the influence of welding process parameters such as laser power, welding velocity, clamping force, beam size and number of passes, on weld quality and are focused on flat to flat surface samples. This article presents a study on the influence of the presence of a welding rib, which is expected to provide an increase in joint area and, therefore, an increase in weld strength, by providing additional material to form the weld. Furthermore, the influence of welding process parameters, on the strength of the joint with the rib, will be analysed.

Methods and experimental work

In this study, the influence of the presence of the welding rib, its section shape and dimensions as well as the process parameters were studied, by comparing the spreading, compression and strength of the welding joint between the welded samples.

Table 1
Process parameters used for welding samples without ribs.

Temperature [°C]	Velocity [mm/s]	Clamp force [N]	Clamp pressure [MPa]
240–350 (ΔT = 10)	10	117	0.31
300	4–20 (Δv = 2)	117	0.31
300	10	33–201 (ΔF = 28)	0.09–0.54

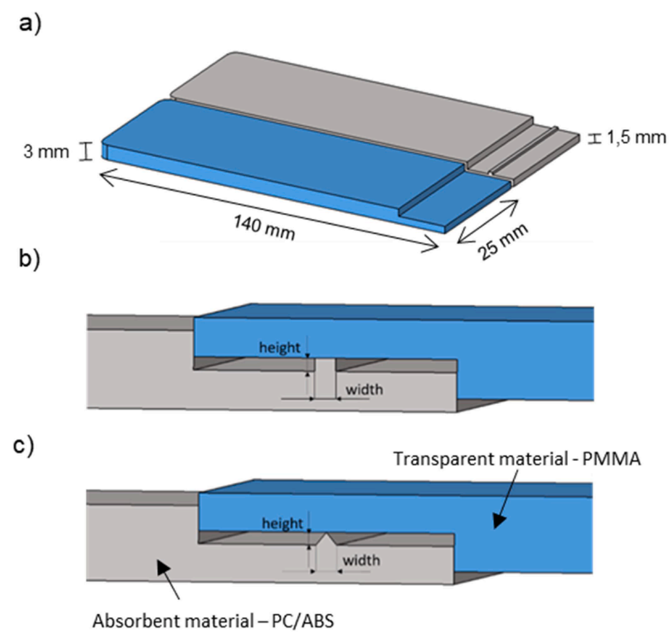


Fig. 1. Samples for welding: a) PMMA (blue) and PC/ABS (grey); b) PC/ABS sample with rectangular section of the rib; c) PC/ABS sample with triangular section of the rib.

In a first phase, samples without ribs were produced, by injection moulding, and welded, firstly to analyse the influence of the welding parameters on the behaviour of the welded samples, and secondly to allow the analysis of the influence of the presence of the ribs, by comparing the results obtained with these samples to the ones obtained for the samples with ribs.

The study of the welding parameters was performed in three groups, to allow analysing, separately, the influence of the temperature generated by the laser beam in the welding, welding velocity and clamp force and thus defining the welding process range. The studied temperatures varied from 240 to 350 °C with a 10 °C increment, velocity ranged from 4 to 20 mm/s with a 2 mm/s increment and clamp force varied from 33 to 201 N with a 28 N increment. These values correspond to the weight of the plates used to press the rib. Although clamp force is applied, the results will be shown in terms of clamp pressure, in order to include the influence of the area where the force is applied.

Table 1 presents the process parameters of the carried out welds.

In a second phase, samples with ribs were studied. In a preliminary analysis, a sample with a rectangular rib was used to study the influence of each process parameter (temperature, welding velocity, clamp force, number of passes and laser beam size) on the strength of the joint, so an optimized set of parameters could be achieved, which would serve as basis to further studies for other rib geometries.

Then, in a third phase, for each geometry configuration, namely rectangular and triangular ribs with different rib dimensions, the same analysis was done in order to evaluate both the influence of the rib

Table 2
Dimensions of studied ribs.

	Height of the rib [mm]	Width of the rib [mm]
Rectangular	0.5	0.8
	0.5	1.0
	0.5	1.2
	0.8	0.8
	1.1	0.8
Triangular	0.5	0.8
	0.5	1.0
	0.5	1.2
	0.8	0.8
	1.1	0.8

geometry and size on the welding parameters and also to evaluate its influence in the strength of the joint, so a better set of studied parameters could be achieved for each rib geometry. For this study, only the results obtained for the best set of studied parameters will be presented, due to the sheer amount of results obtained with this study.

The studies that recommend the use of ribs for laser transmission welding only mention rectangular ribs. Triangular ribs were also analysed in this study, because they add less quantity of material to the samples and they might be easier to spread, since it should be easier to melt the whole rib (better heat distribution).

For all these studies, samples of 74 × 25 × 1.5 mm of both materials, Polymethyl methacrylate (PMMA PLEXIGLAS® 8 N) and polycarbonate and acrylonitrile butadiene styrene (PC/ABS CYCOLOY™ RESIN C1200HF), were produced, by injection moulding, and were joined by transmission laser welding. For each set of parameters analysed, 8 samples were used for average value and standard deviation calculations.

In the PMMA samples, as this material is transparent to laser radiation (transmittance: 82–89 %), welding area was flat with 1.5 mm of thickness. The PC/ABS samples, as this material absorbs the laser radiation (transmittance: 0–2 %), had various configurations, flat or with a rib with rectangular or triangular section (Fig. 1). Dimensions of studied ribs can be seen in Table 2.

Samples were properly aligned and fixed on a table specially developed for this research (Fig. 2a) and then a clamp force was applied by placing plates, with known weight, on top of the sample (Fig. 2b). Samples were joined by contour welding method using a Diode Laser LM100 of 940 nm wave length attached to a Motoman IA20 robot. A pyrometer was attached to the robot arm, in order to control the temperature applied by the laser. Four samples were welded at the same time, using the same conditions, and used to calculate the averaged results.

The Diode Laser LM100 works with a pyrometer that reads the temperature at the top surface of the transparent sample and controls the power to achieve the defined temperature.

After welding, dimensions of the compressed rib were measured from the side view of the sample using an Infinite Focus SL optical microscope (see Fig. 3).

As can be seen in Fig. 3, the presented sample is not completely compressed, which is expected since the welding parameters are not optimized. The white marks visible in the bottom sample, near the bottom of the rib, appear due to the laser beam size that is slightly bigger than the rib width, thus part of the laser heat goes to these areas and melts the sample also outside of the rib.

The microscopy tests allowed the analysis of the rib compression and spreading (weld seam width), which can be associated with the strength of the joint. It is expected that a higher rib compression, and consequently a higher spreading of material, would lead to greater welded area and a higher strength of the joint.

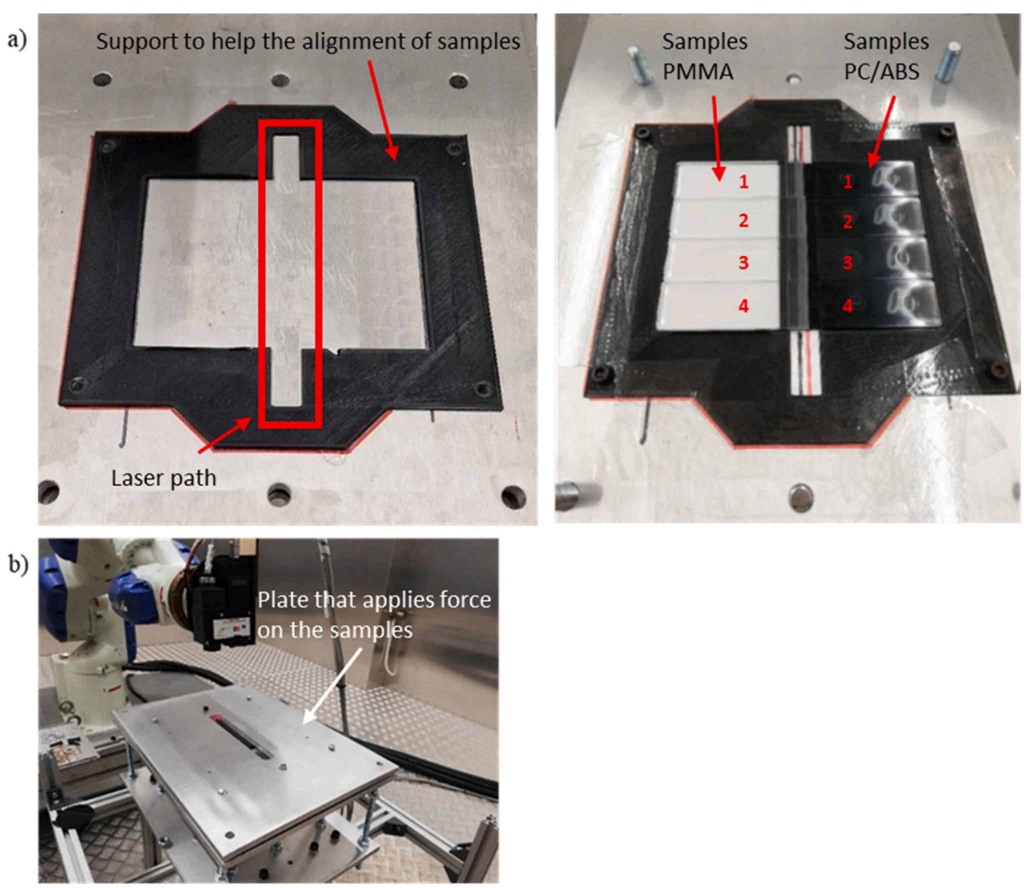


Fig. 2. Welding process experimental set-up: a) alignment of the samples; b) application of clamp force.

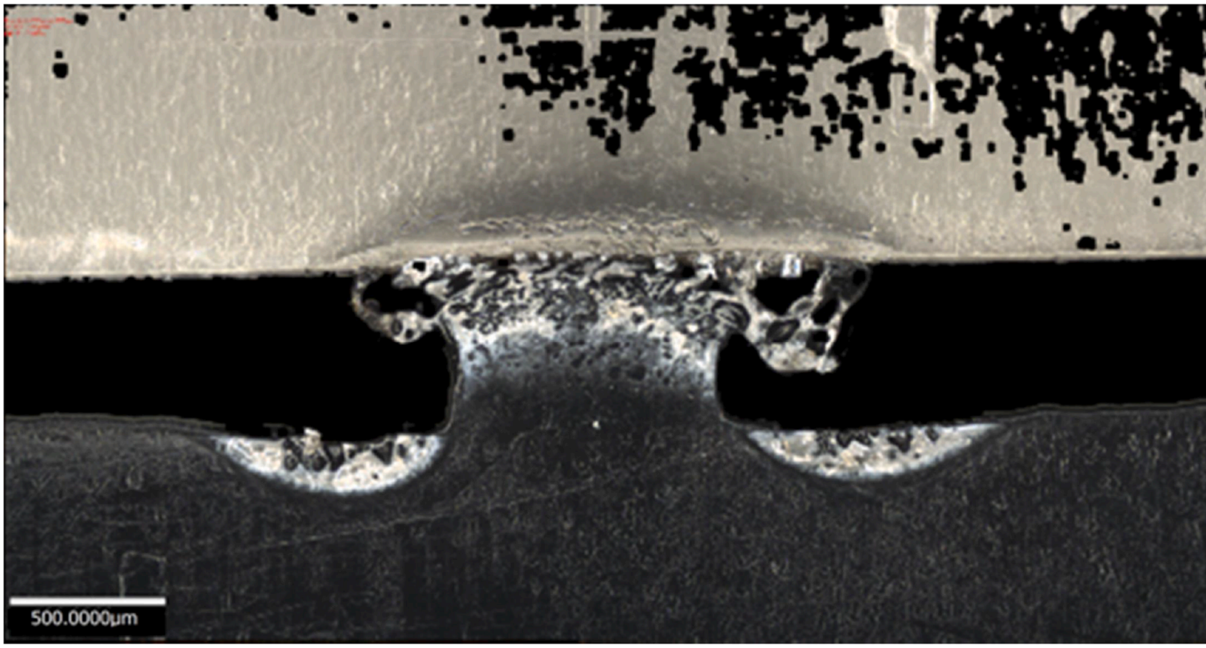


Fig. 3. Microscopic image from side of a welded sample with rectangular rib.

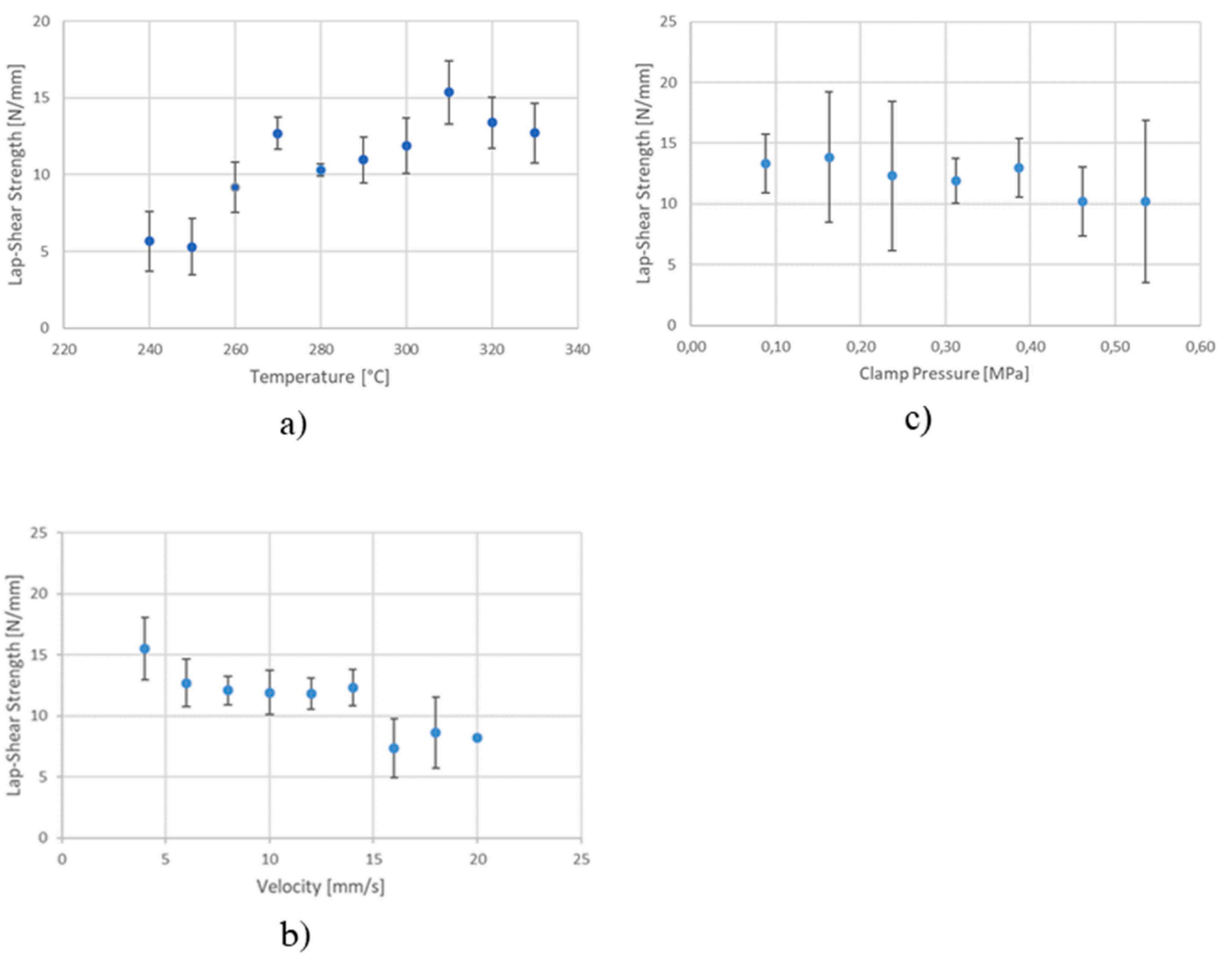


Fig. 4. Influence of parameters on lap-shear strength in the samples without rib.

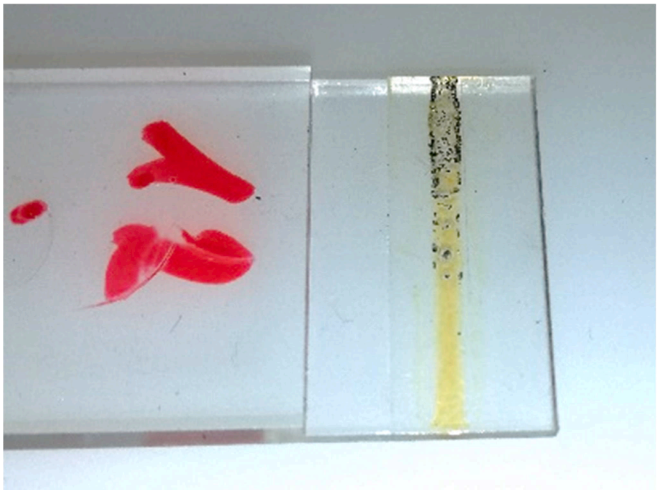


Fig. 5. PMMA burnt in samples welded at 350 °C.

The welded samples were also subjected to tensile tests, performed in a Shimadzu AGX -50 kN universal testing machine at 1 mm/min speed, to support a further analysis of the process parameters and to evaluate the correlation between parameters, strength of the joint and microscopy results.

For this, the quantity of energy applied to the rib was increased, by increasing the temperature, number of passages or beam size or by decreasing the welding velocity, until the rib was fully compressed or visible degradation marks appeared. Clamp pressure was also studied, since its increase might lead to an improvement in rib compression.

Results and discussion

In this section, the influence of welding parameters on joint strength of samples, with and without ribs, is presented and discussed, as well as the influence of rib geometry on welding parameters and on the strength of the joint. Finally, the best set of parameters achieved for each studied geometry is shown.

Influence of welding parameters on joint strength for samples without ribs

Fig. 4 presents the results obtained for lap-shear weld strength in function of the studied parameters, temperature, velocity and clamp force applied in the welding process. Weld strength was measured as the maximum load to failure per unit length of the weld (Acherjee et al., 2009).

Although values of standard deviation are relatively high, a tendency of joint strength increase can be observed with the increase of temperature (Fig. 4a). A maximum value of 15.4 ± 6.6 N/mm, for the lap-shear strength, was achieved for a temperature of 310 °C. For higher temperatures, lap-shear strength values start to decrease and visible burn marks appear on the PMMA sample for temperatures above 340 °C (Fig. 5), therefore those samples were not subjected to tensile tests.

Furthermore, an increase of welding velocity decreases weld strength, as the quantity of heat applied to the welding area is smaller (Fig. 4b). A maximum value of 15.5 ± 2.6 N/mm, for the lap-shear strength, was registered for a velocity of 4 mm/s.

It can also be observed, that weld strength seems to have a very small decreasing tendency with the increase of clamp pressure (Fig. 4c). However, the standard deviation of these measurements is big, in comparison with the mean value, that no solid conclusions can be drawn.

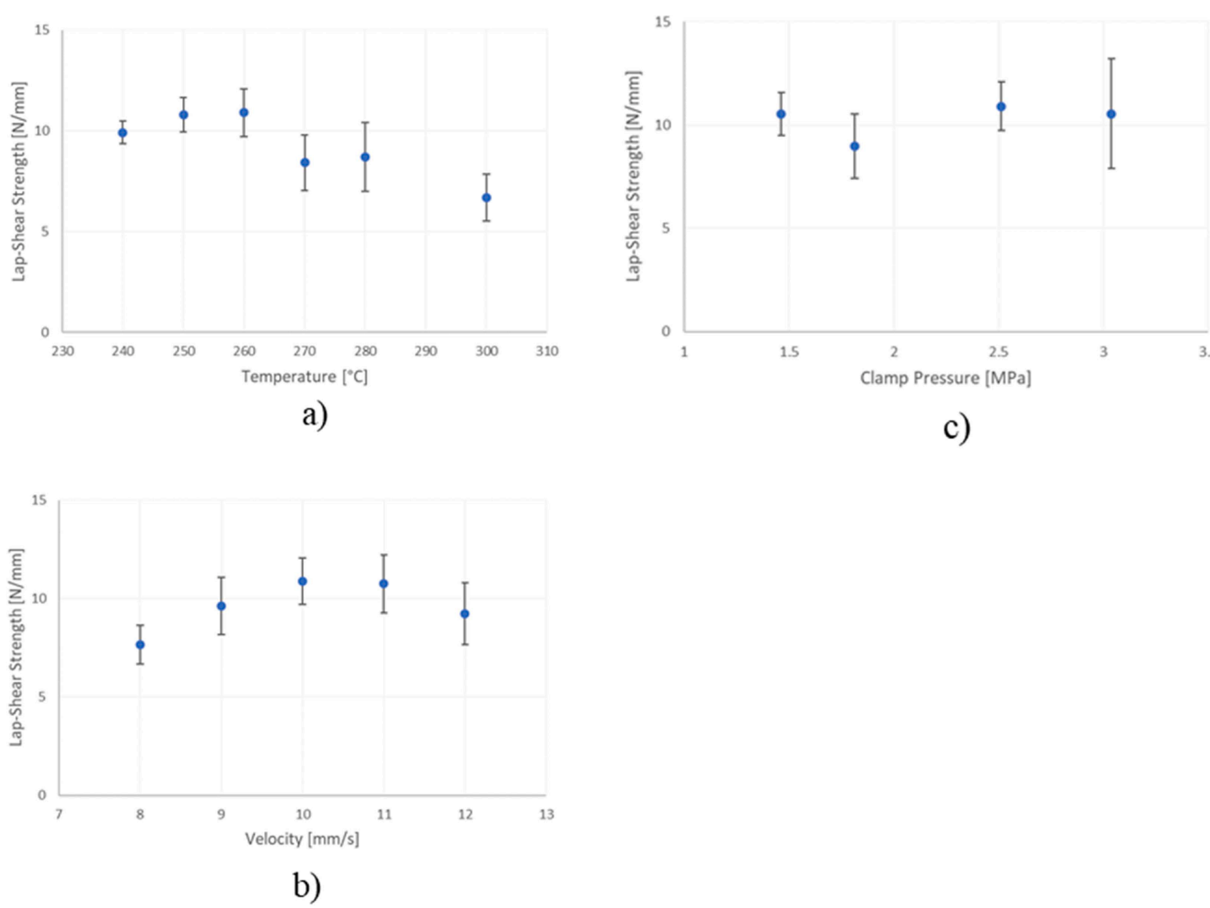


Fig. 6. Influence of the parameters on lap-shear strength in the samples with a rectangular rib.

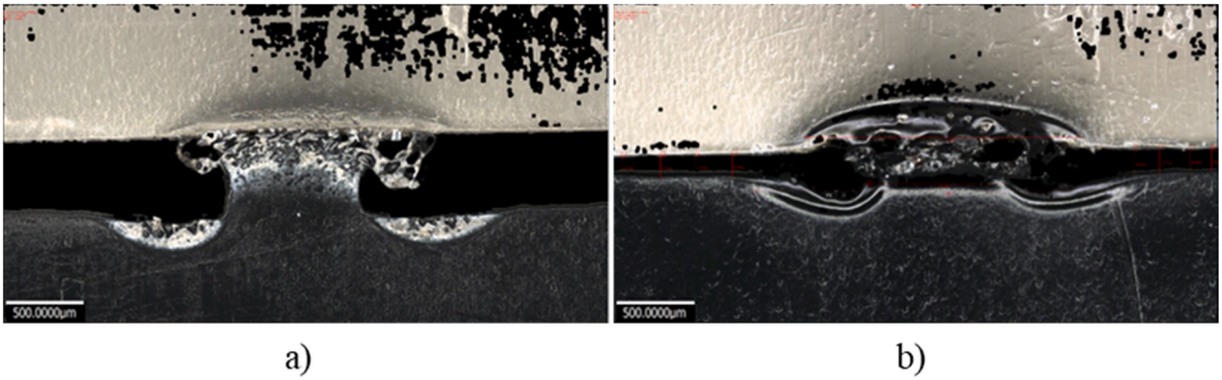


Fig. 7. Microscopic image of the side view of the sample with rectangular rib with 0.8 mm width and height welded with non-optimized (a) and best set of parameters (b).

Regarding the clamping pressure, it seems that the increase of clamping pressure does not have a significant impact in the lap shear strength. This is in accordance with the study of Van De Ven and Erdman (2007), which also mentions the work of Potente et al. (2001) on this issue, that shows that the clamping pressure does not have a significant influence on lap-shear strength, and also mentions that no firm conclusions can be achieved. However other studies (Acherjee et al., 2009; Wu et al., 2021; Acherjee et al., 2012) mention that with the increase of clamping pressure a slight increase of lap-shear strength is expected.

As it was expected, the highest values of joint strength were observed for welds performed with a high temperature (330 °C) and velocity (10 mm/s) and with a lower velocity (4 mm/s) and temperature (300 °C). From the industrial point of view, the faster the welding is performed the better, therefore the first option is more advantageous.

Influence of welding parameters on joint strength for samples with ribs

The best results obtained for the samples without ribs served as a preliminary study that will support the analysis of parameters for the samples with ribs. Furthermore, the temperature was decreased to avoid a possible material degradation in the HAZ, since in the case of samples with ribs the heat will be concentrated in a small area (rib) with limited possibility to its dissipation, due to the low conductivity coefficient that polymers, in general, have.

In Fig. 6 is presented the study of the influence of welding parameters on the strength of the joint for the sample with a rib with 0.8 mm of height and 0.8 mm of width.

For the temperature analysis, all samples were welded with a velocity of 10 mm/s, a clamp force of 201 N, a beam size of 2 mm and 1 laser pass. It can be noticed that the highest values of joint strength are achieved for a temperature between 250 and 260 °C (Fig. 6a), that is 10.8 ± 0.9 and 10.9 ± 1.2 N/mm, respectively. There is a decreasing tendency of the joint strength for higher temperatures, probably due to excess of energy applied leading to material degradation, although it is not visually noticed on the surface of the samples. On the other hand, the lower strength obtained for lower temperatures may be explained by the lack of energy applied, therefore not enough material is melted to create the bonding and a large gap is observed between samples, since the rib did not compress or spread.

For the velocity analysis, all samples were welded with a temperature of 260 °C, a clamp force of 201 N, a beam size of 2 mm and 1 laser pass. Similarly to what is observed for the temperature, an increase of velocity improves joint strength, until it achieves the maximum value for a welding velocity of 10 and 11 mm/s (10.9 ± 1.2 N/mm and 10.8 ± 1.5 N/mm, respectively). A further increase of velocity shows a decreasing tendency on joint strength (see Fig. 6b). Increasing the welding velocity too much leads to insufficient heating and formation of a weak weld, while using a low velocity may lead to material degradation.

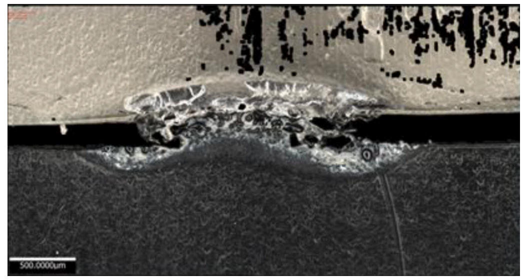
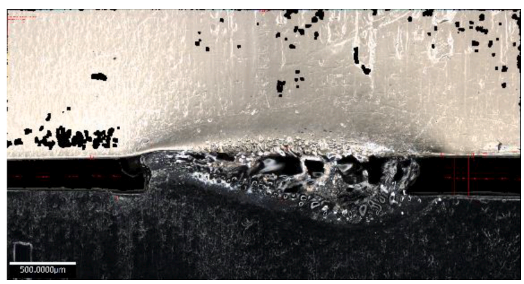
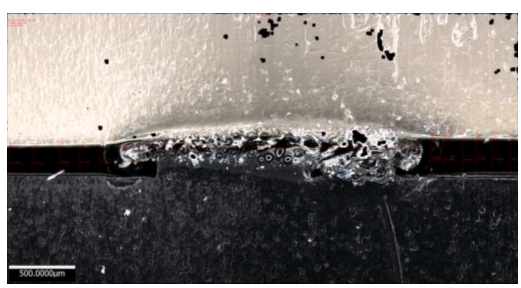
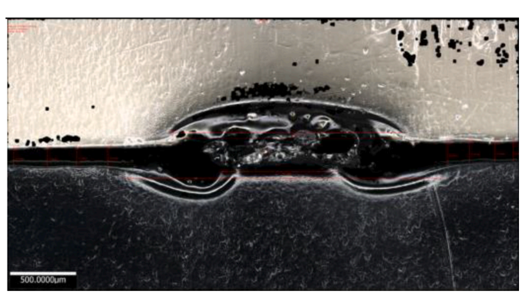
For the clamp pressure, it was expected that, in the case of samples with ribs, it would have a bigger influence on the weld strength, in comparison with samples without ribs, since it not only provides contact for better heat transfer between welded materials, but also increases compression of the melted rib. This promotes the increase of joint area between both materials, therefore increase of joint strength. However, this was not observed as it can be seen in Fig. 6c, which presents the influence of clamp pressure on joint strength in the sample with the rib. For the whole studied range of clamp pressure the strength of the joint remained at around 10 N/mm, thus it seems that clamp pressure does not have a meaningful influence on the lap-shear strength, similarly to what happens in the samples without ribs, and it serves only to

Table 3
Best welding parameters for samples with ribs.

	Height of the rib [mm]	Width of the rib [mm]	Temperature [°C]	Velocity [mm/s]	Clamp force [N]	Clamp pressure* [MPa]	Beam size [mm]	Number of passes
Rectangular	0.5	0.8	280	10	201	10.05	2	1
	0.5	1.0	260	6	201	8.04	2	2
	0.5	1.2	260	10	173	5.77	2	2
	0.8	0.8	260	10	201	10.05	2	2
	1.1	0.8	220	10	243	12.15	2	2
Triangular	0.5	0.8	240	10	243	12.15	2	2
	0.5	1.0	240	12	201	8.04	2	2
	0.5	1.2	240	10	201	6.70	2	2
	0.8	0.8	240	10	243	12.15	2	2
	1.1	0.8	220	4	201	10.05	2	2

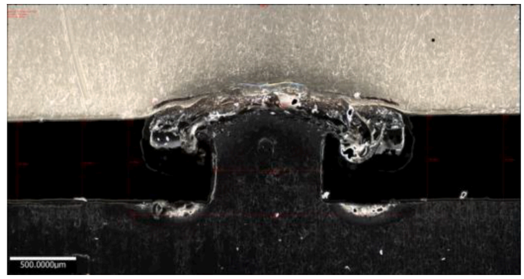
* Clamp pressure varies throughout the welding process, since the rib area varies as the material spreads. For triangular ribs the area considered for the pressure calculations corresponds to the area at the base of the rib.

Table 4
Microscopy and strength results obtained using the best set of welding parameters for the rectangular ribs.

Height of the rib [mm]	Width of the rib [mm]	Microscopy results	Strength of the joint [N/mm]
0.5	0.8		15.79 (±1.8)
0.5	1.0		22.16 (±1.3)
0.5	1.2		22.44 (±2.5)
0.8	0.8		17.54 (±2.6)

(*continued on next page*)

Table 4 (*continued*)

Height of the rib [mm]	Width of the rib [mm]	Microscopy results	Strength of the joint [N/mm]
1.1	0.8		15.99 (±0.7)

guarantee contact between sample.

The influence of the laser beam size on the strength of the joint was also studied. The laser beam has a circular shape and the diameters of 1 mm and 2 mm were studied. It was observed that the increase of beam size, while maintaining all other parameters, seems to result in the improvement of the strength of the joint (1 mm–6.81 N/mm; 2 mm–8.71 N/mm). This could be explained by the fact that the same temperature is applied to a bigger area, therefore the heat transferred to the sample is higher.

Finally, the influence of the number of laser passes on the strength of the joint was also studied. It was observed that the increase of laser passes, from 1 to 2, significantly improved the strength of the joint, almost doubling the lap-shear strength (1 pass – 10.90 N/mm; 2 passes – 17,54 N/mm).

Fig. 7 presents a comparison between the rib joint with non-optimized (Fig. 7a) and with the best set of studied parameters (Fig. 7b). These images refer to the microscopy results obtained for a rib with 0.8 mm of height and width.

As it it can be noticed, for the case where the best set of parameteres was used, the rib is almost completely melted and compressed, and a strength of the joint of 17.5 ± 2.6 N/mm is obtained.

Influence of rib geometry on welding parameters

The same study of process parameters presented previously for the rib with a rectangular geometry, was also performed for other rib geometries and dimensions, which allowed to analyse how the geometry of the ribs influences the process parameters. As mentioned before, only the best results obtained for the studied parameters will be presented.

The best studied parameters, obtained for each studied geometry, are presented in Table 3. In Tables 4 and 5 are presented the results obtained in the microscopy tests and the strength of the joint obtained for each geometry.

It can be observed that in case of rectangular ribs, the higher the rib was, the lower temperature was needed in order to obtain higher strength (maintaining the same velocity of 10 mm/s). An increase of clamp pressure was also needed for high ribs. As the height is increased it becomes more difficult to heat the whole rib, which means that a greater force is needed to compress the rib, due to the lack of temperature in the lower part of the rib.

It was also observed that, wider ribs need slightly lower temperatures and significantly lower clamping pressures to achieve higher joint strength. This can be explained by the fact that these wider ribs have larger initial contact areas, thus might need less energy and pressure for the same amount of rib spreading to be obtained.

Regarding the laser velocity, the optimal velocity value does not vary with the rib geometry.

As for the number of passes, for the lowest and less wide rib, a complete melt and compression of the rib was achieved with only one pass of the laser. It was also found that, the higher is the rib, the bigger is the improvement of the joint strength due to the increase of the number of laser passes.

Regarding beam size, and similarly to what was observed in the preliminary tests, a beneficial influence was noticed on the strength of the joint with the increase of beam size, from 1 to 2 mm, for both triangular and rectangular ribs, as the HAZ is larger.

In general, the optimal temperature obtained for triangular ribs was lower than the one obtained for rectangular ribs. This can be explained by the fact that a smaller amount of material is needed to be melt. There was also almost no temperature variation for different sizes of the triangular ribs. The width of the triangular rib, within the studied range, does not influence the optimal welding conditions and they can be defined as 240 °C, 10–12 mm/s and 201–243 N, which corresponds to a pressure of 6. –12.15 MPa.

Similarly to the rectangular ribs, for triangular ribs higher and less wide ribs need more clamping pressure to achieve higher values of joint strength, and the laser velocity does not vary with the rib geometry.

As can be seen from the microscopy tests (Tables 4 and 5) and as expected, the lap-shear strength is strongly connected to rib compression and spreading, for a higher compression and spreading of the rib, a higher lap-shear strength is obtained. As mentioned before, triangular ribs present a higher lap-shear strength, which can be related to the fact that the triangular ribs have a better compression/spreading, with little to no gap between samples. Rectangular ribs have similar rib spreading, but present larger distances between samples, since in some areas it seems that the rib could be further compressed. These gaps promote misalignment of the sample with the axis of tensile test machine, therefore there is more torsion of the sample and lower strength can be achieved.

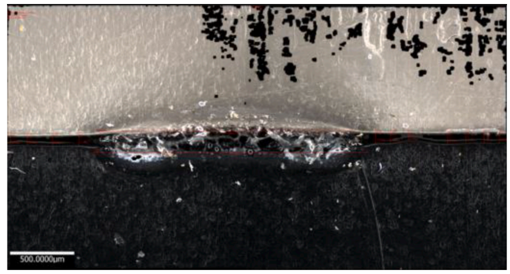
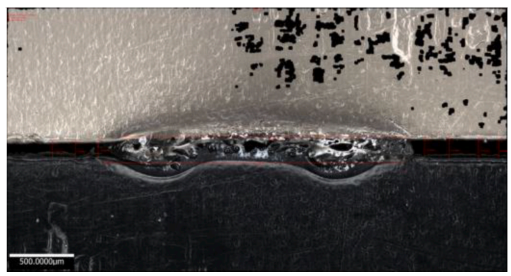
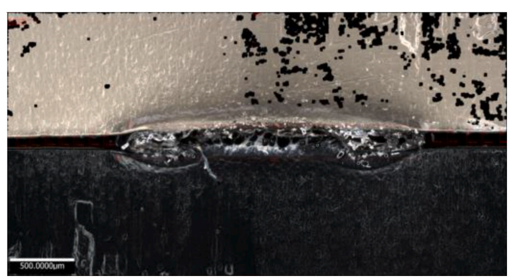
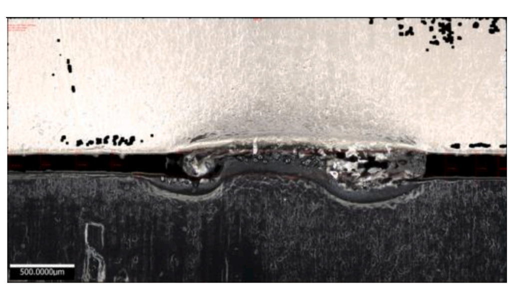
Influence of rib geometry on the strength of the joint

The influence of the rib geometry on the strength of the joints was also studied, for both rectangular and triangular ribs.

Figs. 8 and 9 depict the influence of the rib dimensions on the strength of the joint. For this, the samples were welded using the same welding parameters and the rib dimensions were varied. All the samples with rectangular ribs were welded with a temperature of 280 °C, a velocity of 10 mm/s, a clamp force of 201 N, a beam size of 2 mm and 1 laser pass. The sample with the highest rib was an exception, since it was welded with a temperature of 260 °C. All the samples with triangular ribs were welded with a temperature of 240 °C, a velocity of 10 mm/s, a clamp force of 201 N, a beam size of 1 mm and 2 laser passes. Samples without ribs were welded with temperatures of 280 °C and 240 °C, to allow the comparison with the results obtained for rectangular and triangular ribs, respectively. Although the clamp force used for the welding of samples without ribs was different than in those with ribs, this can be neglected, since it seems not to influence the strength of the joint, as observed in Figs. 4c and 6c.

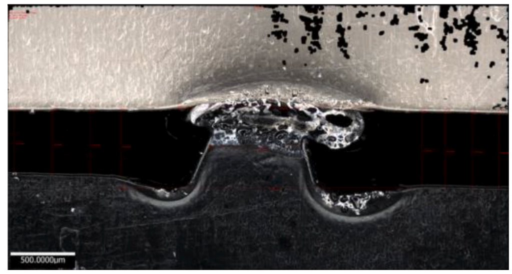
It can be seen (Figs. 8 and 9) that the presence of the low rib (0.5 mm

Table 5
Microscopy and strength results obtained using the best set of parameters welding parameters for the triangular ribs.

Height of the rib [mm]	Width of the rib [mm]	Microscopy results	Strength of the joint [N/mm]
0.5	0.8		23.59 (±2.6)
0.5	1.0		20.48 (±2.1)
0.5	1.2		28.09 (±1.5)
0.8	0.8		23.21 (±2.2)

(continued on next page)

Table 5 (*continued*)

Height of the rib [mm]	Width of the rib [mm]	Microscopy results	Strength of the joint [N/mm]
1.1	0.8		14.77 (±1.2)

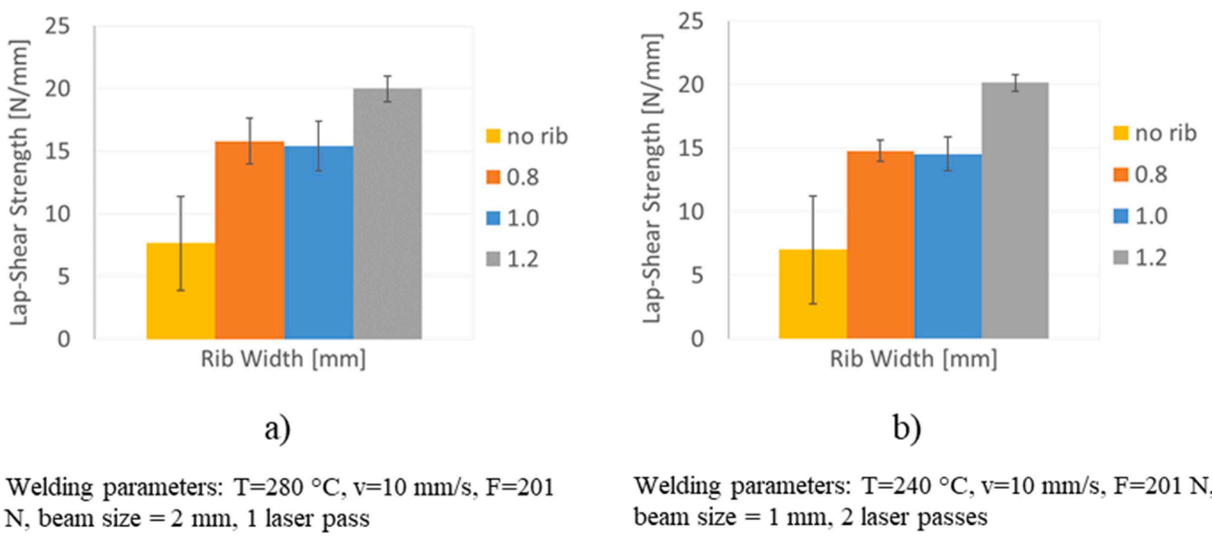


Fig. 8. Influence of the width of the rib on the strength of the joint: a) rectangular rib; b) triangular rib.

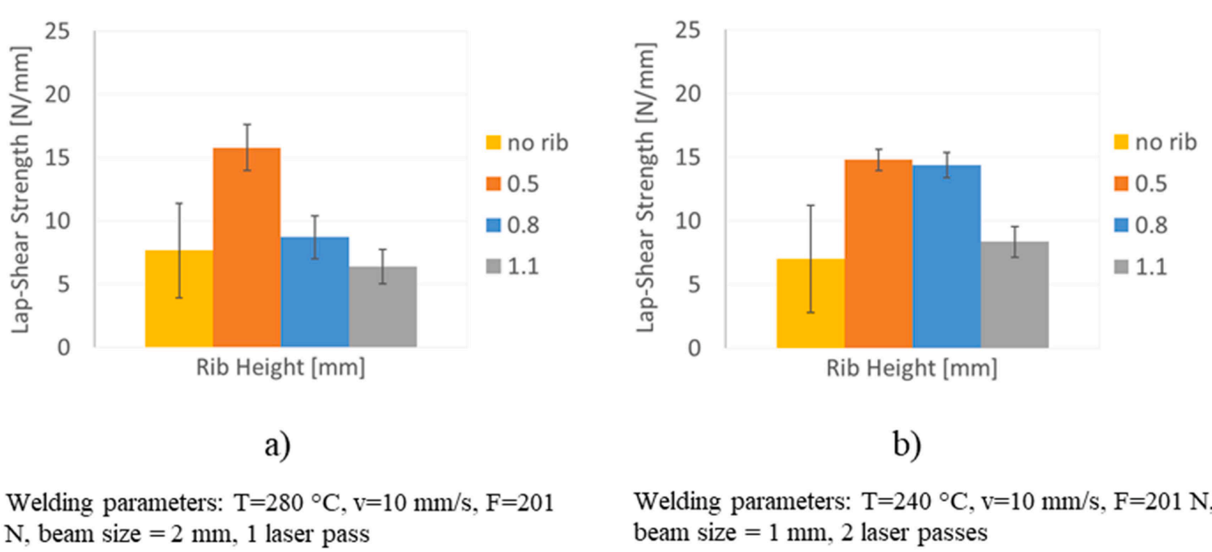


Fig. 9. Influence of the height of the rib on the strength of the joint: a) rectangular rib; b) triangular rib.

of height) is always beneficial, especially if it is 1.2 mm wide.

For both rectangular and triangular ribs there is no difference in strength of the joint for ribs with 0.8–1.0 mm of width. However, an increase of width to 1.2 mm improves the strength of the joint in about 25 % (Fig. 8).

The increase of the height of the rib decreases strength of the joint (Fig. 10). In the case of rectangular ribs there is a significant difference of 45 % in rib strength between 0.5 and 0.8 mm height (Fig. 10a). In the case of triangular ribs (Fig. 10b), the results obtained for ribs with 0.5 and 0.8 mm height do not present apparent differences in joint strength,

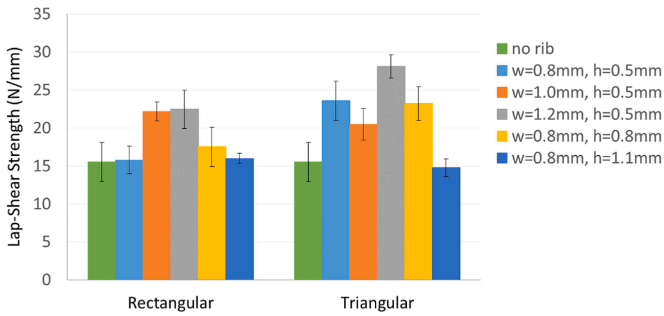


Fig. 10. Comparison of the best strength results obtained for each geometry.

while further increase of the height to 1.1 mm leads to a 53 % drop in relation to the rib with 0.5 mm height. The difference in behaviour between rectangular and triangular ribs with 0.8 mm height might be explained by the fact that it is easier to compress/spread the material for the case with a triangular rib, due to its geometry. Triangular ribs seem to present a better compromise between welding area and material quantity, since they are easier to compress, due to a better distributed heating throughout the whole rib, i.e. for rectangular ribs it is harder to achieve a good heating at the base of the rib.

When the rib is more melted and compressed, the distance between the components of the sample is smaller and, as mentioned before, this promotes less misalignment of the sample with the axis of tensile test machine, and consequently higher strength.

The study of the influence of the welding process parameters allowed obtaining a set of parameters, for each geometry, that would lead to better joint strength results.

Fig. 10 presents the comparison of the best results obtained for each geometry, for both rectangular and triangular ribs, with the best result obtained for the sample without the rib.

It can be noticed that for samples welded with triangular ribs a higher joint strength is obtained for almost all geometries in comparison with samples with rectangular ribs and without rib. This should be related to the fact that for rectangular ribs it is harder to achieve a good heating at the base of the rib, as mentioned before. The geometries with a width of 1 mm and a height of 0.5 mm, where the triangular and rectangular ribs have similar lap-shear strengths (triangular – 20.48 ± 2.05 N/mm; rectangular – 22.16 ± 1.26 N/mm). The ribs with 1.1 mm of height also have similar lap shear strengths, having considerably worse behaviour then other rib dimensions and having similar strength as the samples without rib.

Furthermore, comparing with the results obtained with the unoptimized set of parameters, similar conclusions can be achieved. Increasing the width of the rib seems to improve the strength of the joint, for both rectangular and triangular ribs. For rectangular ribs, it seems that adding a rib with a width of 0.8 mm does not improve the lap-shear strength significantly. However, adding a wider rib (width of 1 mm or 1.2 mm) seem to have a significantly positive influence on lap-shear strength. For triangular ribs, the presence of the rib, for every studied width, seem to improve the lap-shear strength.

On the other hand, increasing the rib height seem to have a negative or no impact on lap-shear strength. For rectangular ribs, the height increase seems to have no significant influence on lap shear-strength. However, as can be seen from microscopy tests, rib compression is significantly affected by this increase, where ribs with 1.1 mm of height have significantly worse compression then shorter ribs, which might be prejudicial for mechanical behaviour as mentioned before. For triangular ribs, an increase from 0.5 mm to 0.8 mm does not significantly influence the lap-shear strength, but increasing the height to 1.1 mm the strength is considerably decreased, by almost 40 %. The lap-shear strength obtained for the triangular rib with a height of 1.1 mm is similar to the one obtained with samples without rib.

The highest strength of the joint obtained was of 28.1 ± 1.5 N/mm and it was obtained for the triangular rib with 1.2 mm of width and 0.5 mm of height, which is 45 % more than the best result obtained with the sample without rib. As it can be seen in Fig. 11, the rib is completely melted and compressed.

Conclusions

The influence of the geometry of the rib and welding parameters in laser transmission welding of thermoplastics was investigated. It can be concluded that the presence of the tested ribs improves the strength of the joint and that the influence of the welding parameters on the strength of the joint depends on the rib geometry. Analysed triangular ribs seem to be more beneficial than rectangular ones, as they allow obtaining a better joint strength. Triangular ribs seem to present a better compromise between welding area and material quantity, since they are easier to compress, due to a better heat distribution throughout the whole rib. For rectangular ribs it is harder to achieve a good heating at the base of the rib. From microscopy tests, it is observed that smaller gaps between samples are obtained for triangular ribs. Thus, since the triangular rib use less material and need lower temperatures, they are more cost effective.

An increase of the width of the rib, within the diameter of the laser, has a positive influence on lap-shear strength, since the welded area is increased. On the other hand, regarding the height of the rib, an increase from 0.5 mm to 0.8 mm does not significantly influence the lap-shear strength, while an increase of the height to 1.1 mm decreases joint strength significantly, to a point where the use of rib becomes useless (same lap-shear strength as the samples without ribs). An excessive

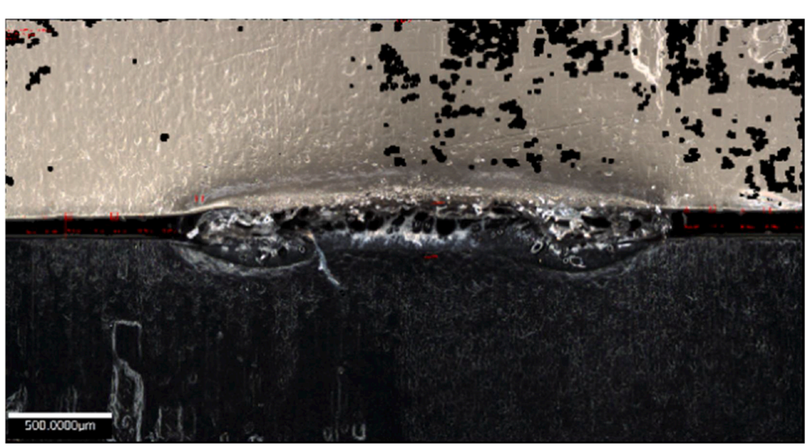


Fig. 11. Microscopic image from the side of the sample that resulted in the highest strength of the joint (triangular rib with 1.2 mm width and 0.5 mm height).

increase in rib height is not advantageous, since there is no capacity to melt the whole rib.

The presence of the rib seems to be very beneficial in terms of joint strength, but it is important to use an adequate rib height and guarantee that the whole rib is melted.

Regarding welding parameters, it was found that samples with ribs need lower welding temperature than samples without ribs, especially the triangular ribs. The optimal value of velocity is the same for all the ribs, with the exception of the highest triangular rib tested, for which velocity should be significantly decreased. No solid conclusions can be drawn concerning the influence of clamp pressure on joint strength due to the very high values of standard deviation in conducted tests. The increase of beam size and number of laser passes also improves the results in all cases of studied ribs.

CRediT authorship contribution statement

Lourenço Bastos: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Marco Alves:** Investigation, Methodology, Resources. **Bruno Sousa:** Formal analysis, Investigation, Methodology, Resources. **Andreia Vilela:** Data curation, Investigation. **Luciano Rietter:** Investigation. **Fernando Duarte:** Investigation, Supervision, Validation, Writing – original draft, Conceptualization. **Filipa Carneiro:** Conceptualization, Supervision, Validation. **Agnieszka Żmijewska-Rocha:** Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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