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HIGHLIGHTS

Flat shoulder tool is inadequate for performing copper friction stir welds;

Scrolled shoulder provides the largest range of non-defective welds;

Scrolled shoulder provides welds with finer grain structure and higher strength;

Conical and scrolled shoulders require a minimum rotational speed to avoid defects.

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INFLUENCE OF TOOL SHOULDER GEOMETRY ON PROPERTIES OF FRICTION STIR WELDS IN THIN COPPER SHEETS

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ABSTRACT

The aim of this work is to study the influence of the shoulder geometry on friction stir welding of 1 mm-thick copper-DHP plates. The welds were produced using three different shoulder geometries, flat, conical and scrolled, and varying the rotation and traverse speeds of the tool. The flat shoulder tool proved to be inadequate for performing welds, because many defects were produced for all welding conditions. In turn, the scrolled shoulder tool is more effective than the conical one in the production of defect free welds. However, both geometries required a minimum rotational speed to avoid internal defects. For the same welding parameters, greater grain refinement, higher hardness and improved strength are also achieved in the nugget of the welds, using the scrolled tool.

Keywords: Friction Stir Welding; Shoulder geometry; Microstructure; Mechanical properties; Copper.

INTRODUCTION

Although many researchers recognize that tool geometry is a fundamental parameter in the friction stir welding (FSW) process, the knowledge of its influence on heat generation, material flow and the properties of the welds is still limited (Nandan et al., 2008). In fact, as the geometry of the tools is complex and difficult to characterize, most of the studies consider the effect of the tool shoulder and pin separately, as in Zao et al. (2006) and Leal et al. (2008). As it is well-known, the basic functions of the tool are to generate heat, in order to plasticize the material, and to direct the flow of plasticized material, preventing the formation of defects. In particular, the tool pin plays an important role in the flow of material in the thickness direction, especially in thick plates. This way, in recent years, instead of the traditional cylindrical or conical threaded pins, tools with pins of complex geometry have been developed, as showed by Thomas et al. (2003). Fuller (2007) and Rai

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et al. (2011) summarize very well the tool geometries developed in recent years as well their effects on the welding process. The virtues attributed to these complex geometries are related to the increased flow of material in the thickness direction as well as to higher heat generation due to the increased interface area between the tool and the workpiece. However, Schmidt et al. (2004) developed an analytical model for a tool with a conical shoulder and cylindrical pin, which showed that most of the heat is generated by the shoulder and only about 14% is generated by the pin. Moreover, Mehta et al. (2011), on FSW in 7075-T6 alloy, pointed out that the heat generated increases with increasing shoulder diameter. These authors also stated that the optimum diameter is a function of the tool's rotation speed.

Dawes and Thomas (1999), in a further shoulder geometry study, showed that the use of a scrolled-shoulder tool allows welds in aluminum alloys to be produced without tool tilting, which besides improving the surface finishing and the mechanical properties of the welds, allows higher welding speeds. Although this study was published in 1999, only few recent studies, such as Scialpi et al. (2008), Gratecap et al. (2008) and Leal et al. (2011), have addressed the influence of the shoulder geometry on the quality of friction stir welds, particularly in reduced thickness welds, where material flow is more constrained due to the cooling effect of the backing plate.

Copper and alloys, although expensive, have great potential to be used in industry due to their high electrical and thermal conductivities and excellent corrosion resistance. As mentioned by McNelley et al. (2007) and Cederqvist et al. (2009), they are used for components in a wide range of marine systems and, for example, for the encapsulation of nuclear waste material. However, copper alloys are difficult to weld by fusion because adherent oxides inhibit welding, or volatile and toxic elements, such as zinc, may be present in the alloys, requiring adequate ventilation. Therefore, FSW is a good option for joining parts made of these materials. The optimization of FSW tool geometry and process parameters is still required. To this end, the current study addresses the effect of tool shoulder geometry on the microstructure and mechanical properties of friction stir welds in

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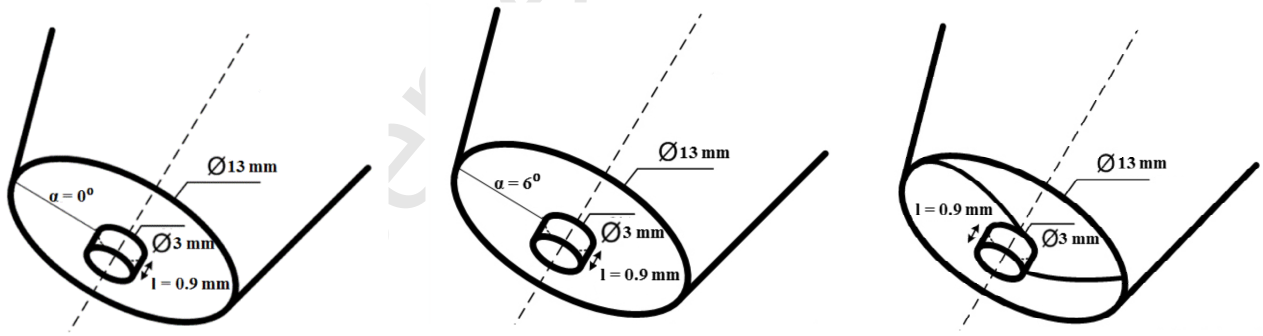
thin copper sheets. The effect of shoulder geometry on the heat generated in the process is also discussed.

EXPERIMENTAL PROCEDURE

Copper plates, 1 mm-thick and 250 mm-long, were butt joined by friction stir welding. The base material was deoxidized copper (copper-DHP), temper class R240, with a grain size of 18 µm and an average hardness of 92 $HV_{0.2}$. Three tools with a 3 mm-diameter and 0.9 mm-length right-handed-thread cylindrical pin and a 13 mm-diameter shoulder were used. The shoulder diameter was chosen in order to maximize the effect of this part of the tool. Three shoulder geometries were selected, flat (F), because of its simplicity, 6º conical concave (C), which has been widely used in previous studies, such as Scialpi et al. (2008) and Gratecap et al. (2008), and scrolled (S). The scrolled shoulder was composed of two helical whorls protruding 0.4 mm above the shoulder. Detailed characteristics of the shoulders are schematically illustrated in **Figure 1**.



(a) (b) (c)

Figure 1 - Schematic representation of the flat (a) conical concave (b) and scrolled (c) shouldered tools.

The welds were performed in an ESAB Legio FSW machine with a maximum vertical down force of 25 KN. This machine allows the torque required during weld tests to be registered. All

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welds were done using an axial force of 7000 N, which was adjusted in advance to avoid the pin touching the backing plate. A tool tilt angle of 2° was used for the flat and concave tools and 0 ° for the scrolled tool, in order to drive the material flow better. The set of welding parameters tested was selected based on previous experience. The tool rotation speed (W) was varied in the range of 400 to 1000 rev.min^{-1} and the traverse speed (v) between 160 and 250 mm.min^{-1}. Although a few experiments have been done at 1500 rev.min^{-1} or 500 mm.min^{-1}, no proper welding conditions were achieved for these speeds.

Individual welds are identified in the text by a code that contains the description of the tool (F, C or S) followed by W and the rotation speed divided by 100, and V and the traverse speed in cm.min^{-1}. Thus, a weld made with the scrolled shoulder tool, using 1000 rev.min^{-1} and 250 mm.min^{-1}, is identified as S_W10V25.

Metallographic specimens were removed transverse to the welding direction, polished and etched, at room temperature, by immersion for 20 seconds in a solution consisting of $FeCl_3$ (2.5 g), H_2O (100 ml) and HCl (15 ml). The grain size of the base material and welds was measured using the mean linear intercept method. For welds with finer grain in the nugget, TEM was used to evaluate the grain size. TEM specimens were prepared by conventional procedures. Vickers hardness was measured using a 200 gf load for 15 seconds. Root bending, according to ASTM E190, and tensile testing, according to ASTM E8, were carried out on transverse specimens. The tensile specimens, 12.5 mm wide and with a 50 mm gauge length, were taken only from the defect-free welds. These tests were performed using an optical extensometer in order to assess the degree of deformation in different regions of the welds.

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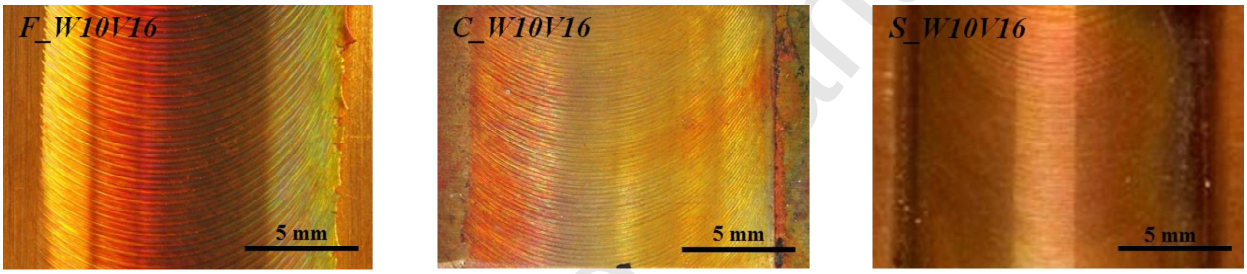
RESULTS

Welds Morphology

Independently of welding parameters, all tools gave rise to the production of welds with excellent surface appearance, with regular and well-distributed grooves. Effectively, from **Figure 2**, which illustrates the surface of three welds produced with the different geometries under study, but using the same welding parameters, it can be observed that smooth surfaces with virtually no flash, either on the advancing or retreating side of the welds, were produced.



(a) (b) (c)

Figure 2 - Surface appearance of the F_W10V16 (a), C_W10V16 (b) and S_W10V16 (c) welds.

In spite of the good surface finishing, metallographic analysis and bending tests revealed that some welds had root defects and, in some cases, internal defects too. **Table 1** summarizes the defects observed in the three series of welds. All specimens with root defects failed during bending tests, although no complete fracture was observed in any specimen. The table shows that all welds produced at the lowest rotational speed (400 rev.min^{-1}) had root defects or root defects and voids, as illustrated in **Figures 3.a and b** for welds C_W4V16 and S_W4V25, respectively. Nevertheless, as observed in the cross-section macrographs of the nugget of welds illustrated in **Figure 4**, for higher rotational speeds, these defects tended to disappear in the joints produced with the conical (**Figure 4.a**) and scrolled (**Figure 4.b**) tools, as opposed to those made with the flat shouldered tool (**Figure**

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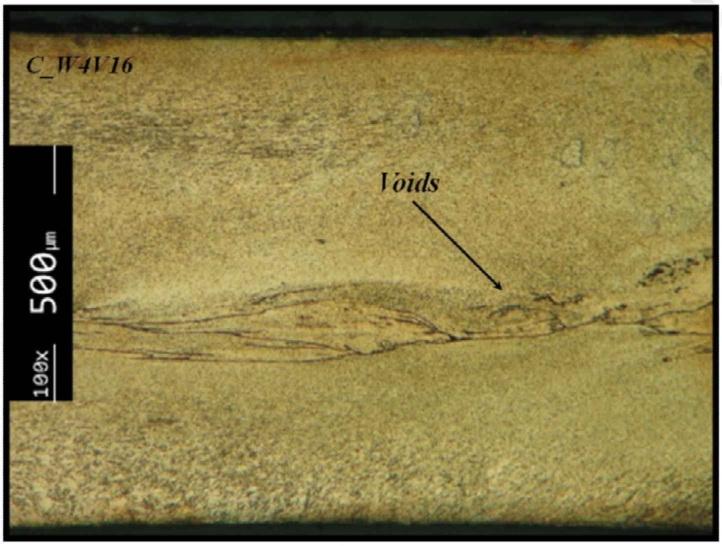
4.c), which exhibited root defects for all welding parameters. **Figure 4.b**, of the weld S_W10V25, shows a joint line remnant caused by the oxides of the plates, but no defects. **Figure 4.c** illustrates, in addition to a root defect and voids, the shoulder driven and pin driven material flow zones, separated by a dotted line.

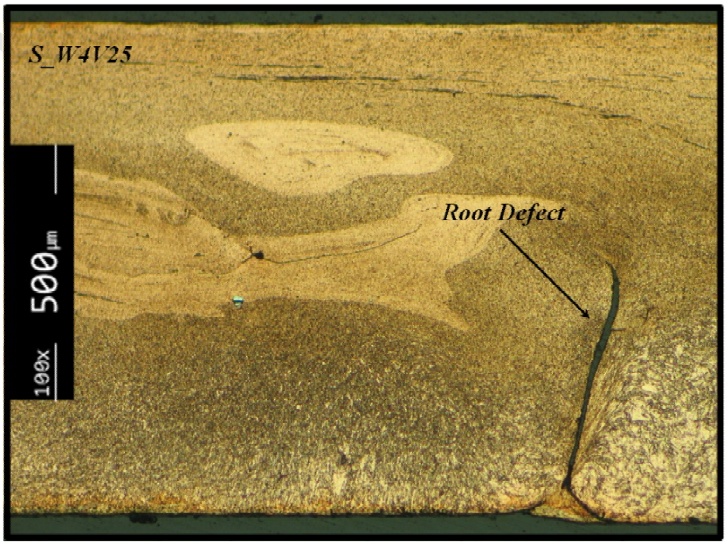
Table 1 - Resume of the defects observed in the welds.

Welding Parameters	*Shoulder Geometry*		
	Flat	*Conical*	*Scrolled*
W4V16	------------	Root Defects + Voids[1]	Root Defects + Voids[1]
W4V25	------------	Root Defects + Voids[1]	Root Defects + Voids[1]
W7.5V16	Root Defects	Root Defects	No Defects
W7.5V25	Root Defects	Root Defects + Voids[1]	No Defects
W10V16	Root Defects	No Defects	No Defects
W10V25	Root Defects	No Defects	No Defects

[1]Voids located mainly on the advancing side.



(a)



(b)

Figure 3 - Defects observed in welds produced at 400 rev.min^{-1}: C_W4V16 (a) and S_W4V25 (b).

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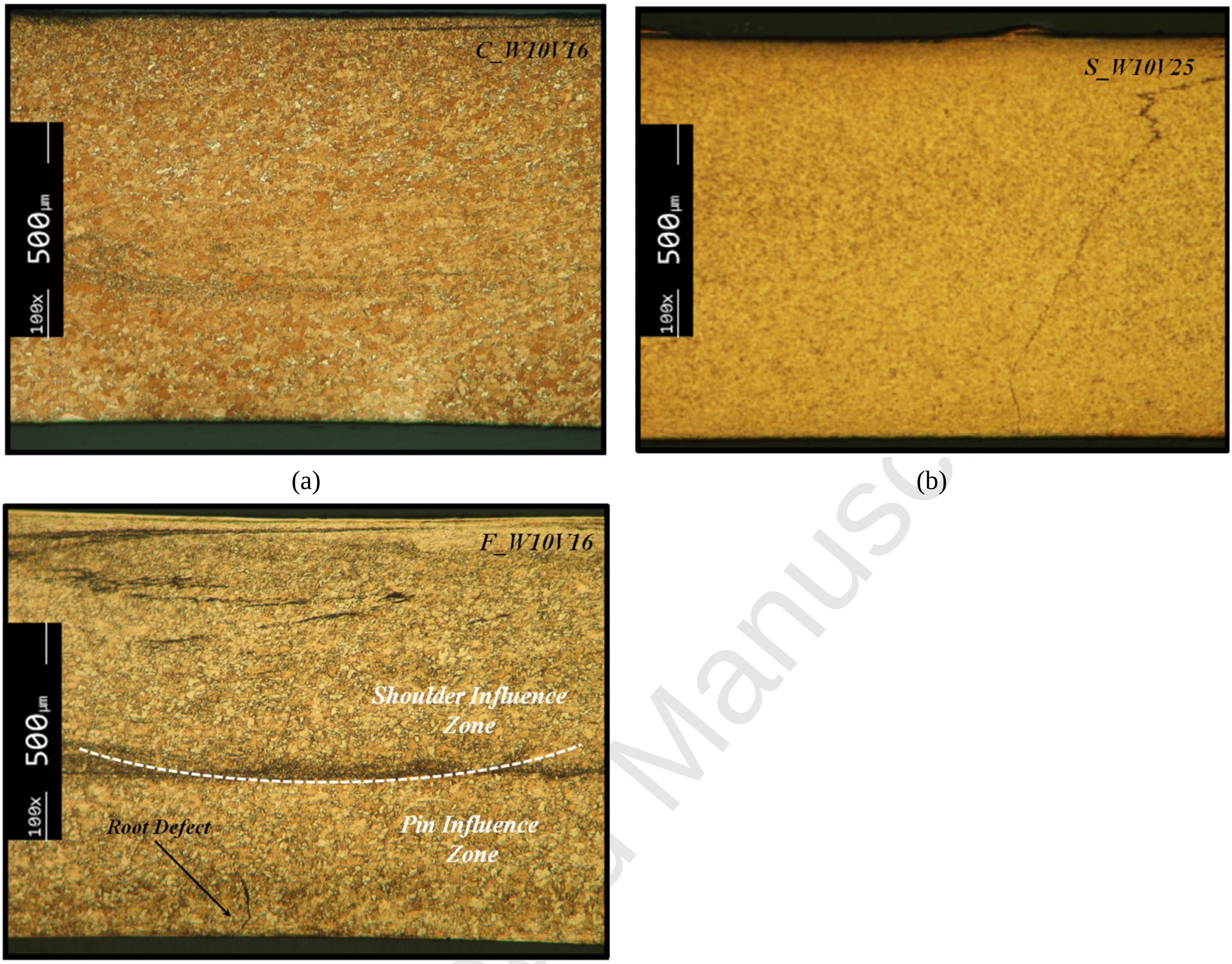

(a) (b)

(c)

Figure 4 - Macrographs of the nugget of the C_W10V16 (a), S_W10V25 (b) and F_W10V16 (c) welds.

Spindle Torque

The torque consumed during welding is a measure of the opposition to the rotation of the tool that depends on the material shear strength, which, in turn, is a function of operating temperature. So, as mentioned by Khandkar et al. (2003), torque can be used to provide an estimate of the temperature field in welding. According to Peel et al. (2006) and Arora et al. (2009), torque depends, besides the

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geometry of the tool, on other variables, such as the rotational and traverse speeds of the tool and the axial force. Nevertheless since, in current investigation, these variables are the same for the three tool geometries under study, torque can be taken as an indicator of the influence of tool geometry on temperature.

Figure 5 shows the evolution of the average torque values as a function of the welding parameters (v and W), for the different tool geometries. The torque value registered in welding at 1500 rev.min^{-1} with the flat shoulder has also been included in the figure, in order to better illustrate the evolution of the torque with W. However, for this rotation there was welding of the copper plates to the backing plate, due to the excess heat generated. The general trend of the curves in **Figure 5** indicates a reduction in torque with increasing rotation speed. This figure also shows that, for all welding parameters tested, the lowest torque values were registered in welds carried out using the flat shoulder tool.

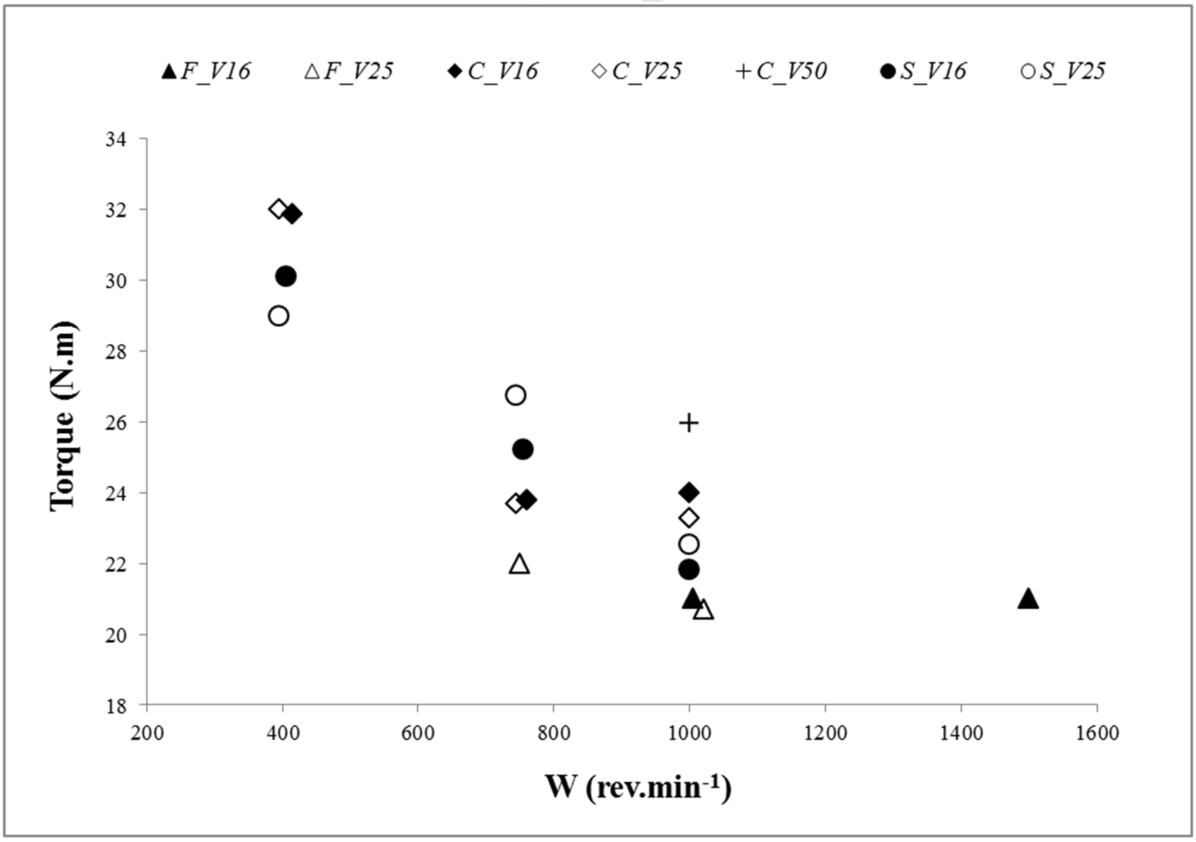

Figure 5 - Influence of rotational speed and tool geometry on average welding Torque.

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Microstructure and Mechanical Properties

As mentioned by several researchers, such as Li et al. (1999) and Xie et al. (2007), the grain size in the nugget is related to the heat generated in the process, which depends on the tool and process parameters. As in the current study the process parameters used for all the tools were the same, the grain size in the nugget of the welds can give useful information about the influence of tool geometry on generated heat.

Figure 6 illustrates the evolution of the average grain size in the nugget of the welds as a function of rotational speed and tool geometry. From the figure it can be observed that the evolution of grain size in welds produced with the flat and conical shoulders is similar and increases with rotation. In turn, the grain in the welds made with the scrolled shoulder is much finer and less dependent on the rotation speed, for the range of speeds tested. Nevertheless, it is important to stress that the grain size is not uniform in the nugget of the welds, particularly for those carried out with the conical and scrolled shoulders. As illustrated in **Figure 7.a** for weld C_W10V16, some bands with finer grains (1-2 µm) than the overall structure (7-8 µm) were observed at the nugget of the welds made with the conical shoulder at 1000 rev.min^{-1}. In the same way, although **Figure 6** depicts an average grain size of 1 µm for the welds made with the scrolled tool at 1000 rev.min^{-1}, grains larger than 1 µm coexist with grains of about 0.5 µm in the nugget of these welds, as illustrated in **Figure 7.b**.

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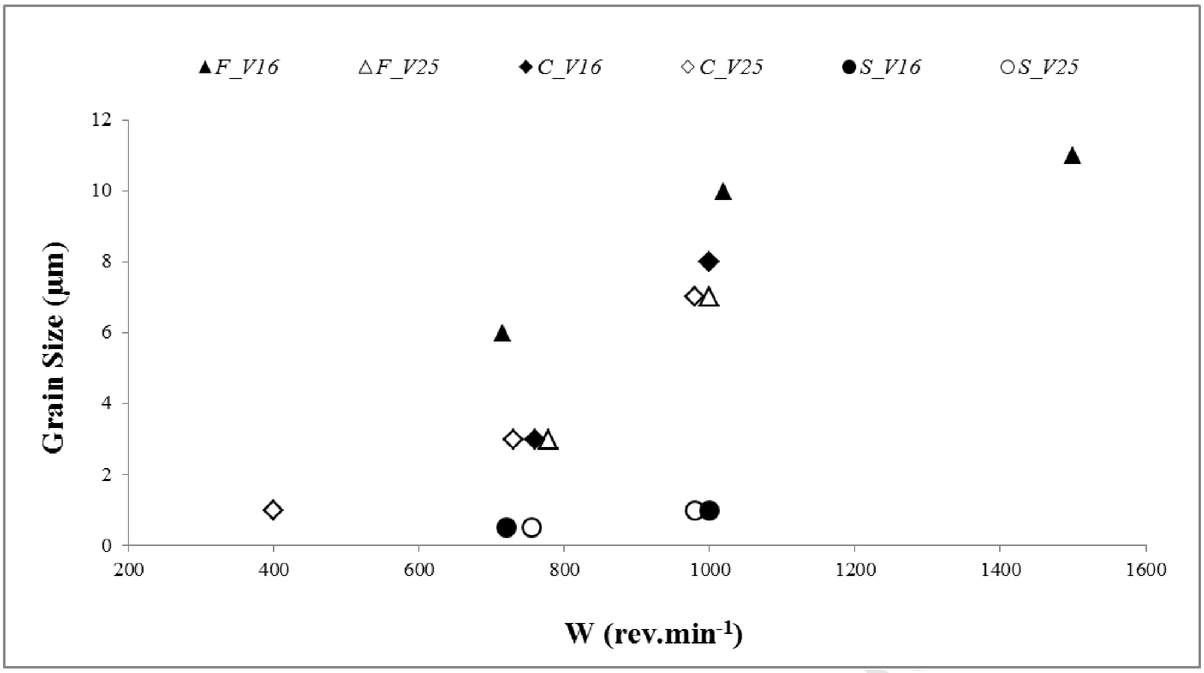
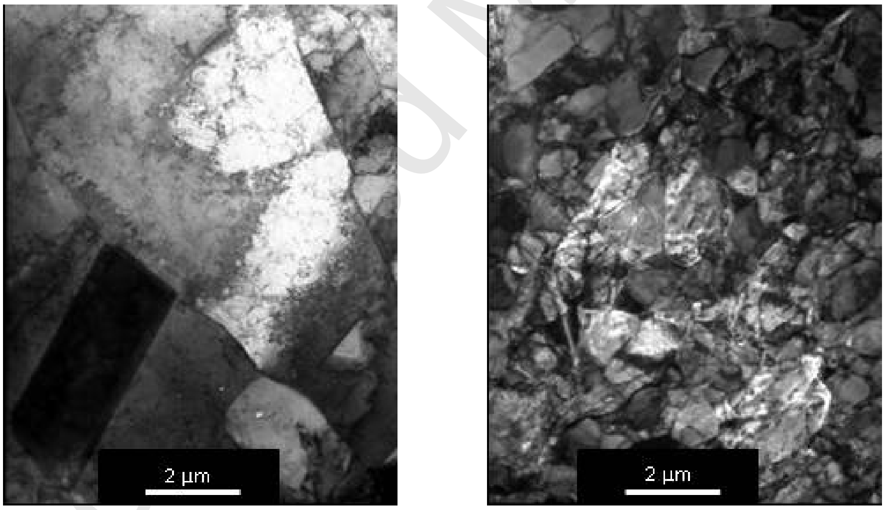


Figure 6 - Influence of rotational speed and tool geometry on the weld nugget average grain size.



(a) (b)

Figure 7 - TEM micrographs illustrating the grain structure in the nugget of the C_W10V16 (a) and S_W10V16 (b) welds.

Figure 8 illustrates the hardness profiles measured in the cross section of the welds produced at 1000 rev.min^{-1} and 250 mm.min^{-1}. The weld centerline is located in the nugget of the welds. The

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width of the non-recrystallized TMAZ varies slightly from one specimen to another. As mentioned above, the average hardness of copper-DHP is about 92 $HV_{0.2}$. So, from the figure it can be observed that the welds made with the flat and conical shoulders have only a slight increase in hardness in the TMAZ, on the advancing side. This local hardening results from competition between softening, produced by heat generated in the process, and hardening, which is given by plastic deformation and grain refinement. **Figure 8** also illustrates that, for the same welding parameters, the highest hardness increase was achieved in the nugget and TMAZ of the welds produced with the scrolled tool, i.e., about 30% of base material hardness. For welds produced with the same tool, but with lower rotational speed, the hardness values were even higher, as shown for weld S_W4V25.

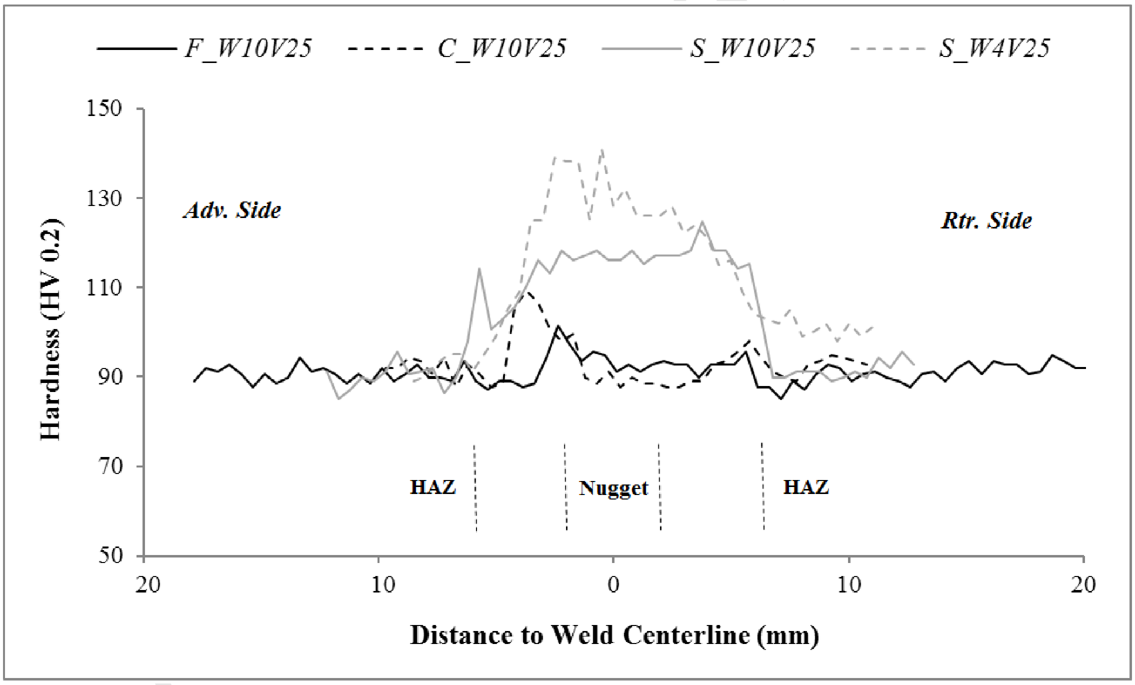

Figure 8 - Hardness distribution in the cross section of the F_W10V25, C_W10V25, S_W10V25 and S_W4V25 welds.

Local stress-strain curves corresponding to different zones of transverse specimens taken from the welds S_W10V25 (**Figure 9.a**) and C_W10V25 (**Figure 9.b**), as well as images of the

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longitudinal strain distribution in the specimens just after maximum load, which were acquired using an optical extensometer, are illustrated in **Figure 9**. From **Figure 9.a** it can be observed that the nugget of the weld made with the scrolled shoulder (low deformation dark blue zone of specimen's strain field) experienced only elastic deformation during tensile testing as opposed to the BM (high deformation red region of specimen's strain field), where plastic deformation predominates. The strong hardening registered in the nugget and TMAZ of the welds produced with this tool was responsible for the collapse in the base material region of the tensile specimens. Contrary to this, **Figure 9.b** shows that the specimen removed from a weld produced with the conical shoulder tool at high rotation rate failed in the transition between the TMAZ and the HAZ. In fact, as shown in the specimen's strain field illustrated in the figure, the tensile specimens removed from these welds experienced higher deformation in that region. This is confirmed by the stress strain curve measured in the transition between the TMAZ and the HAZ on the retreating side, which experienced the largest plastic deformation, as shown in **Figure 9.b**. Finally, **Table 2** resumes the fracture zones and the mechanical efficiency, defined as the ratio between the tensile strength of transverse specimens and the strength of the base material, for the high rate welds produced with scrolled and conical shouldered tools. From the table it can be inferred that, although good tensile behavior has been displayed by all of these welds, the joints carried out with the scrolled tool displayed higher mechanical efficiency.

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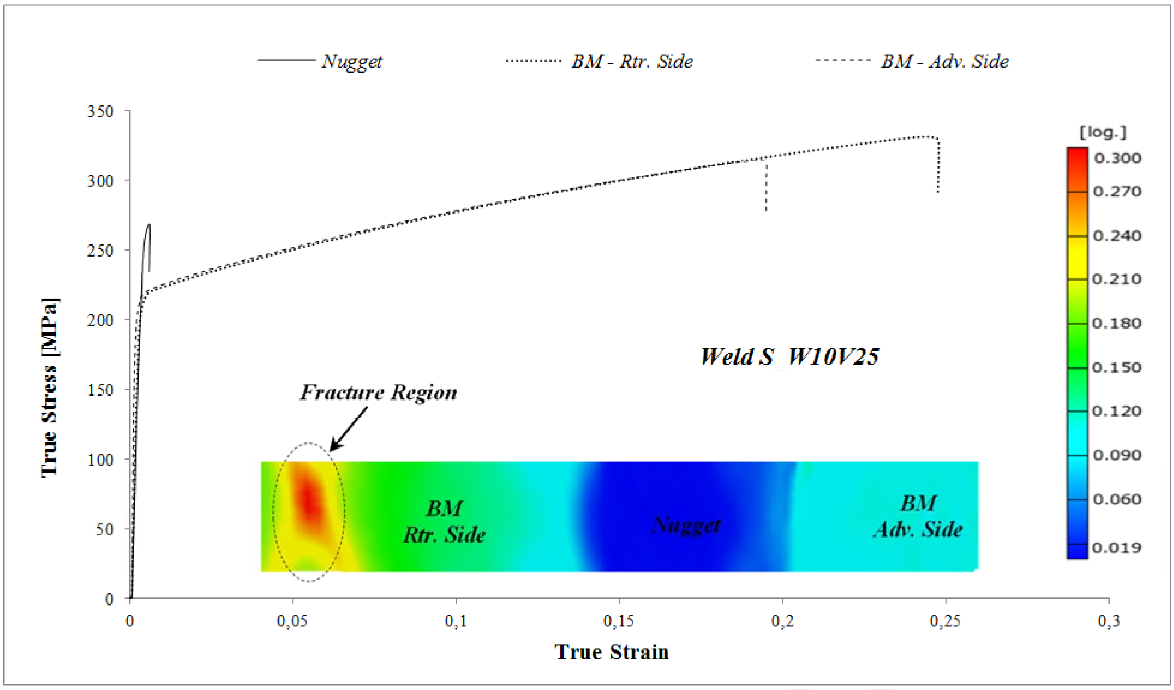
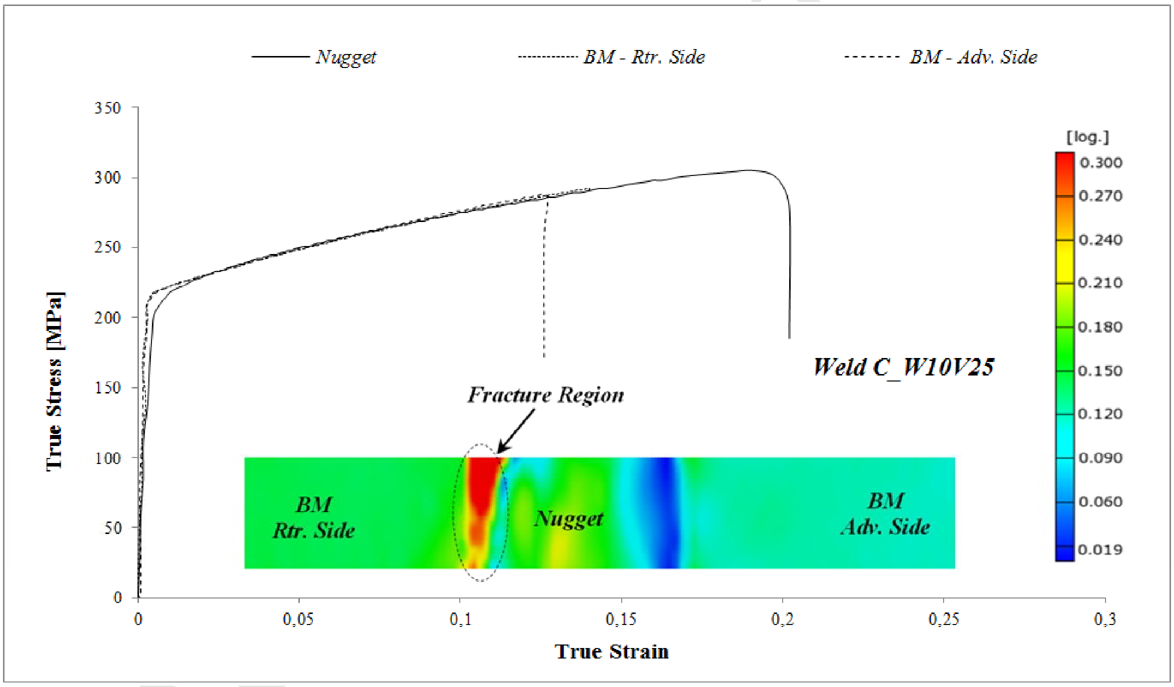


(a)



(b)

Figure 9 - Local stress-strain curves corresponding to different zones (BM and Nugget) of transverse specimens taken from the welds S_W10V25 (a) and C_W10V25 (b), and images of the longitudinal strain distribution in the specimens just after maximum load.

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Table 2 - Weld efficiency and fracture position of tensile specimens removed from C and S welds produced at high rate.

Specimen	*True Tensile Strength (MPa)*	*Weld Efficiency*	*Fracture Zone*
Copper-DHP	320	------------	------------
C_W10V16	287	0.90	TMAZ/HAZ
C_W10V25	299	0.93	TMAZ/HAZ
S_W10V16	325	1	BM
S_W10V25	323	1	BM

DISCUSSION

The formation of internal defects, such as voids and root defects, mentioned in **Table 1** and shown in **Figures 3 and 4**, can be attributed to insufficient and inadequate material flow around the tool. In fact, as noted by present authors in a previous paper on thin aluminum plates, Leal et al. (2008), the shoulder should drag the material into the pin influence zone. In turn, the pin pushes the material towards the root, compressing it on the advancing side, even promoting the extrusion of that material towards the surface. However, the results displayed in **Table 1** indicate that the flat shoulder is unable to perform this function at all rotational speeds tested, unlike the conical and scrolled shoulders, which only fail to do this at lower rotational speeds. The inadequate material flow has been mentioned, by Leal and Loureiro (2004) and Crawford et al. (2006), to explain the formation of similar defects on FS welds in aluminum alloys.

Material flow, besides depending on the ability of the tool to guide the deformed material towards the root of the weld, also depends on the degree of plasticization of the material under the tool, which is influenced by the heat generated in the process and the physical properties of the material. In turn, as pointed out by Nandan et al. (2006) and Kim et al. (2006) on steel and aluminum FSW, respectively, the heat is generated by friction at the interface between the tool and the material and by plastic deformation of the material under the shoulder, and is dependent on the welding parameters, in particular, the rotation speed and axial force of the tool. So, in the current

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investigation, the weld defects produced by any of the tools at a speed of 400 rev. min^{-1} were caused by insufficient heat to provide good plasticization and proper flow of material.

For higher rotational speeds, the different tools produced welds with different morphologies. As the parameters (W, v and F) used in the three series of welds were the same, this suggests that the tool geometries under study generate different amounts of heat or provide material in different streams in the TMAZ. In fact, whereas welds made with flat and conical shoulders at the speed of 750 rev. min^{-1} exhibit defects, no defects were identified in the welds performed with the scrolled shoulder. Nevertheless, the effect of the flat and conical shoulders is not identical, because, as mentioned above, unlike the latter, the former does not produce sound welds even at the rotation speed of 1000 rev. min^{-1} (**Table 1** and **Figure 4**). Although temperatures were not measured in the weld vicinity, due to the difficulty in fixing thermocouples to such thin plates, those results suggest that the flat shoulder generates little heat, the conical shoulder generates an intermediate level of heat and the scrolled shoulder generates the most heat, which favors the plasticization of the material and its flow around the tool. However, these results contradict those of De Giorgi et al. (2009), obtained on FSW in 6082 aluminum alloy, using flat, conical and scrolled shoulder tools, all with fillet at the edge. These authors inferred, based on nugget grain size and TMAZ hardness, that the most heat was generated by the flat shouldered tool. According to them, progressively less heat was generated by the scrolled and conical shouldered tools, although the difference was small. These discrepancies with the results of De Giorgi et al. (2009) may be attributed to differences in the geometry of the tools used and to the difference in the welded material. However, Biswas and Mandal (2011), on FSW in aluminum, also found that the flat shoulder provides higher temperatures than the conical one.

On the other hand, the general decrease of the spindle torque with tool rotation speed, illustrated in **Figure 5**, could be due to increased heat generated by the tool, which reduces the shear strength of the material to be welded. In fact Arora et al. (2009) and Cui et al. (2010) mentioned that heat generated increased with rotation speed. Analyzing **Figure 5**, the lowest torque values are

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registered in welds carried out with the flat shoulder tool, for all welding parameters, which suggest that it is this tool that generates most heat, producing the maximum shear stress reduction of the material under the tool. These results are in good agreement with those of De Giorgi et al. (2009), referred to above. However, a contradiction in the present study can be found by comparing torque results and the morphology of the welds, i.e., if the flat shoulder generates more heat, it should not lead to defects, contrary to what was observed in all welds produced with this tool. Furthermore, for 750 rev.min^{-1}, the torque values of the scrolled shoulder are superior to those of the conical shoulder, which could indicate less heat generation and a greater likelihood of internal defects, which is precisely the reverse of that displayed in **Table 1**. In fact, the torque depends not only on the heat generated, but also on the volume of material swept around by the shoulder during each revolution, as mentioned by Cui et al. (2010). So, the low torque values measured in the welds produced with the flat shoulder can be attributed to the limited ability of this tool to drag the base material, limiting the interaction between the shoulder-driven and pin-driven material streams, as suggested by Lorrain et al. (2010) and Leal et al. (2008). This can be observed in **Figure 4.c**, where a white dotted line marks the separation between the two material streams. So, taking into account the strong influence on the torque of the volume of material dragged by the tool each revolution, it can be concluded that a direct relation between the measured torque and the heat generated cannot be established.

The lower grain size observed in the nugget of the welds produced with the scrolled tool, as shown in **Figure 6**, suggests that this geometry generates the lowest heat, which does not agree well with the distribution of defects in welds, mentioned in **Table 1** and discussed earlier. This discrepancy can be explained by dynamic recrystallization, which is responsible for the formation of new grains, being a function not only of temperature but also of the amount and rate of deformation induced in the material by the tool, as pointed out by Hallberg et al. (2010) and Chashchukina et al. (2011). Furthermore, Leal et al. (2008) have shown, with regard to FSW in 1 mm-thick plates of aluminum alloys that, compared to the conical shoulder, the scrolled geometry

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induces more significant material flow, as well as a higher amount of plastic deformation in the welded material. So, as the rate of nucleation of new grains is proportional to the rate of plastic deformation, higher nucleation points and, consequently, lower grain growth would be expected in the nugget of the welds produced with the scrolled tool. Nevertheless, it is also reasonable that lower heat generation takes place in the welds produced with this tool geometry. In fact, the prominent striations contained in the shoulder, which penetrate and drag the material during rotation, can provide a situation identical to sticking material to the tool, in which heat is generated mainly by plastic deformation, as described by Schmidt et al. (2004). There is further support for the current results in the literature. Biswas and Mandal (2011) stated that friction gives the largest contribution to the heat generation in the process and plastic deformation has only a marginal contribution to make. In conclusion the higher grain refinement observed in welds produced with the scrolled shoulder tool is very affected by the larger material flow rate induced by this tool, although the lowest possible heat generated also contributes to the refinement. The higher volume of material dragged by the scrolled shoulder, which provides material flow through thickness, as suggested by **Figure 4.b** where no separation between shoulder driven and pin driven zones can be observed, explains the tendency of the scrolled shoulder tool to produce defect free welds. The authors have already proved for FSW in aluminum alloys that the scrolled shoulder favors material flow throughout the thickness of the weld (Leal et al., 2008).

The grain refinement produced by scrolled shoulder increased the hardness and mechanical efficiency of these welds relative to those done with a conical concave or flat shoulder. These results are in accordance with those of Xie et al. (2007), which were obtained from the FSW of pure copper.

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CONCLUSIONS

This investigation aimed to study the influence of the shoulder geometry on friction stir welding of 1 mm-thick copper-DHP plates. The following conclusions could be drawn from the experimental results:

- The flat shoulder tool requires lower weld spindle torque than conical or scrolled shoulder tools.
- The scrolled shoulder tool provides the most suitable material flow and the flat shoulder the worst, producing only defective welds.
- The scrolled shoulder provides greater grain refinement in the nugget of the welds than the conical or flat shoulders.
- That refinement is responsible for the increased hardness and mechanical strength of the welds made with this tool.

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