

Research Article

Influence of Initial Contact Geometry on Mechanical Properties in Friction Welding of Dissimilar Materials Aluminum 6351 T6 and SAE 1020 Steel

Marlon A. Pinheiro ^{1,2} and Alexandre Q. Bracarense³

¹Ph.D. Student of Postgraduate Program in Mechanical Engineering, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais 31270-901, Brazil

²CEFET-MG, Minas Gerais, Brazil

³Ph.D., Professor, Department of Mechanical Engineering, Simulation and Welding Robotics Laboratory, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais 31270-901, Brazil

Correspondence should be addressed to Marlon A. Pinheiro; marlonpinheiro@cefetmg.br

Received 26 December 2018; Accepted 23 April 2019; Published 7 August 2019

Academic Editor: Yee-wen Yen

Copyright © 2019 Marlon A. Pinheiro and Alexandre Q. Bracarense. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Friction welding is a solid-state bonding process that presents itself as an interesting option as it generates less residual stress, less distortion, and crack formation when compared to the fusion welding process. The characteristics of this process also allow satisfactory welding of dissimilar materials, with good results in terms of mechanical strength. In this work, the butt welding of aluminum ASTM A6351-T6 and SAE 1020 steel was carried out aiming at evaluating the effects of the initial contact geometry on the mechanical properties of the welded joint. The methodology consisted of friction weld aluminum bars with different initial contact geometry with steel bars in a machine specially developed for the application. The results indicated the influence of this parameter on the mechanical properties of the welded joint.

1. Introduction

Friction welding is a solid-state bonding process consisting of the microscopic joining of the contact surfaces of the parts at temperatures below their melting points. The main bonding mechanism of materials in friction welding is diffusion [1, 2].

These processes, in the absence of melting and solidification, are characterized by the formation of a narrow thermally affected zone, which results in good metallurgical and mechanical properties, as well as advantages such as reduction of residual stresses, distortions, and cracking, consequently joints of high quality and excellent mechanical results [3].

The process can be used to weld similar or dissimilar materials, where very often the behavior of such materials and the formation of intermetallic compounds may be unpredictable and damaging to the weld [4–7].

Yilbas and Sahin [7] carried out frictional welds of dissimilar materials from the aluminum and copper alloys and aluminum and steel and reports that when soldering these metals, problems arise not only related to the different hardnesses and melting points, but also the possibility of interaction producing phases fragile intermetallic or low melting point elements. Specifically in the welding of aluminum and steel, the author reported that the major problem was the formation of intermetallic compounds.

Jessop et al. [8] also showed that in the welding of aluminum and austenitic stainless steel, the intermetallic compounds were formed closer to the edges of the axes.

Ogawa et al. [9] states that in the specific case of welding of aluminum and steel, the formation of intermetallic compounds is common and interferes negatively, damaging the diffusion between aluminum and steel, interfering in the mechanical properties, considering that in

the balance diagram Fe-Al, there is no solubility between the two elements.

The friction welding process basically consists of the generation of friction between two surfaces, the generation of heat as a result of this friction and subsequently the deformation. The variables of the friction welding process related to the machine are the rotation, or speed of contact between the two surfaces, contact force, and also the force of forging, besides the times of application of the respective forces. The variables that do not belong to the machine are the type of materials, geometry, and diameter of the specimens [10]. As for the initial contact geometry of the pieces, some researches have been carried out and may be cited Alves [11], Sasidharan et al. [12], Khan [10], and Ambroziak [4].

Specifically, Alves [11] friction-welded ASTM A6351 T6 aluminum and AISI 304L stainless steel using flat and conical geometry and observed that with conic geometry that it was possible to remove oxides, impurities, and other contaminants from the surfaces as a result of deformation and temperature rise in the central region of the weld interface, providing better dynamic flow of the material, resulting in better physical and chemical adhesion and greater atomic diffusion.

Sasidharan et al. [12] also conducted researches with changes in the geometry of the contact face and concluded that significant changes occur in the results of mechanical resistance. The research with pins with conical geometry presented superior mechanical resistance in approximately 7% to those manufactured with flat geometry.

Khan [10] also conducted experiments with friction welding of dissimilar aluminum 6061 materials and AISI 304 stainless steel, pure aluminum and copper, and also aluminum 6061 and copper, all with flat and conical geometry. The conic geometry obtained better results in all dissimilar welded materials, with higher mechanical strength and greater uniformity along the bond line.

It is important to emphasize that the welding parameters are mainly related to rotation, force, and time, and the important thing is to establish or facilitate the occurrence of diffusion between the parts being joined.

The objective of this work was to study the effect of the initial contact geometry and the resistance limit to the tensile strength of welds produced by conventional rotary friction of ASTM A6351-T6 and SAE 1020 carbon steel.

2. Materials and Methods

SAE 1020 steel and ASTM A6351-T6 aluminum bars were used as base metal. The choice of those two materials is due to the wide use of them in the automobile industry, aeronautics, and industries in general. The application of dissimilar materials allows us to take better advantage of the properties of each material. The nominal chemical composition of the materials used is described in Table 1.

It appears that the aluminum alloy A6351-T6 has a percentage of 0.08% magnesium, favoring the aspects of

TABLE 1: Chemical composition of the materials used.

Material	Elements (% weight)								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	
A6351-T6 aluminum	1.30	0.50	0.10	0.80	0.08	—	—	0.22	
SAE 1020 steel	C	Mn	Si	P	S	Mo	Al	Ni	
	0.19	0.48	0.07	0.01	0.01	0.00	0.02	0.01	

corrosion resistance; however, it favors the formation of intermetallic compounds during the friction welding. The presence of manganese increases the tensile strength.

Table 2 shows the mechanical properties of A6351-T6 aluminum and SAE 1020 steel.

The proof-bodies/specimens have a diameter of 9.53 mm (3/8"). The lengths used were 55 mm for the aluminum parts and 50 mm for the steel parts. The length of the aluminum pins is slightly higher than the steel pins to compensate for the length reduction during welding. Figure 1 shows the variation of the initial geometry of the aluminum contact points used to make the welding.

The machining of the steel bars surface was also made, which during the tests were used as flat surfaces. It is important to emphasize that machining on the contact surfaces is fundamental to ensure similar roughness and also a better distribution of forces at the moment of contact.

For the accomplishment of the studies, the direct drive friction welding machine shown in Figure 2 was developed.

Initially minimum value parameters for carrying out the welding, such as welding force, welding time, forging time, and forging force, were defined. Those parameters were based on the literature applied in the welding of dissimilar aluminum and steel materials. Table 3 shows the parameters used.

Several initial tests were performed using two flat surfaces for both steel pins, as for aluminum. The best results were obtained using welding pressure and forging pressure equal to 21.63 MPa, welding time of 4 s, and forging time of 6 s, in addition to rotation of 1750 RPM.

The specimens, after welding, were cut and analyzed metallographically.

3. Results and Discussion

3.1. Subheadings. Tensile tests were carried out, according to ASTM E 8 [13], wherein the test specimens were machined for this purpose, as Figure 3. This test was important to verify the mechanical tensile strength of the welded joint, according to the parameters used.

Analyzes of the structure were performed, initially with the optical microscope. In this analysis, it was possible to evaluate and verify the aluminum bonding interface with steel, aspects of the thermally affected zone, structural changes, granular structure, and aspects of mechanical contact, under pressure, between two parts with relative movement. Figure 4 shows the welded joint microscopy consisting of two images of the junction sample, of the peripheral region of the specimen.

TABLE 2: Mechanical properties of A6351-T6 aluminum and SAE 1020 steel.

Alloy	Hardening	Tensile strength limit MPa (N/mm ²)	Yield limit MPa (N/mm ²) Min.	Minimum elongating (%)	Hardness Brinell (HB)
Al 6351	T6	290	255	8	95
SAE 1020 STEEL	—	420	350	15	121

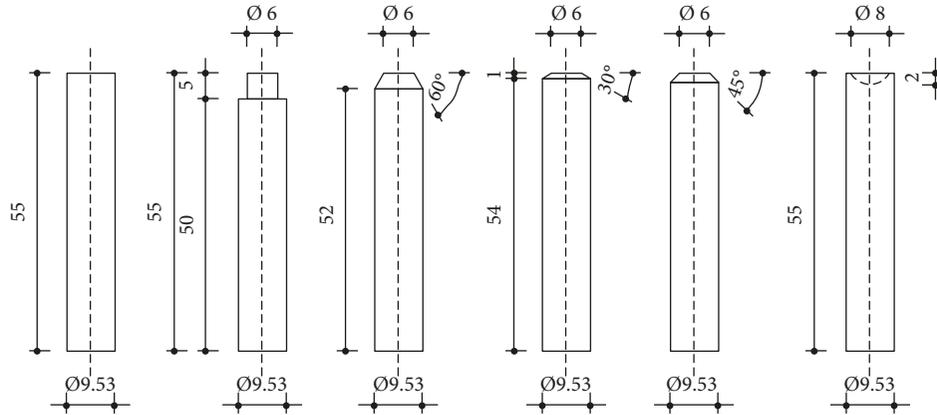


FIGURE 1: Variation of the initial geometry of the used contact point of the aluminum pins.

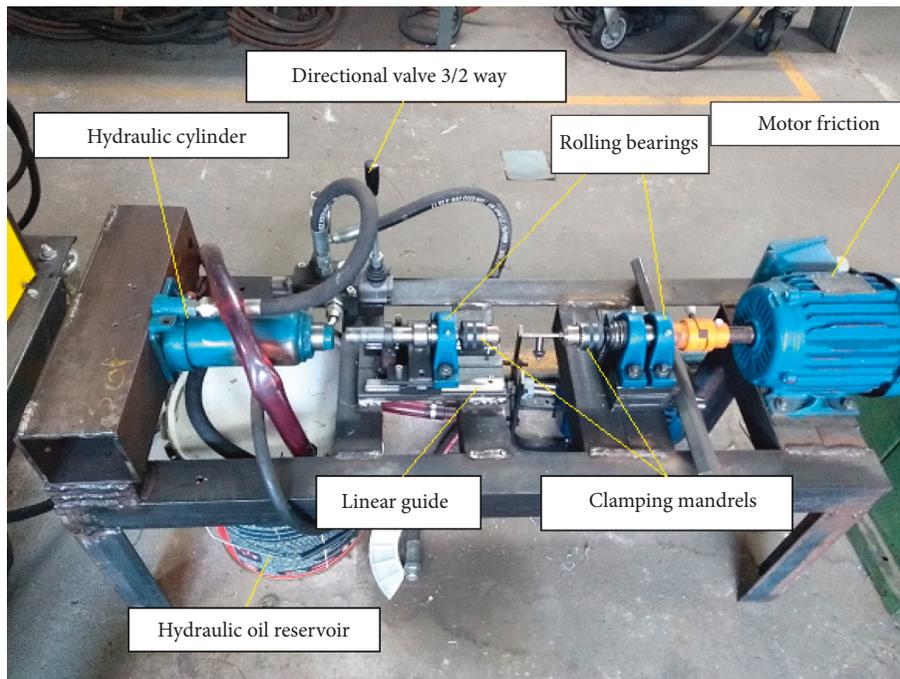


FIGURE 2: Friction welding machine.

TABLE 3: Initial test parameters.

Welding time	4 s, 7 s, and 10 s
Welding pressure	21.63 MPa; 43.33 MPa; 64.90 MPa
Forging pressure	The same of welding pressure
Temperature	Room temperature (without preheating)
Rotation	1750 RPM (fixed)
Forging time	6 s (fixed)
Diameter	3/8" = 9.53 mm (fixed)



FIGURE 3: Machined test body for tensile testing.

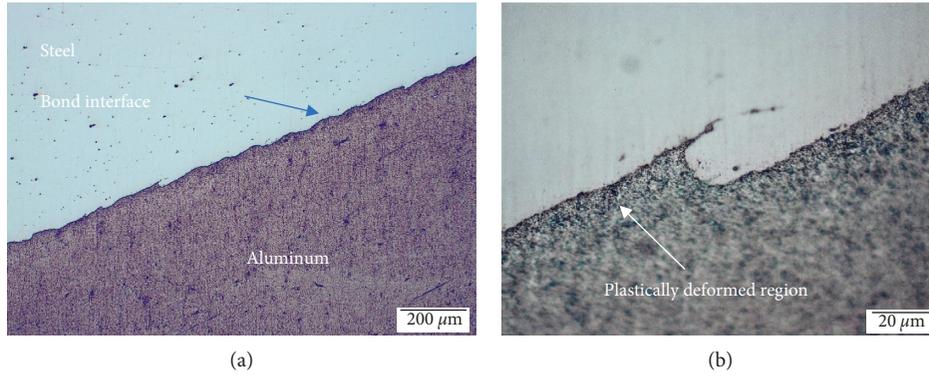


FIGURE 4: Metallographic images of the welded joint. (a) 100x magnification and (b) 1000x magnification.

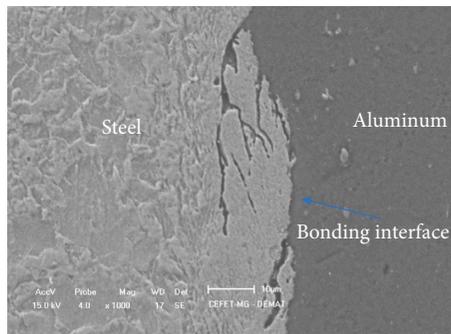


FIGURE 5: Welded joint (scanning electron microscope magnification 1000x).

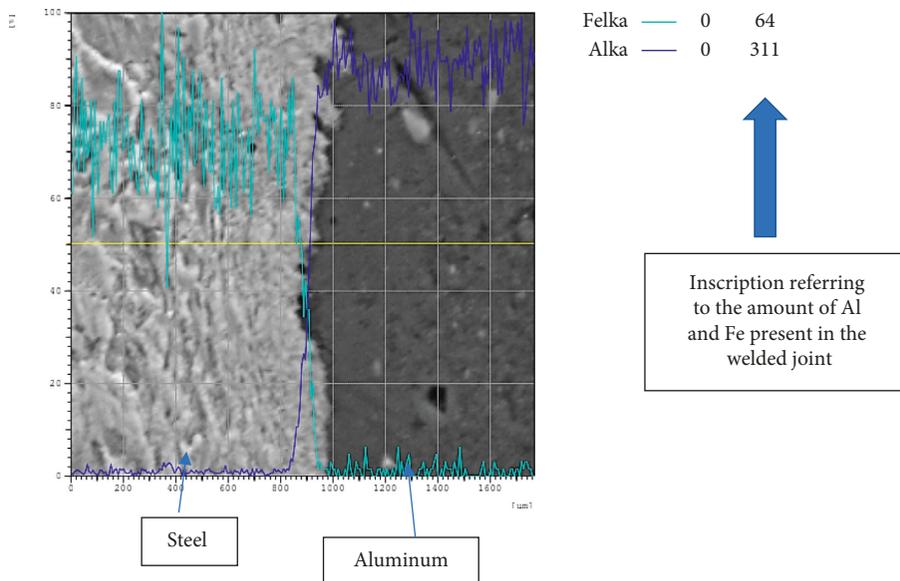


FIGURE 6: Semiquantitative analysis performed by EDS at the junction of aluminum and steel.

It can be observed in the microscope images that the bonding interface presents imperfections in the welded joint, characteristic of the friction welding process, more specifically due to the occurrence of intense rotating contact between two parts of aluminum and steel. The occurrence of an intermediate line in the welded joint is shown in

Figure 4(b). It can be seen still in Figure 4(b) the occurrence of deformation of the aluminum grains in the joint.

Figure 5, obtained with the scanning electron microscope, confirms what was observed in the analysis using the optical microscope that the deformations resulting from the friction welding process.

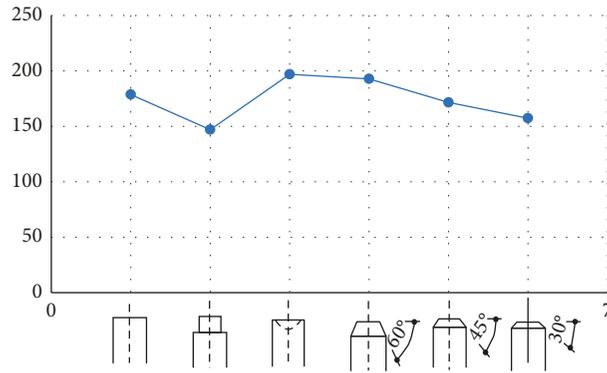


FIGURE 7: Tensile strength limit obtained with aluminum pins with altered geometries.



FIGURE 8: Specimens ruptured after the tensile test.

Conical tip			Plan tip			Bulged tip		
Steel		Al	Steel		Al	Steel		Al
Thickness of intermetallic layer (μm)								
0.168;0.168;0.158;0.137; 0.158. Average: 0.158 Standard deviation: 0.011321			0.137;0.126;0.221;0.147; 0.084 Average: 0.143 Standard deviation: 0.044511			0.127;0.116;0.105;0.053; 0.116 Average: 0.103 Standard deviation: 0.026143		

FIGURE 9: Intermetallic layer formed in the friction welding.

Semiquantitative analysis was also performed by EDS (dispersive energy spectroscopy), shown in Figure 6, where it is evident that in the interface region of the weld, on the side of the aluminum, the presence of iron occurs and on the side of the steel, the presence of aluminum occurs, that is, as the weld junction is exceeded, it is possible to verify the occurrence of interdiffusion between aluminum and steel.

In order to reach the proposed objectives, the welds were made using aluminum pins with tips with modified geometries as shown in Figure 1. The following parameters were used, using the best parameters, which resulted in a higher mechanical tensile strength, when the welding was performed with flat surfaces, i.e., welding pressure and forging pressure equal to 21.63 MPa; welding time equal to 4 s and forging time equal to 6 s.

During the welding, it was verified that the conical and bulged tips provided a smoother displacement, with less vibration, besides formation of less flash.

Subsequently, they followed the machining procedures and preparation of the test specimens to perform the tensile tests, according to ASTM E 8 [13].

Figure 7 shows the results of the tensile strength limits, for each type of initial contact geometry, of the aluminum pins obtained in the process. Figure 8 shows the specimens after rupture in the tensile test.

By analyzing the results, the influence of the initial contact geometry on friction welding can be observed. This influence can be seen in the results of the tensile strength limit of the welded parts. It is observed that the bulged tip and the conical tip with 60° inclination presented better tensile strength results.

The structures obtained in the welding, using the tapered pins 60° and bulged, were also analyzed and obtained with the scanning electron microscope and compared with the flat pins. It is observed in Figure 9 that the main structural difference was the formation of intermetallic compounds (IM), which was identified, through a contrast existing at the junction, by an intermediate layer formed between aluminum and steel. Fe and Al, in this case form these compounds, and their distribution shape and thickness have negative influence of the mechanical resistance of the welded joint.

Five measurements were made of the layers 1 in the center and 4 in the periphery of the welded joints. Figure 9 shows the difference in joint aspects and thickness values of the intermetallic layers obtained.

It is observed that the conical tips presented a higher average thickness of intermetallic layers; however, the distribution is more uniform, whereas the flat tips have great thicknesses and also an irregular distribution. This different formation of intermetallic compounds is mainly caused by the distribution of heat generated during and friction.

4. Conclusions

There was influence of the initial contact geometry on the tensile strength of the welded joints, and the conical point of 60° showed an increase in tensile strength in relation to the flat surface around 7.9% and the bulged tip presented an increase of about of 10.2% increase in tensile strength.

An interesting aspect is that flat geometry does not provide uniform force at the interface of the joint, which is a smaller force in the internal region compared to the outside, which can cause entrapment of oxides and other contaminants.

Another important aspect is that the altered geometries change the generation and distribution of heat on the frictioned surface, which may favor the larger and irregular formation of intermetallic compounds.

Data Availability

All data generated or analyzed during this study are included within the article.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to thank the members of the Laboratory of Robotics, Welding and Simulation of the Federal University of Minas Gerais, Brazil, and the Federal Center of Technological Education (CEFET-MG).

References

- [1] A. Fuji, M. Kimura, T. H. North, K. Ameyama, and M. Aki, "Mechanical properties of titanium-5083 aluminium alloy friction joints," *Materials Science and Technology*, vol. 13, no. 8, pp. 673–678, 1997.
- [2] S. Fukumoto, H. Tsubakino, K. Okita, M. Aritoshi, and T. Tomita, "Friction welding process of 5052 aluminum alloy to 304 stainless steel," *Materials Science and Technology*, vol. 15, p. 1080, 1999.
- [3] R. S. Parmar, *Welding Processes and Technology*, Khanna Publishing House, New Delhi, India, 3rd edition, 1995.
- [4] A. Ambroziak, *Badania Zgrzewanych Tarciowo Złaczy AlMg₃-Stal Austenityczna: Inżynieria Materiałowa*, vol. 24, no. 6, pp. 701–704, 2003.
- [5] N. Yamamoto, M. Takahashi, M. Aritoshi, and K. Ikeuchi, "Effect of intermetallic compound layer on bond strength of friction-welded interface of Al-Mg5052 alloy to mild steel," *Quarterly Journal of the Japan Welding Society*, vol. 23, no. 2, pp. 352–358, 2005.
- [6] C. Maldonado-Zepeda, *The Effect of Interlayers on Dissimilar Friction Weld Properties*, M.S. thesis, National Library of Canada, Ottawa, Canada, 2001.
- [7] B. S. Yilbas and A. Z. Sahin, *Friction Welding: Thermal and Metallurgical Characteristics*, Springer, New York, NY, USA, 2014.
- [8] T. Jessop, E. D. Nicholas, and O. W. Dindsdale, "Friction welding of dissimilar metals," in *Proceedings of the 4th International Conference on Advances in Welding Processes*, New York, NY, USA, May 1978.
- [9] K. Ogawa, H. Ochi, Y. Yamamoto, and Y. Suga, "Friction welding of aluminum alloy and steel," *International Journal of Offshore and Polar Engineering*, vol. 8, no. 2, pp. 140–143, 1998.
- [10] I. A. Khan, "Experimental and numerical investigation on the friction welding process," Thesis, Doctor of Mechanical

- Engineering, Jawaharlal Nehru Technological University, Kakinada, India, 2011.
- [11] E. P. Alves, “Caracterização mecânica e estudo do perfil térmico na soldagem por fricção rotativa de materiais dissimilares,” Tese de Doutorado em Engenharia e Tecnologia de Materiais e Sensores. INPE, São José dos Campos, Brazil, 2016, <http://sid.inpe.br/mtc-m21b/2016/03.15.19.09-TDI>.
- [12] B. Sasidharan, K. P. Narayanan, and R. Arivazhakan, “Influence of interface surface geometries in the tensile characteristics of friction welded joints from aluminium alloys,” *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 2, no. 1, 2013.
- [13] American Society for Testing and Materials, *E 8M-04: Standard Test Methods for Tension Testing of Metallic Materials*, ASTM, West Conshohocken, PA, USA, 2004.
- [14] American Welding Society (AWS), *Recommend Practices for Friction Welding*, American Welding Society, Miami, FL, USA, 1989.



Hindawi
Submit your manuscripts at
www.hindawi.com

