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FINITE ELEMENT ANALYSIS OF A FRICTION SPOT WELD SHEAR TEST[1]

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Abstract

Friction spot welding (FSpW) is one of the most recently developed solid state joining technology. This process employs a non-consumable rotating tool to produce an overlapped connection between similar or dissimilar sheets, and exhibits some advantages over competitor techniques as absence of consumables, lower material loss, shorter cycles and power saving. In this work, based on former publications, a computer aided draft and engineering resource was used to model a FSpW joint on AZ31 magnesium alloy sheets and subsequently submit the assembly to a typical shear test loading in order to conceive mechanical tests results. Finite element analysis shows that the crack initiation must happen on the welded zone periphery where tensile stresses reach the highest values. It is supposed that "through the weld" and "circumferential pull-out" variants should be the main failure behaviors, although mechanical testing may provide other types of fracture due to metallurgical features.

Key words: Friction spot welding; Finite element analysis; Shear test.

ANÁLISE POR ELEMENTOS FINITOS DO ENSAIO DE CISALHAMENTO DE UMA SOLDA POR FRICÇÃO POR PONTO

Resumo

A soldagem por fricção por ponto (FSpW) é uma das tecnologias mais recentemente desenvolvidas no que se refere à união no estado sólido. Este processo emprega uma ferramenta rotacional não consumível para produzir uma junta sobreposta entre chapas similares ou dissimilares, e exibe algumas vantagens em relação às técnicas concorrentes, tais como ausência de consumíveis, menor perda de material, ciclos mais curtos e maior eficiência energética. Neste trabalho, com base em publicações anteriores, foi utilizado um recurso computacional de desenho e projeto para modelar uma junta por FSpW em chapas de liga de magnésio AZ31 e posteriormente submeter o conjunto a uma carga de cisalhamento típica a fim de compreender os resultados dos ensaios mecânicos. A análise por elementos finitos mostra que a nucleação da trinca deve ocorrer na periferia da zona soldada onde as tensões de tração atingem os seus maiores valores. Presume-se que as variantes "através da solda" e "arrancamento circunferencial" sejam os principais modos de falha, ainda que os ensaios mecânicos venham a apresentar outros tipos de fratura em razão de fatores metalúrgicos.

Palavras-chave: Soldagem por fricção por ponto; Análise por elementos finitos; Ensaio de cisalhamento.

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1 INTRODUCTION

Friction based joining techniques derived from friction stir welding (FSW) have increased the interest of automotive and aircraft industries due to the advantages over the conventional fusion processes, including the possibility of joining dissimilar and non-weldable materials such as highly alloyed 2XXX and 7XXX aluminum series. With the welding procedure being conducted in the solid state, the main restrictions associated to the metal solidification (e.g. hot cracking, porosity and splash) are fully avoided and the intrinsic lower energy input reduces the distortion of the workpiece and the microstructural changes.(1) One of the most recent techniques, friction spot welding (FSpW) employs an especially designed non-consumable tool (consisting of pin, sleeve and clamping ring) to produce a spot connection between overlapped similar/dissimilar sheets through frictional heat and plastic deformation.(2) Figure 1 shows a schematic illustration of the four typical steps resulting from the independent motion of each tool component in “sleeve plunge variant”.

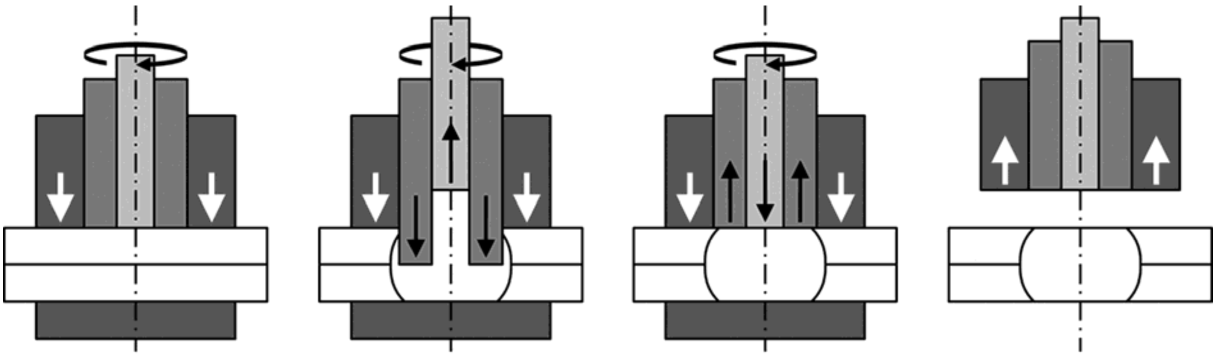

Figure 1. Illustration of “sleeve plunge variant” stages: (a) clamping and tool rotation; (b) sleeve plunge and pin retraction; (c) parts back to surface level; and (d) tool removal.

Basically, while clamping ring fixes the overlapped sheets against an anvil, the plunging and rotating component (either pin or sleeve) generates frictional heat and softens the surrounding material, which flows to create a solid state bond between the upper and lower sheets.
FSpW was developed to reduce the limitations of consolidated techniques currently applied in the spot joining of structural components in the transportation sector, such as weight penalty, high consumable costs and corrosion problems in mechanical fastening (clinching, riveting and self-piercing riveting)(3) or defects associated to material melting and solidification in fusion welding processes (resistance and laser spot welding).(4,5) Friction spot connections exhibit good surface finishing and, as far as there is low material loss, no keyhole is left on the surface at the end of the joining operation contrary to friction stir spot welding (FSSW) process. Whether the mechanical performance of FSpW joints is demonstrated to be at least similar, the process may be capable of replacing the mentioned techniques in some applications.
Analytical and numerical modeling has been increasingly applied as an effort to better comprehend the friction spot joining mechanisms. Muci-Küchler, Kalagara and Arbegast(6) developed a thermo-mechanical finite element model (FEM) in Abaqus/Explicit software to calculate the temperature distribution and plastic deformation of a refill FSSW process. FEM was also used by Li and Kang(7) to evaluate the thermal field in FSSW joints of AM60B magnesium alloy performed with different combinations of parameters. In case of Hirasawa et al.,(8) besides the

evaluation of temperature distribution, the material flow resulting from different FSSW tool geometries was analyzed by means of an elastic-plastic deformation model using the particle method. Kim et al.[9] evaluated the performance of FSSW aluminum joints through the development of a FEM in PAM-Crash software, to predict the effect of distinct tool geometries on weld strength, and a finite volume method (FVM) in STAR-CD software, to analyze the material flow patterns around the tool and therefore explain the considerable different strengths achieved among the tool geometries.

Mazzaferro et al.[10] originally extend the referred efforts to FSpW technique in order to comprehend the joint mechanical behavior and failure modes, including the effect of the morphology and properties of each welding region. Different numerical models were developed in SolidWorks and Abaqus software to reproduce both the specimen geometry and the load conditions in lap shear and cross tensile mechanical tests. Experimental results and simulations exhibited a satisfactory compatibility, with similarities in the levels of stresses and the specimen distortions.

In this way, the purpose of this work is to develop a finite element model of an AZ31 magnesium alloy friction spot joint and verify the stress distribution in the vicinity of the weld nugget subjected to a typical tensile shear loading, thus helping the assessment of the different resulting failure behaviors.

2 MATERIALS AND METHODS

In a former work developed by the authors,[11] lap shear tests were carried out in order to discuss the effect of some important welding parameters like rotational speed, plunge depth and dwell time over the resistance of a FSpW joint. Microstructural examination on the cross-sections of the welded joints provided the identification of three different zones: base material (BM), thermo-mechanically affected zone (TMAZ) and stir zone (SZ), besides the “hook” at the interface of the overlapped sheets. Nonetheless, microhardness profile (Figure

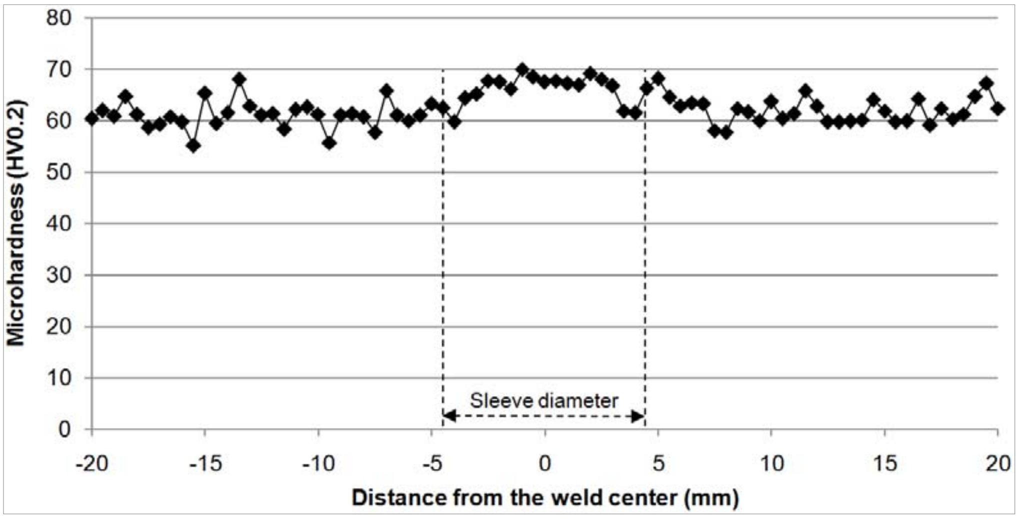

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Figure) presents no pronounced variation along the welded joint.

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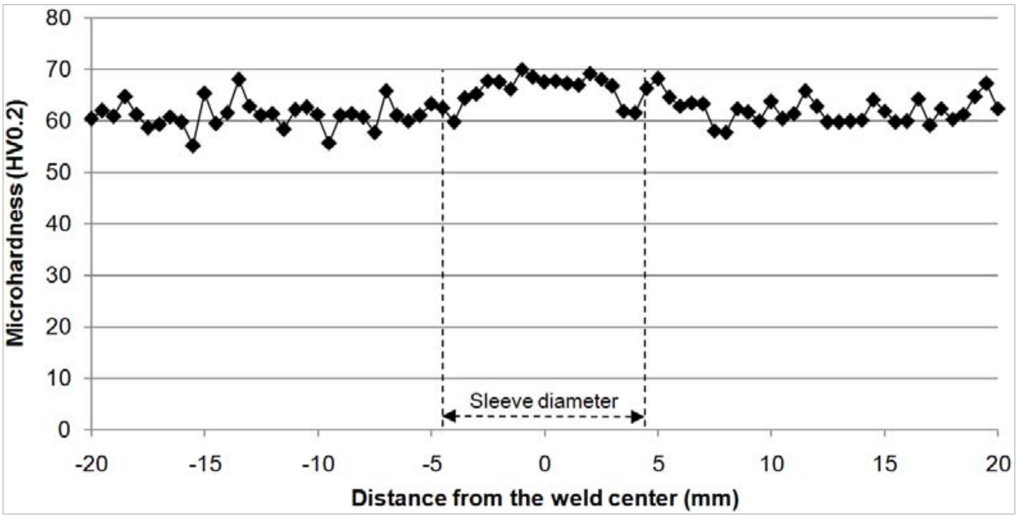

Figure 2. Typical microhardness profile at the cross section of the joint.[11]

Face to that, it was decided to explore geometric modelling of the welded joint to apply on the finite element analysis (FEA) of a typical lap shear test, so that failure behaviours of the specimens could be predicted or even explained. The approach considers the distinction of the weld nugget and the presence of the hook, and then four different models are proposed, according to Figure 3: indistinct weld nugget without hook, indistinct weld nugget with hook, distinct weld nugget without hook and distinct weld nugget with hook.

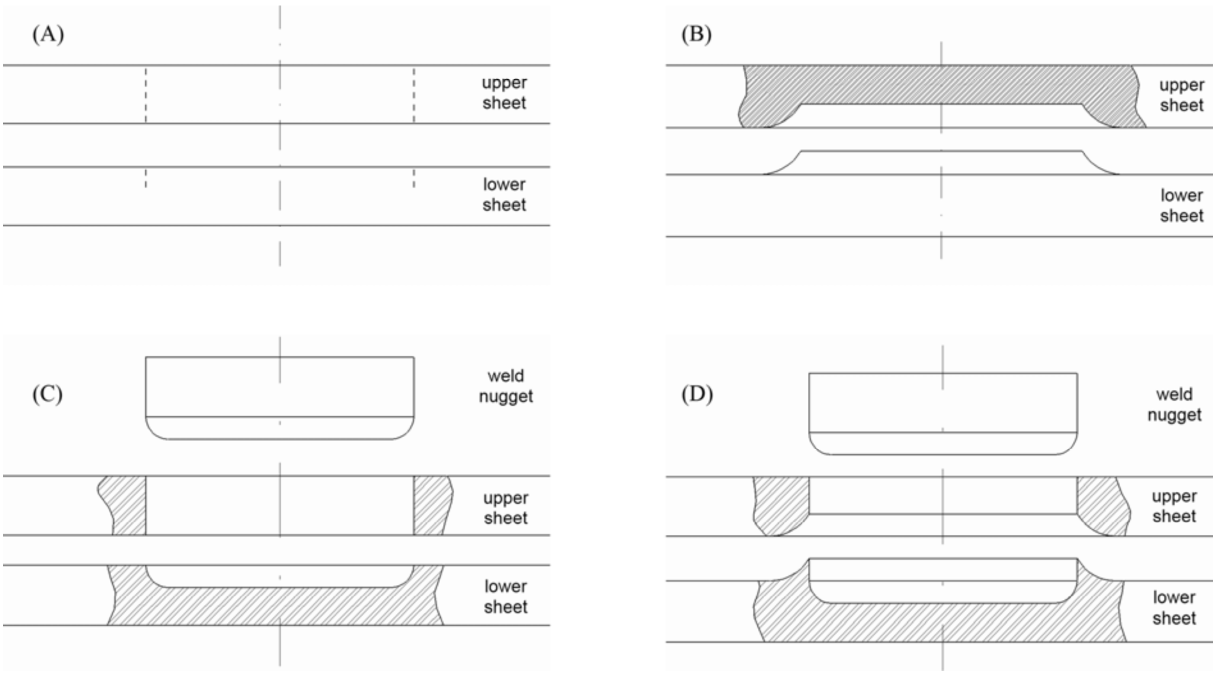

Figure 3. Different geometric models of the welded joint: (a) indistinct weld nugget without hook; (b) indistinct weld nugget with hook; (c) distinct weld nugget without hook; and (d) distinct weld nugget with hook.

Both bending and vertical displacement of the extremity of the interface between the sheets in the models containing hook are intentionally magnified in order to intensify the effect of the hook over the mechanical performance. In the models without hook, the flat extremity of the interface is representative of the insignificant vertical

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displacement of such defect. Using CosmosWorks®, a couple of AZ31 magnesium alloy sheets (2 mm thick, 60 mm wide and 138 mm long) joined by a 9 mm friction spot weld on the middle of the 46 mm overlap (dimensions according to ISO 14273:2000 standard)[12] is subjected to a 5 kN shearing load, value about the ultimate force measured on the real test (Figure 4).

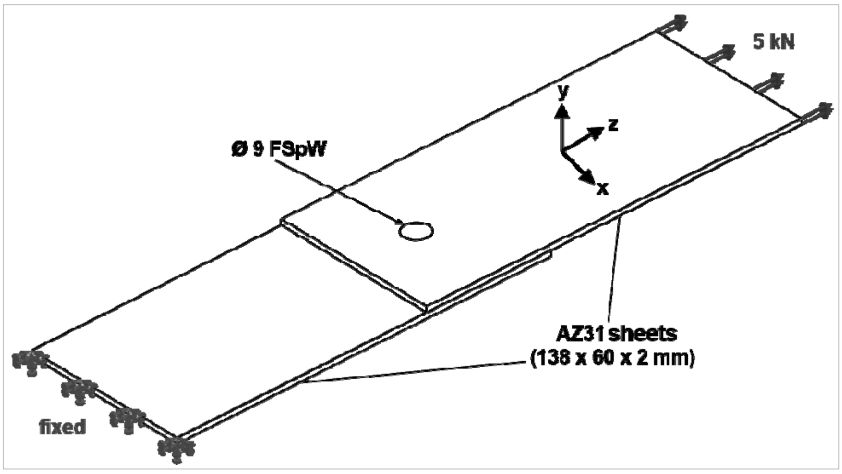

Figure 4. Shear test assembly for finite element analysis.

As no significant difference of hardness was found between base material, thermo-mechanically affected zone and stir zone, both sheets and the weld nugget (on models C and D) were modeled as the same isotropic linear elastic material. Table 1 presents elastic modulus (E), Poisson ratio (ν), yield (σ_y) and ultimate strength (σ_u) of the AZ31B-H24 magnesium alloy obtained from a tensile test and adopted in the simulation.

Table 1. Mechanical properties of AZ31 magnesium alloy

Alloy	E (GPa)	ν	σ_y (MPa)	σ_u (MPa)
AZ31B-H24	46	0.35	131	268

Contact between the sheets, on models A and B, and between each sheet and the weld nugget, on models C and D, is set as bonded and restricted to the spot weld boundary (not on the hook). Meshes were generated using parabolic tetrahedral elements. On the solution of the problem, h-adaptative method was applied in order to improve the accuracy. From generalized Hooke's Law (Equation 1),[13] it is possible to correlate the stress state of each node of the mesh discretized in the FEA model with the corresponding strain state, obtained from nodal displacement. Note that S_x, S_y and S_z mean normal stress while τ_{yz}, τ_{zx} and τ_{xy} mean shear stress; on the other hand, ε_x, ε_y and ε_z are linear strains whilst γ_{yz}, γ_{zx} and γ_{xy} are angular strains.

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$$\begin{Bmatrix} S_x \\ S_y \\ S_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+v)(1-2v)} \begin{bmatrix} -v & v & v & 0 & 0 & 0 \\ v & 1-v & v & 0 & 0 & 0 \\ v & v & 1-v & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2v}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2v}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2v}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_x \\ \varepsilon_x \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix}$$

(1)[13]

3 RESULTS AND DISCUSSION

Figure 5 shows the z-normal stress distribution around the spot joint during lap shear test for the models previously introduced (Figure 3). The surfaces illustrated correspond to the transverse cutting plane parallel to the loading direction, where the highest tensile and compressive stresses are identified.

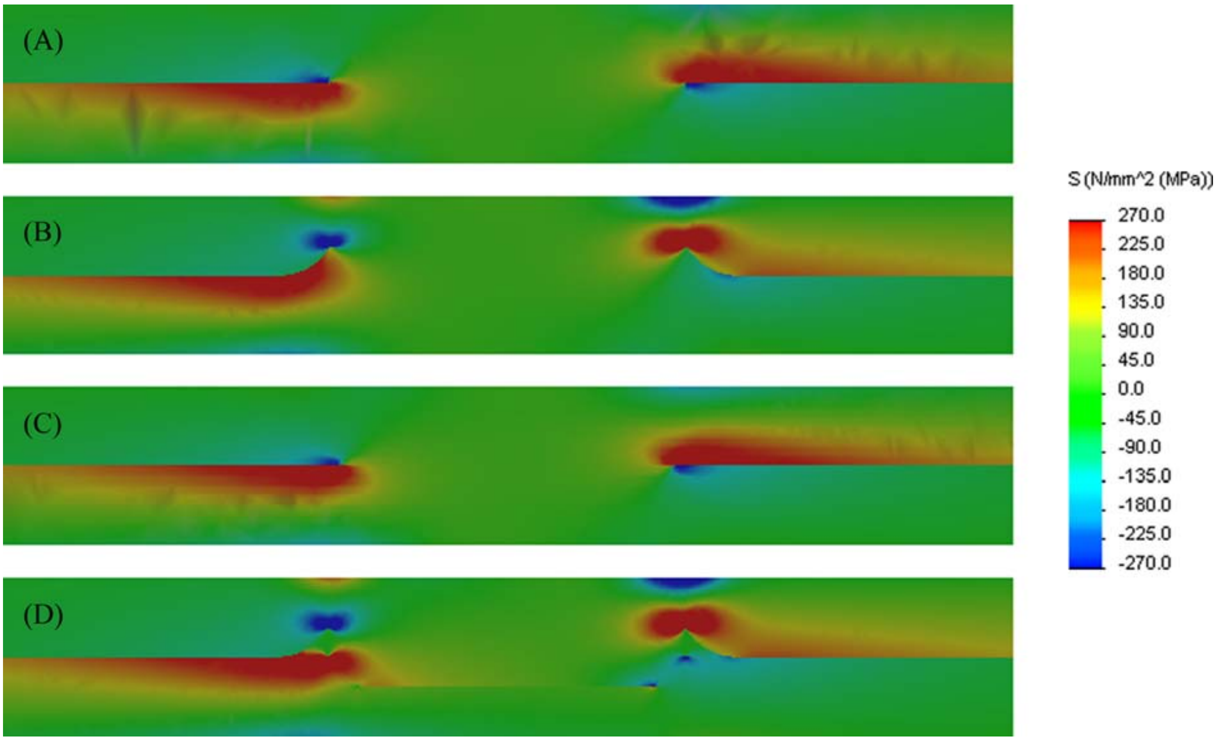

Figure 5. Stress distribution around the spot joint: (a) indistinct weld nugget without hook; (b) indistinct weld nugget with hook; (c) distinct weld nugget without hook; and (d) distinct weld nugget with hook.

Considering the distinction of the weld nugget, a comparison between models A and C illustrates that the stress distribution is similar for both cases. In the presence of hook, however, the distribution around the joint presents some particularities in model D in comparison to model B. The existence of a distinct weld nugget promotes the extension of both tensile and compressive regions along the curvature of the nugget base. Regarding the occurrence of the hook, the presence of such defect slightly changes the stress distribution on the upper sheet. The tensile and compressive regions above the interface between the overlapped sheets are concentrated on the tip of hook pattern. Moreover, the stresses are fully intensified at the top surface.

Fracture initiation generally takes place in the regions subjected to the highest tensile stresses, which are located below the extremity of the interface in the “left side” and above the extremity in the “right side”, when the ultimate tensile strength is reached. Specifically for models A and C, independently of the distinction of the weld nugget, fracture may propagate through the welded zone until the complete separation of the joint, although it is possible that propagation initially occurs through the external surface of the sheet in both sides until a compressive zone is reached. The mentioned fracture behavior is known as “through the weld” (TW) mode and is possible for all simulated models, but it is the unique for the models that contemplate absence of hook.

For models B and D, two different crack propagation paths are possible. Failure originated in the “left side” tends to get away from the compressive zone in the tip of hook region. Therefore, crack may propagate through the welded region or around the zone under compression towards the tensile stressed region at the top surface and then surrounding the welded joint. For the fracture nucleated in the “right side”, crack starts propagating perpendicularly to the surface. Since a compressive zone is observed near the surface of the upper sheet, the failure front may stop extending. In this case, crack may be reached by the crack growing though the welded region to completely separate the joint (TW mode). However, if the opposite failure propagation happened surrounding the welded region, less effort is required for the “right side” crack to propagate through the region under compression and therefore the weld nugget is entirely removed from the joint. Such fracture behavior is designated “circumferential pull-out” (CPO) mode.

As previously mentioned, model D presents some particularities related to the extension of both tensile and compressive regions along the curvature of the nugget base. In this case, crack nucleated in the “left side” may propagate initially towards the surface of the lower sheet following the tensile stressed extension. Continuing with the propagation, failure may proceed to the region under high tensile stresses in the “right side” where the crack already existing is reached. The described fracture behavior can also be pointed out as a particular TW mode.

4 CONCLUSIONS

Results show that finite element analysis can be successfully applied on conceiving the fracture behavior of friction spot joints submitted to lap shear loading. Each proposed geometric model was useful to predict the different failure paths. According to that, crack must nucleate on the vicinity of the welded zone where tensile stresses reach the highest values. Crack propagation is therefore expected to proceed through the welded zone, resulting on the complete collapse of the joint (“through the weld” variant). Otherwise, crack would flow around the weld nugget boundary, inducing its detachment (“circumferential pull-out” variant). Other fracture behavior modes may only be ascribed to metallurgical features, which cannot be considered on a linear elastic approach.

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