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TECHNICAL NOTE

Thermal Analysis of Friction Stir Welding with a Complex Curved Welding Seam

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ABSTRACT

Friction stir welding (FSW) can be defined as a green technology, because the consumption of energy during this process is less than other welding methods. In addition, during the process there is no gas, filler material or other consumables. It should be noted that, complex curved shapes are now commonly used in different industries in a bid to have lightweight structures. According to the above-mentioned descriptions, several investigations into the potential benefits of adopting Friction Stir Welding (FSW) in the production and joining different materials are being undertaken. The work presented in this paper is focused on thermal behavior of the curved FSW and its benefits for the green technology. Due to the robust nature of FSW process aluminum 6061-T6 alloy has been selected as the welding material. The results of the study showed that, the total peak temperature value of 300°C happened at time, t = 3 s at the plunge stage (outside of the welding seam). Meanwhile, at the dwell stage (between t = 3 s to t = 5 s), there is a stable situation in the amount of the generated heat from the plastic deformation as well as the contact shear stress at the tool-workpiece contact interfaces, thus the interfacial temperature is found to be stable. By the end of the dwelling step, the total generated heat is stable to the maximum value of 300°C. At the step time of t = 12.8 s, the temperature is distributed asymmetrically across the workpiece until the time step of 19.6 s which at this point the asymmetric contour expanded in the stir zone.

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1. INTRODUCTION

The potential benefits of the FSW welding process includes; reduced operating costs, process robustness, improved mechanical properties (like tensile strength and fatigue), reduced waste and consumables, reduced environmental issues and health risks. These benefits are some parts of the reason that the automotive, railway and shipbuilding industries are now adopting the FSW process[1, 2].

The automotive applications of FSW came to the public domain in 1998. The pioneer study was on the aluminum tailored blanks for door panels which was started by The Welding Institute (TWI). These studies demonstrated new concepts of the process for drive shafts of cars and space frames. The above-mentioned projects were sponsored by some companies like BMW, DaimlerChrysler, EWI, Ford, General Motors, Rover, Tower Automotive, and Volvo. Nowadays, as mentioned earlier, FSW is developed and is being employed in a lot of automotive companies for different applications such as, mobile cranes, body frames and truck bodies. Presently, there are three general areas of application of FSW in the automotive industry, they include; the joining of tailor welded blanks, the joining of extrusions to form ‘larger extrusions’, and the joining for different assembly applications. Therefore, there are distinct benefits in the use of FSW and its application in the abovementioned areas.

The process is also adopted in the railway industry in the production process of chassis cradles and engines, container bodies, attachments of hydroformed tubes, wheel rims, buses, fuel tankers, mobile cranes, airfield transportation vehicles, armour plate vehicles, bridges,

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tailored blanks (such as the welding of several sheets with varying thicknesses), space frames (like joining extruded tubes to cast nodes), truck bodies, tail lifts for lorries, caravans, motorcycle and bicycle frames, articulated lifts and personnel, skips, repair of aluminum cars, aluminum and magnesium joints.

For the processes mentioned above, detailed attention is given at the quality of the joints. It should be noted that, both basic and complex configurations are being used for general assembly of the joining applications and also extrusions. The most basic joint design employed by researchers is the lap weld and partial penetration butt weld, which are both intrinsic for high volume production processes.

In addition, during the past decades the welding of complex curved plates is increasing sharply due to the needs in the automotive and railway industries. However, because of the simplification of the model a lot of researchers [3-5] have only simulated thermal analysis of butt and lap welding. Therefore, there is a lack of knowledge on the thermal analysis of the curved FSW [6]. The simulation of the curved plate will have some challenges, because the commercial software is only able to simulate a single point movement for the tool, therefore the software needs to be developed in order to have a high accuracy perpendicular movement for the tool. Thus, a 3D finite element model is developed in this paper in order to focus on the thermal analysis of a complex curved friction stir welding (FSW).

2. METHODOLOGY

2. 1. Geometry and the Mesh Descriptions A three-dimensional analysis of the FSW welding process is performed in ABAQUS® as shown in Figure 1 due to its significant capabilities in thermal analysis of the process [7]. Aluminum 6061-T6 alloy is employed as the workpiece material which is modelled as a deformable part and the tool was assumed to be as a rigid body.

Arbitrary Lagrangian Eulerian (ALE) is employed for the mesh refinement at the contact region in order to

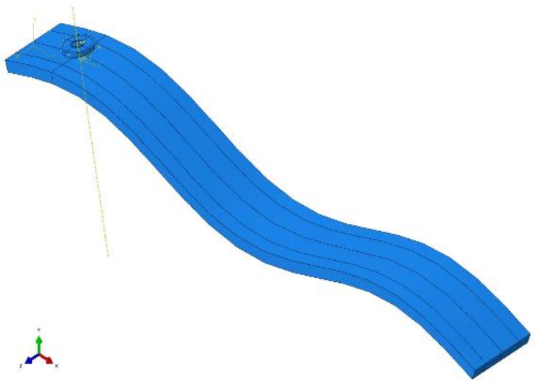

Figure 1. Assembled model of the curved FSW

obtain more reliable results, and the technique is used to follow the workpiece deformations. The FSW model was assigned to have a fixed boundary condition at the bottom surface of the workpiece with zero velocity for all workpiece movements. Also, transverse movements (X and Y directions) and the angular velocity were also assigned to the tool by using VDISP user defined subroutine.

Convectional heat transfer coefficient is defined between the workpiece and the tool environment, while temperature dependent material properties and friction coefficient are applied to the model using Coulomb's law of friction [8-15]. The mesh and the element are shown in Figure 2. In the model C3D8RT element as a temperature-displacement continuum element is used.

3. RESULTS AND DISCUSSION

The temperature field of the steady-state simulation is shown in Figure 3. It was observed during the plunging step that the highest temperature occurs near the shoulder (about 300 °C) and this temperature is below the melting point (580 °C) of the 6061-T6 aluminum alloy [4]. This shows that the results of the simulation are accurate, and the model was able to simulate the thermal behavior of the FSW process.

At the welding starting point, the workpiece was still solid, because the FSW process is a solid-state joining

Figure 2. An isometric view of Finite Element mesh

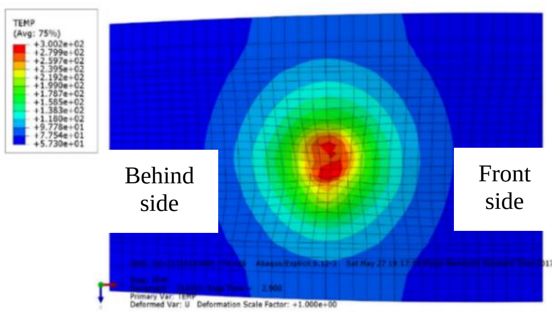

Figure 3. The workpiece temperature field at the top view point

method. Also, at that point, there was no melting or welding defects. These observations reflect the benefits of FSW technique. Furthermore, between the back side and the front side of the tool, in small localized ranges near the shoulder, the temperature field is approximately asymmetrical. It was also detected that, the temperature pattern at the front side of the tool is observed to be higher than the temperature of the behind side the tool.

Like the top view of the weld (Horizontal section Figure 3), the temperature field lies asymmetrically along the center line of the weld (Figure 4). It was observed that, the advancing side temperature being higher than the retreating side. This issue has been also reported by many researchers [3, 16-18]. Also, there is sparse isotherm distribution behind the welding tool than in the front of the welding tool which densely distributed. For the purpose of verification, the simulation results for 9 welding process parameters were compared favourably with other published results [5, 19-22] as shown in Table 1. As can be seen a good agreement with the literature is found. Finally, it is observed that, the increase of the rotation speed at the constant traverse speed increases the temperature, while the increase of the welding transfers speed decreases the welding temperature.

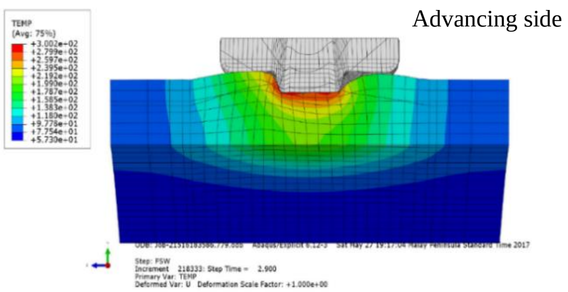

Figure 4. The temperature distribution of the workpiece at the cross section

TABLE 1. Temperature distribution comparison at the welding stage between the literature [19] and Emamian et al. [21] and the simulated model [19-21][19-21][17-1917-19]

Welding parameter	Model type	Temperature ℃ (3 mm away from the tool shoulder)
800-40 RPM-mm/min	Literature	295.828
	FE model	251.159
800-70 RPM-mm/min	Literature	285.366
	Curved model	236.875
800-100 RPM-mm/min	Literature	247.956
	Curved model	203.634
1200-40 RPM-mm/min	Literature	304.592
	Curved model	256.863
1200-70 RPM-mm/min	Literature	295.828
	Curved model	246.586
1200-100 RPM-mm/min	Literature	296.551
	Curved model	245.763
1600-40 RPM-mm/min	Literature	357.146
	Curved model	302.258
1600-70 RPM-mm/min	Literature	338.173
	Curved model	295.612
1600-100 RPM-mm/min	Literature	308.893
	Curved model	263.224

4. CONCLUSIONS

The results of this study showed that:

- The total peak temperature value of 300 °C happened at time t = 3 s during the welding plunge stage.
- At the dwell stage (between t = 3 s to t= 5 s), there is a stable situation in the amount of the generated heat from the plastic deformation as well as the contact shear stress at the tool-workpiece contact interfaces.
- The interfacial temperature is found to be stable during the welding.
- By the end of the welding dwelling step, the total generated heat is stable to the maximum value of 300 °C.
- Through the welding step, the temperature reached to the peak value of about 531 °C at the initial welding stage before remaining steady through the quasi-steady welding stage.
- Between the step time of t = 12.8 s and 19.6 s the temperature was asymmetrically distributed across the workpiece.
- At the step time of t= 19.6 s the asymmetric contour expanded in the stir zone.

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چکیده

جوشکاری اصطلاکی اغتشاشی (FSW) می تواند به عنوان یک فناوری سبز تعریف شود ، زیرا مصرف انرژی در طی این فرایند کمتر از سایر روش های جوشکاری است. علاوه بر این ، در طی فرایند ، هیچ گاز ، مواد پرکننده یا سایر مواد مصرفی وجود ندارد. لازم به ذکر است که ، در حال حاضر برای داشتن ساختارهای سبک وزن ، از اشکال منحنی پیچیده پیچیده معمولاً در صنایع مختلف استفاده می شود. مطابق توضیحات فوق ، تحقیقات متعددی در مورد مزایای احتمالی اتخاذ جوشکاری اصطکاک (FSW) در تولید و پیوستن به مواد مختلف انجام می شود. کار ارائه شده در این مقاله بر رفتار حرارتی FSW منحنی و مزایای آن برای فناوری سبز متمرکز شده است. با توجه به ماهیت قوی فرآیند FSW ، آلیاژ آلومینیوم T6-۶۰۶۱ به عنوان ماده جوش انتخاب شده است. نتایج مطالعه نشان داد که ، مقدار دمای کل اوج ۳۰۰ درجه سانتیگراد در زمان ، $t = 3$ ثانیه در مرحله غوطه وری (خارج از درز جوش) اتفاق افتاده است. در همین حال ، در مرحله ساکن (بین $t = 3$ ثانیه تا $t = 5$ ثانیه) ، وضعیت پایداری در میزان گرمای تولید شده از تغییر شکل پلاستیک و همچنین تنش برشی مخاطب در رابط های تماس با قطعه ابزار وجود دارد ، بنابراین دمای سطحی پایدار است. با پایان مرحله سکونت ، کل حرارت تولید شده تا حداکثر مقدار ۳۰۰ درجه سانتیگراد پایدار است. در زمان مرحله $t = 12.8$ ثانیه ، درجه حرارت به طور نامتقارن در قطعه کار تا مرحله زمانی ۱۹.۶ ثانیه توزیع می شود که در این مرحله کانتور نامتقارن در منطقه همزن گسترش می یابد.

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