Publishing House
A K A P I T

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 9, 2009, No. 1

NUMERICAL SIMULATION OF MODIFIED FRICTION STIR SPOT WELDING PROCESSES

GIANLUCA BUFFA, LIVAN FRATINI

Dipartimento di Tecnologia Meccanica, Produzione e Ingegneria Gestionale
University of Palermo, Italy
Corresponding Author: fratini@dtpm.unipa.it (L. Fratini)

Abstract

Spot welding can be considered a very common joining technique in automotive and generally in transportation industries as it permits to obtain effective lap-joints with short process times and what is more it is easily developed through robots and automated systems. Recently the Friction Stir Spot Welding (FSSW) process has been proposed as a natural evolution of the already known Friction Stir Welding (FSW) process, allowing to obtain sound spot joints that do not suffer from the insurgence of typical welding defects due to the fusion of the base material. In the paper, a variation of the Friction Stir Spot Welding (FSSW) process has been considered with different peculiar tool paths given to the tool, after the sinking phase, nearby the initial penetration site, with the aim to enhance the final joint mechanical properties. A continuum based FEM model for Friction Stir Spot Welding process is proposed, that is 3D Lagrangian implicit, coupled, rigid-viscoplastic. This model is used to investigate the distribution of the main field variables, namely temperature, strain and strain rate in the heat affected zone and the weld nugget, thus getting important information on the final material microstructure and joint resistance. The developed model appears an effective tool in order to design effective spot joints.

Key words: spot welding, friction stir welding, tool path, FEM

1. INTRODUCTION

Spot welding can be considered a very common joining technique in automotive and generally in transportation industries. Apart from the utilized joining technology and in particular from the heat source (Joule effect, electric arc and so on) it permits to obtain effective lap-joints with short process times and what is more it is easily developed through robots and automated systems [1-3]. It should be observed that in the last decades also mechanical fastening techniques, such as clinching and riveting, have been widely utilized, since they permit to obtain the same advantages of the former welding processes and, what is more, they do not suffer from the insurgence of typical welding defects due to the fusion of the base material [4-6].

Friction Stir Welding (FSW) has been presented and proposed at the beginning of the nineties just as an innovative technique able to develop the joining of the so called un-weldable or difficult to be welded light weight alloys which are very common materials in automotive or aerospace industries; actually classic welding processes, i.e. TIG or laser, determine quite weak joints due to a strong increase of the average grain size observed in the melted material and to quite large thermally affected zones. Furthermore strong precautions have to be considered during classic weldings in order to avoid inclusions and other typical defects in the joint core. In turn, FSW is a solid state welding process in which a specially designed rotating pin is first inserted into the adjoining edges of the sheets to be welded with a proper nuting angle and then moved all along the

 ISSN 1641-8581

joint. Such pin produces frictional and plastic deformation heating in the welding zone; actually no melting of material is observed during friction stir welding. Furthermore, as the tool moves, material is forced to flow around the tool in a quite complex flow pattern determining a very particular microstructure characterized by continuous dynamic recrystallization phenomena [7-9].

As a natural evolution of the FSW process, the Friction Stir Spot Welding (FSSW) has been proposed for many automotive and aeronautical applications [10-11]. In such a process, directly based on the friction stir welding process mechanics, a rotating tool with a probe pin is introduced in the two blanks to be jointed supported by a proper backplate. The rotating tool generates friction heat in the specimens and at the same time a material flow is determined. The heated and softened material close to the tool plastically deforms and a bond is made between the surfaces of the upper and lower sheets. No linear movement is given to the tool which is retracted from the workpiece when the stirring process is completed.

As far as the process parameters are regarded, both geometrical and technological aspects have to be considered: both the former and the latter affect the material flow during the process and the generated heat flux. In this way the tool shoulder and the pin shapes and geometries are very important since they influence on the circumferential material flow. Furthermore, the tool sinking into the blanks, i.e. the applied normal load, determines the friction forces work and then the generated heat flux, together with the chosen tool rotating speed. As far as technological parameters are considered, also the process times, namely the tool descending time, the process time length and finally the tool ascending time, play an important role in the FSSW process.

Recently the authors presented a modification of the FSSW process in which a tool path is given after the sinking phase in order to improve the material flow and consequently the joint resistance [12]. The mechanics of such promising modified process is still not completely clear, and no numerical simulation based approach, as known by the authors, has been developed to better understand the effect of the given tool path on the joint microstructure.

In the paper, a variation of the Friction Stir Spot Welding (FSSW) process has been considered for two 1.5 mm thick AA6082-T6 aluminum alloy sheets. In detail, different peculiar tool paths are given to the tool, after the sinking phase, nearby the initial penetration site, with the aim to enhance the final joint mechanical properties. A continuum based FEM model for Friction Stir Spot Welding process is proposed, that is 3D Lagrangian implicit, coupled, rigid-viscoplastic. This model is used to investigate the distribution of temperature, strain and strain rate in the heat affected zone and the weld nugget. In particular, the large values and gradients of temperature and strain found in the weld zone during the process can be used to determine the effectiveness of the bonding, which is heavily affected by the Continuous Dynamic Recrystallization (CDRX) process that takes place in the weld nugget. In this way, the extension of the nugget can be predicted with the ultimate goal to get information on the joint mechanical resistance. The developed model appears an effective tool in order to design effective spot joints.

2. "TRADITIONAL" AND MODIFIED FSSW PROCESS

As briefly described before, FSSW is aimed to obtain lap-joints utilizing a cylindrical tool with a pin tip centered on one circular face; in the "traditional" process, the tool rotates on its axis at room temperature and it is inserted into the specimens to be jointed with a normal force. In other words the tool is pushed down into the two overlapped blanks until a proper level of reaction force is reached. A back plate is utilized on the bottom side of the specimens to support the applied load and no linear translation is given to the tool, which is retracted after a proper process time length.

As the rotating tool is inserted into the sheets a local backward extrusion mechanics is observed and a full contact between the upper sheet and the tool shoulder is reached. Then a heat flux is generated by the friction forces work decaying into heat.

The observation of the material flow and of its locally reached microstructure leads to the full understanding of the process mechanics. Considering a section of the joint (figure 1), the backward extrusion mechanics is highlighted for the two overlapped sheets. Due to the absence of tool feed rate no asymmetry in the metal flow, typical of the FSW processes, is observed. In particular, the interface surface of the lower specimen is deformed upwards and such material develops the role of a mechanical anchor between the two jointed sheets.

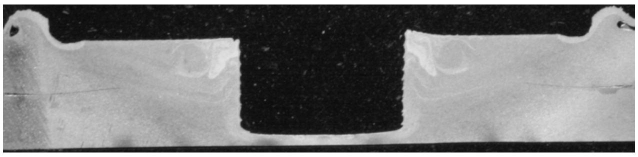

Fig. 1. the FSSW joint transverse section

As in FSW processes, a detailed observation of the material microstructure in the joint section allows to find out a few different areas, as shown in the next figure 2 [12], where a 250X image of the material zone on the lateral surface of the pin is reported.

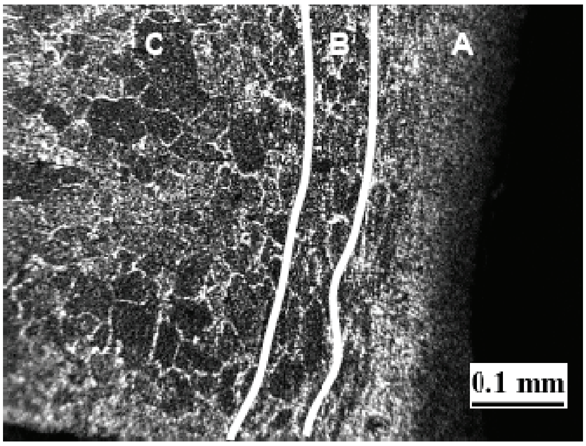

Fig. 2. The FSSW joint microstructure

In particular, as in FSW, moving towards the welding line, i.e. towards the tool pin surface, first of all the parent material is found out in which no metallurgical modification are observed after the welding process. Then a simple heat affected zone (HAZ, C) is reached, in which material has undergone a thermal cycle which has modified the microstructure and the mechanical properties. Continuing towards the welding spot, a zone in which the material has been plastically deformed by the stirring action of the tool is found out. It should be observed that in such zone the effects of the induced heat flux are also observed with an enlargement of the material average grain size. In this way, this zone is a thermomechanically affected one (TMAZ, B). Finally the so called nugget is found out (A). The latter is a recrystallized area in which the original grain and subgrain boundaries appear to be replaced with fine, equiaxed recrystallized grains characterized by a nominal dimension of few μm. It should be observed that the peculiarities of the obtained microstructures strongly determine the joint effectiveness and its mechanical behavior. As far as the nugget is regarded, several authors suggest that the microstructure observed in it are to be referred to a "continuous" dynamic recrystallization (CDRX) process, analogous to that which gives rise to subgrain formation during hot rolling, occurs. Actually, the thermo-mechanical action of the tool pin rather determines a grains demolition in the blanks material up to a microstructure characterized by very fine, equiaxed grains [13-14].

The main limitation of such process is that the nugget area, which, as it is known is strictly connected to the joint mechanical resistance, is relatively small. An increase in such area would certainly lead to an increase in the joint mechanical performances. Based on the above observation, the modified FSSW process has been developed, in which a tool path is given after the completion of the sinking phase and before the tool leaves the sheets to be welded. Four different spiral paths, namely a circle path (C), a square path (Sq), an ellipse-x (Ex) and an ellipse-y (Ey) path - with the major axis respectively orthogonal and parallel to the applied load (F) direction in the tensile tests -, have been chosen with the aim to enlarge both the thermo-mechanically affected area and the nugget, and different rotating speed values based on preliminary tests have been adopted (figure 3, [12]).

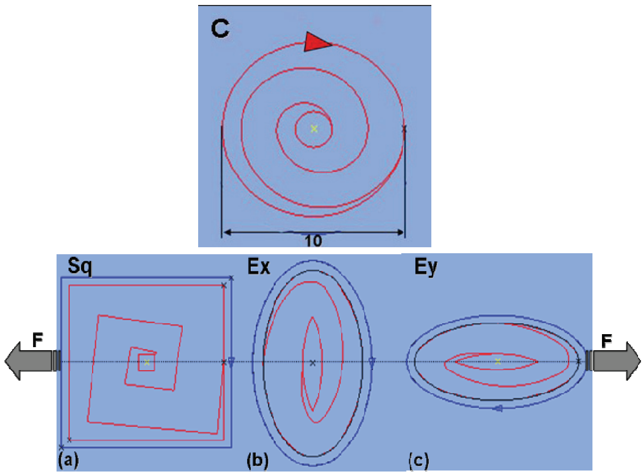

Fig. 3. Sketch of the assigned tool axis paths with respect to the tensile tests applied force direction.

Finally the obtained specimens were properly treated with Keller reagent and observed by a light microscope. As far as the tensile tests are regarded, they have been developed on specimens presenting an average width of 30 mm.

2. NUMERICAL MODEL

The commercial FEA software DEFORM-3D™, which is a Lagrangian implicit code designed for metal forming processes, is used to model FSSW.

The modified FSSW modeling is divided into two stages: 1) sinking stage and, 2) welding (advancing along the path) stage. In other words, FSSW is modeled in this research from its initial state in order to get the field variable distributions due to the whole action of the welding tool. For the thermal characteristics of the utilized AA6082-T6 (1.5 mm in thickness) sheet, the following values were utilized: thermal conductivity 180 [N/(s°C)] and thermal capacity 2.4 [N/(mm^{2}K)]. No variation of such data with temperature was taken into account, while convection phenomena were considered. A rigid-viscoplastic temperature dependent material model is employed (table 1).

Table 1. *constants for the flow stress equation* $\sigma = KT^A \dot{\varepsilon}^B \varepsilon^C$

K	*A*	*B*	*C*
41461194119	-3.1361	0.1318	0.0658

The tool is modeled as a rigid body. A constant thermal exchange coefficient of 11 [N/(mm-s-°C)], was utilized for the contact surfaces. In order to obtain the desired vertical material flow, especially needed for lap joints, different pin shapes can be adopted such as a cylindrical threaded, conical threaded or smooth conical. Nevertheless it is noticed that tool wear during FSW quickly lead to a "self-optimized" smooth pin surface [15]. For this reason a conical smooth pin shape was taken into account in this paper and a set of simulations was performed. In particular, a shoulder diameter of 15 mm, a conical pin characterized by major diameter of 7 mm and conical angle of 40° and a pin height of 2.6 mm, with a 0.5 mm fillet radius at the pin-shoulder interface, were adopted.

A "single block" model (one sheet without separation 40x40x3 mm) is used in order to avoid contact instabilities due to the simultaneous contact at the sheet-sheet and sheet-tool interfaces. The blank was meshed with about 10,000 tetrahedral elements with single edges of about 0.75 mm; in this way about four element were placed along the overall joint thickness. A non uniform mesh with adaptive remeshing was adopted with smaller elements close to the tool. The tool was meshed with about 4,000 tetrahedral elements for the thermal analysis. A constant shear friction factor of 0.46 was used for the tool-sheet interface on the basis of a previous experimental thermal characterization and of a numerical sensitivity analysis for the shear friction factor m [16]. All the simulations are performed using the same tool sinking velocity of 0.1 mm, and no tilt angle is given to the tool like in actual FSSW and "modified" FSSW processes.

The tool plunges in the workpiece at the periphery of the considered tool path and comes out from its center (concentric movement), in order to confer symmetrical resistance properties to the obtained joint. The tool movement along the prescribed path has been implemented through a subroutine that links the CNC program utilized for the actual experiments – performed on a CNC milling machine – to the numerical code in order to reproduce the exact tool trajectory. Finally figure 4 shows the numerical model during the sinking stage together with the utilized tool.

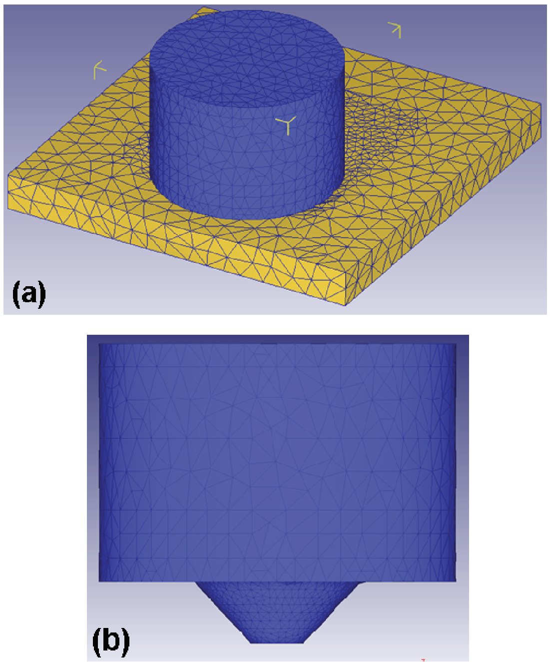

Fig. 4. *Model sketch during the sinking stage (a) and detail of the utilized tool (b)*

3. RESULTS AND DISCUSSION

The experimental campaign carried out by both shear load tests and micro and macro observations highlighted that the square case study presents better mechanical properties at the varying of the process parameters [12]. The next figure 5 shows the maximum load failure for the four case studies at the varying of the rotational speed, with an advancing velocity defined by a constant rotational pitch (RP) of 0.6 mm/rev.

It should be pointed out that lap joints developed by traditional FSSW showed a maximum failure load that is about half of the one obtained for the square path case study. In order to analyze the causes for such a behavior a set of simulations of the square case study, at the varying of the rotational speed, and a set of simulations of the traditional FSSW have been performed. In figure 6 it can be seen a top view of the obtained lap joint for the square path case study (RP = 0.6 mm/rev): in particular the actual welding (figure 6a) and the effective strain distribution calculated by the numerical model (figure 6b) are reported. The area inside the tool path boundary is characterized by large values of strain, indicating that an effective material flow has taken place over a wider zone with respect to the traditional FSSW process.

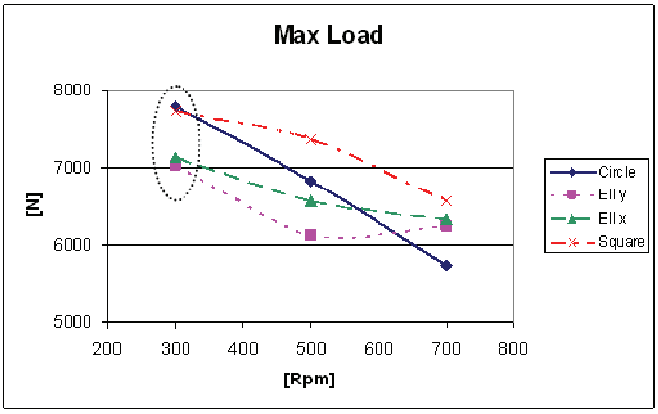

Fig. 5. Shear load tests for the four case studies; RP=0.6 mm/rev

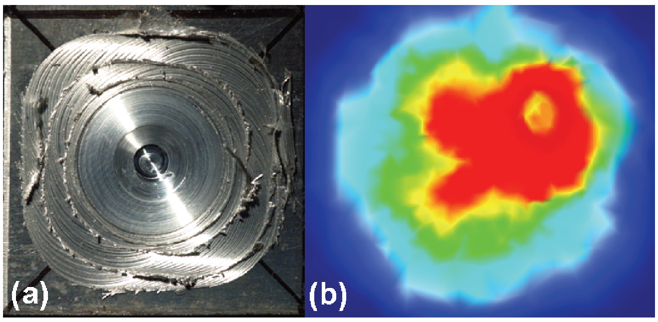

Fig. 6. Top view of the square case study (R = 300 rpm, RP = 0.6 mm/rev); (a) actual welding and (b) calculated effective strain distribution

In order to better understand the close link between the effective strain distribution and the actual material area involved in the bonding process, a comparison between the actual joint transverse section micro-image and the corresponding numerical result in terms of effective strain distribution has been developed. In particular in the next figures 7 and 8 the "no path", i.e. traditional FSSW, and square case studies are reported, respectively. As it can be seen, both for the traditional FSSW and for the modified FSSW, a very good correspondence can be found for the area in which an effective strain value of about 7 is reached and the actual area in which bonding is obtained between the two sheets. In this way the difference in material flow and final microstructure occurring between a joint developed by the traditional FSSW process and one obtained by the modified process can be highlighted: in the latter, the area involved in the stirring process is significantly larger and, consequently, the resistant section is larger, explaining the 1:2 ration in the maximum failure load found out during the shear tests.

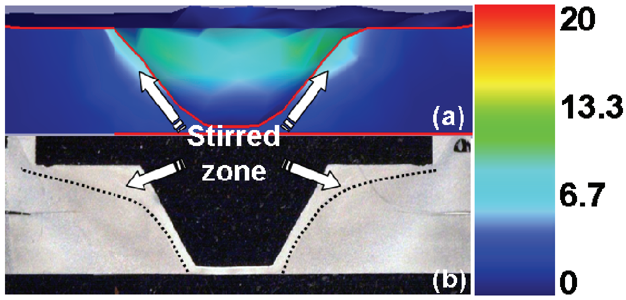

Fig. 7. Transverse section for the traditional FSSW case study (R = 300 rpm): (a)calculated strain and (b) actual experiment.

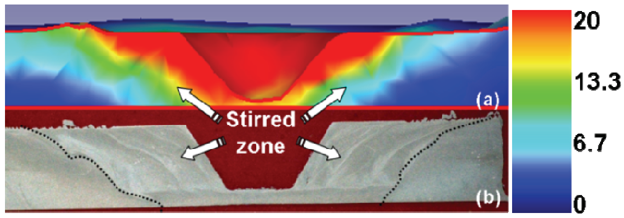

Fig. 8. Transverse section for the square case study (R = 300 rpm, RP = 0.6 mm/rev): (a)calculated strain and (b) actual experiment.

Finally a comparison between the temperature profiles in a joint transverse section taken right at the end of the weld, i.e. when the tool reaches the joint centre at the end of its trajectory, is reported for the two processes (figure 9a and 9b).

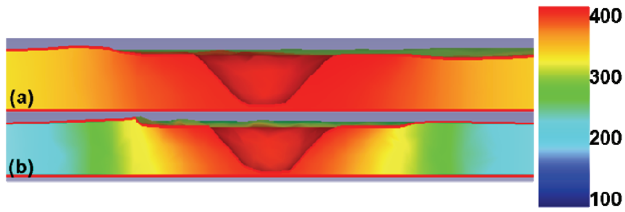

Fig. 9. Temperature profiles in the transverse section for (a) the square case study (R = 300 rpm and (b) the traditional FSSW (R = 300 rpm)

On the basis of the above figure, the main consideration that can be drawn is that although about the same maximum temperature is reached in the two case studies, in the modified process (figure 9a) a more uniform distribution is obtained, thus resulting in a more efficient material flow even far from the final position of the tool pin, namely at the centre of the joint.

5. CONCLUSION REMARKS

In the paper a continuum based FEM model for the modified Friction Stir Spot Welding process is proposed, that is 3D Lagrangian implicit, coupled, rigid-viscoplastic. On the basis of the obtained results the following conclusions can be drawn:

- Utilizing the modified process a maximum failure load in the shear test that is about twice the one corresponding to the traditional process is found; in particular the square case study is the one for which the best performances are found out;
- A strong correspondence can be found between the effective strain distribution and the actual material area involved in the bonding process;
- The developed numerical model is able to give useful information on the material flow, the actual stirred area and temperature distribution thus representing an effective tool for an efficient process design.

AKNLOWLEDGEMENTS

This work was made using MIUR (Italian Ministry for University and Scientific Research) funds.

REFERENCES

1. Chae, S.W., Kwon, K.Y., Lee, T.S., An optimal design system for spot welding locations, Finite Elements in Analysis and Design, 38 (3), 2002, 277-294.
2. Hemmingson, E., Ellqvist, S., Pauwels, J., New robot improves cost-efficiency of spot welding, Fuel and Energy Abstracts, 37 (4), 1996, 273.
3. Darwish, S.M., Al-Dekhial, S.D., Statistical models for spot welding of commercial aluminium sheets , Int. J. of Machine Tools and Manufacture, 39 (10), 1999, 1589-1610.
4. Larsson, J.K., Clinch-joining, Proceedings of the International Conference on Body Engineering, Advanced Technologies and Processes, 10, 1994, 140-145.
5. Lennon, R., Pedreschi, R., Sinh, B.P., 1999, Comparative study of some mechanical connections in cold formed steel, Construction and Building Materials, 13, 109-116.
6. Riches, S.T., Westgate, S.A., Nicholas, E.D., Powell, H.J., Proc. of the Materials for Lean Weight Vehicles Conference, 1995, 137-146.
7. Liu, H.J., Fujii, H., Maeda, M., Nogi, K., Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy, J. Mat. Proc. Techn., 142, 2003, 692–696.
8. Rhodes, C.G., Mahoney, M.W., Bingel, W.H., Spurling, R.A., Bampton, C.C., Effects of friction stir welding on microstructure of 7075 aluminum, Scripta Materialia, 36(1), 1997, 69-75.
9. Shigematsu, I., Kwon, Y.J., Suzuki, K., Imai, T., Saito, N., Joining of 5083 and 6061 aluminum alloys by friction stir welding, J. of Mat. Sci. Letters, 22, 2003, 353-356.
10. Pan T.Y., Joaquin A., Wilkosz, D.E., Reatherford, L., Nicholson, J.M., Feng, Z., Santella, M.L., Proc. 5th Int. Symp. on Friction Stir Welding, 2004, ISBN 1-903761-04-2.
11. Addison, A.C., Robelou, A.J., Proc. 5th Int. Sym. on Friction Stir Welding, 2004, ISBN 1-903761-04-2.
12. Buffa, G., Fratini, L., Piacentini, M., On the influence of tool path in friction stir spot welding of aluminum alloys, J. Mat. Proc. Techn., 208 (1-3), 2008, 309-317.
13. Jata, K.V., Semiatin, S.L., Continuous dynamic recrystallization during friction stir welding of high strength aluminum alloys, Scripta Materialia, 43, 2000, 743-749.
14. Su, J. Q., Nelson, T.W., Mishra R., Mahoney, M., Microstructural investigation of friction stir welded 7050-T651 aluminum, Acta Materialia, 51, 2003, 713-729.
15. Prado, R.A., Murr, L.E., Soto, K.F., Mc Clure, J.C., Self-optimization in tool wear for friction-stir welding of Al 6061 + 20% Al2O3 MMC, Mat. Sci. Eng. A, A349, 2002, 156-165.
16. Fratini, L., Beccari, S., Buffa, G., Friction stir welding FEM model improvement through inverse thermal characterization, Transaction of NAMRI/SME, 33, 2005, 259-266.

SYMULACJA NUMERYCZNA ZMODYFIKOWANEGO PROCESU PUNKTOWEGO ZGRZEWANIA TARCIOWEGO Z MIESZANIEM MATERIAŁU ZGRZEINY

Streszczenie

Proces spawania punktowego jest często wykorzystywanym sposobem łączenia elementów w przemyśle transportowym a w szczególności w przemyśle samochodowym. Podstawową zaletą tej metody jest możliwość uzyskania połączenia zakładkowego w krótkim czasie z wykorzystaniem zautomatyzowanych systemów robotów przemysłowych. Obecnie bardzo dynamicznie rozwija się proces spawania metodą punktowego zgrzewania tarciowego z mieszaniem materiału zgrzeiny (Friction Stir Spot Welding FSSW). Metoda ta jest udoskonaleniem metody Friction Stir Welding (FSW). Uzyskane w ten sposób spawy charakteryzują się lepszymi własnościami niż spawy uzyskane metodą konwencjonalną. Celem niniejszej pracy jest szczegółowa analiza procesu FSSW aby podnieść własności uzyskanego połączenia. Badania skupią się m.in. na badaniu wpływu trajektorii ruchu narzędzia. Opracowany model numeryczny oparty jest o metodę elementów skończonych z jawnym sztywno - lepkoplastycznym modelem. W trakcie pracy analizowano rozkłady temperatury, odkształceń, prędkości odkształcenia w obszarze jądra zgrzeiny oraz otaczającego materiału. Analiza w/w rozkładów dostarczyła istotnych informacji na temat końcowych własności spoiny oraz potwierdziła możliwość wykorzystania symulacji numerycznej do opracowania nowych technologii spawania.

Submitted: October 13, 2008
Submitted in a revised form: October 23, 2008
Accepted: October 27, 2008