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ON THE FEM SIMULATION OF FSW AND LFW OPERATIONS

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Abstract

In the paper some potentialities of FE models of joining by forming operations were showed. In particular FSW and LFW processes were considered.

Solid state welding processes are increasing their application in industrial environments due to their strong advantages with respect to traditional fusion techniques. Advanced FEM tools are requested in order to carry out a detailed engineering of the processes and to get quantitative results useful for the set up of the processes. Also basic investigations regarding process mechanics and material flow are important in order to fully understand the fundamental aspects of the processes and the bonding conditions at the interface of the specimens to be welded. In the paper Friction Stir Welding (FSW) and Linear Friction Welding (LFW) operations are considered and numerical results derived from FE models of the two processes are shown. The proposed results give the idea of the potentialities of the numerical tool for the two considered processes and in particular furnish interesting information on the actual bonding conditions at the welding zone.

Key words: FSW, LFW, FEM, material flow

1. INTRODUCTION

Transportation industries in the last decades more and more require parts and components with reduced weight also contributing to reduced emissions (see for instance Barnes & Pashby, 2000; Marré et al., 2009 for the automotive sector). More in general, it is well known that contemporary manufacturing, working, and end user's requirements demand low-cost and reliable lightweight frame structures in combination with flexible manufacturing. In this way light weight alloys, as aluminum or titanium ones, are surely potentially interesting materials to be used in industrial parts. Actually such materials are often so called "unweldable" or "difficult to be welded" ones; it should be observed that traditional fusion welding operations often determine defects as inclusions, brittle precipitates, voids and so on, on these alloys. From a metallurgical point of view, melting and solidification stages are very dangerous for several aspects due to interaction of melted metal with air and also because of grain dimensions of the final material structure.

As far as joining technologies for light weight materials are regarded, Barnes and Pashby (2000) subdivided joining techniques for aluminum space frames into two categories: on the one hand solid and liquid phase welding (category 1), and on the other hand adhesive bonding and mechanical fasteners (category 2).

In this way well known mechanical fastening techniques such as self pierce riveting and clinching are interesting solution to be used (TWI Bulletin, 1996; Bokhari, 1995; Di Lorenzo & Landolfo, 2004; Porcaro et al., 2004; Porcaro et al., 2006). Actually such joining techniques present a few disadvantages and shortcomings to be properly taken into account in the design of parts and components due to their

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specific process mechanics. Further joining techniques have been proposed as the so called tube expansion (Tang et al., 2009) which is a forming process that enlarges the diameter of a tube to form tight interferential tube–fin joints. Such a process is widely used for instance in the production of tube–fin heat exchanger plate for its high efficiency, cost-effectiveness, and reliability.

As far as tubes are regarded, since their joining constitutes an important aspect of assembly processes, new procedures and techniques have been proposed in recent years. Interesting experimentations started aimed to research potentials for joining tubes by plastic deformation methods. In particular, main technologies offered to the designers which can be used to join tubes are electromagnetic forming, hydroforming and mechanical forming (Barreiro et al., 2006; Przybylski et al., 2008).

As the latter possibility is regarded, the idea that has been pursued in the last years concerns the possibility to join blanks or tubes through rolling processes in a typical solid state welding operation (Przybylski et al., 2008). The technology principle is based on the application of a pressing force to a very stiff burnishing element which rolls on the workpiece and induces plastic deformations into its surface layer along with a reduction of the grain sizes and orientation of the material structure.

Overall in the last decades one of the most investigated principle of welding is the solid state one. All the solid state welding processes in fact are characterized by a lower level of defects due to the fact that no melting of the materials to be welded occurs. It should be observed that it is known from a long time that the mechanical energy generated in overcoming friction between continuous moving surfaces is transformed into heat. In most circumstances the thermal energy generated is regarded as undesirable, but under controlled conditions it can be used to join materials as in the case of friction welding (Mishra & Ma, 2005; Korsunsky et al., 2009; Vairis & Frost, 1998).

Considering the joining technologies which use friction as heat source, in the last two decades Friction Stir Welding has represented a definitively innovative joining technology. FSW was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminium alloys (Mishra & Ma, 2005). The basic concept of FSW is definitively simple: a non-consumable rotating tool with a specially designed pin at its end and a shoulder is inserted into the edges of sheets or plates to be welded and traversed along the line of joint. The tool plays two fundamental roles: heats the workpiece due to frictional forces work and plastic deformation work decaying into heat, and induces the material plastic flow determining the actual bonding of the blanks. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to its back. As a result of this process a joint is produced in ‘solid state’. Because of various geometrical features of the tool, the material movement around the pin can be quite complex. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains (Mishra & Ma, 2005). The fine microstructure in friction stir welds produces good mechanical properties of the joints, both static and dynamic.

The other friction welding operations which show very high potential in the joining of light weight alloys is the Linear Friction Welding (LFW). In general friction welding is a solid state process for joining materials together, through intimate contact of a plasticized interface (Vairis & Frost, 1998). The appropriate interface condition is generated by the heat produced from frictional contact as one component is moved in a relative motion to, and in pressure contact with, the corresponding surface of the other part. The weld is usually consolidated by a forging force, applied after the cessation of relative motion. The joint created, has a confined heat affected zone, and exhibits plastically deformed material around the weld which has been expelled due to the high internal pressures. In other words, a relevant flash is obtained due to the forging action exerted during the process on the two parts to be welded.

It should be observed that there are three basic variations of friction welding: namely rotary, orbital and linear. Rotary friction welding, is the most popular method, where one workpiece is rotated as the two workpieces are brought together under friction pressure. It is widely used for the welding of tubes.

The orbital variation of friction welding can weld non-circular parts as both components rotate in the same direction at the same speed but with their axes offset, resulting in uniform unidirectional relative velocity between the two workpieces over the total interface area.

Finally, Linear Friction Welding (LFW) is a relatively new process aimed at extending the current applications for rotary friction welding to non axisymmetric components. However, the two processes differ considerably in the mode of heat input and the stress field imposed on the plasticized layer (Vairis & Frost, 1998), and therefore existing mathematical models for rotary friction welding are not directly applicable to linear friction welding. The more uniform interfacial energy generation present in linear friction welding may account for the higher integrity welds associated with the process. In contrast to rotary friction welding where a considerable amount of work has been published, little information is available in the literature about linear friction welding, and just few pioneer works are found out. Available published data focuses mainly on thermoplastics and their welding parameters.

The present paper is focused on FSW and LFW technologies. In the last years the authors carried out numerical models based on the finite element method aimed to simulate the two processes. In particular 3D and 2D FEM models for the FSW and the LFW processes were proposed, that are thermo-mechanically coupled and with rigid-viscoplastic material behavior. Also simplified approaches were first presented in literature starting from, for instance, analytical thermal models of the considered processes (Chen & Kovacevic, 2003; Schmidt et al., 2004). It should be observed that FEM simulations even if starting from strong simplifying assumptions permit to better highlight the process mechanics of the joining by forming operations.

A few insights of the process mechanics and of the influence of the most relevant process variables were obtained through the numerical analyses. In this way, the numerical tools become a fundamental instrument to carry out a full engineering of the solid state welding operations.

2. THE FEM SIMULATION OF THE FSW PROCESS

As already mentioned, FSW is obtained by inserting a specially designed rotating pin into the adjoining edges of the sheets to be welded and then moving it all along the joint (Mishra & Ma, 2005). During the process, the tool rotation speed (R) and feed rate (V_f), determining the specific thermal contribution conferred to the joint, are combined in a way that an asymmetric metal flow is obtained. In particular, an advancing side and a retreating side are observed: the former being characterized by the "positive" combination of the tool feed rate and of the peripheral tool velocity while the latter having velocity vectors of feed and rotation opposite to each other. A detailed observation of the material microstructure in the joint section (see for instance Rhodes et al., 1997; Su et al., 2003) indicated that there exists an area located at the core of the welding, called "nugget", where the original grain and subgrain boundaries appear to be replaced with fine, equiaxed recrystallized grains characterized by a nominal dimension of a few μm.

The effectiveness of the obtained joint is strongly dependent on several process parameters (Lee et al., 2003), namely the geometric characteristics of the tool (height and the shape of the pin, shoulder diameter and so on), the force superimposed on the rotating tool during the process or the tool sinking in the sheet and finally the rotating speed and the feed rate, which determine the heat flux during the welding process.

Several investigation have been carried out on FSW in the last years. The latter regarded also the numerical simulation of the processes. Two different approaches have been followed: thermal models were proposed trying to reproduce the thermal condition inside the blanks during the process (Schmidt et al., 2004). A few finite element thermo-mechanical models have been presented in the last years (Chen & Kovacevic, 2003; Buffa et al., 2006). The research group of the authors in cooperation with researchers from Ohio State University, proposed a 3D FEM model (Buffa et al., 2006) aimed to highlight the FSW process mechanics, the occurring material flow and to show the distribution of the most important field variables, namely temperature, strain and strain rate. The model is a 3D Lagrangian implicit, coupled, rigid-viscoplastic model, developed through the commercial FEA software DEFORM-3D^{TM}, which fully describes the FSW operation. In particular the workpiece was modeled as a rigid visco-plastic material, and the welding tool was assumed rigid. As far as the thermal analysis of the model is regarded, the temperature levels were generated in FSW due to both plastic deformation and frictional conditions at the tool-workpiece interface (Buffa et al., 2006).

The FSW numerical simulation was divided into two stages: the sinking stage and the welding (advancing) one. During the sinking stage the tool with a tilt angle, first moves down vertically at 0.1 mm/sec with an assumed rotating speed, then, during welding or advancing stage, the rotating tool moves along the welding line (seam). The sinking stage is modeled to reach a large enough temperature level for the subsequent welding process and the advancing stage is modeled to investigate the thermo-mechanical phenomena occurring during the solid state welding process.

The tool was modeled as rigid body and meshed, for the thermal analysis, with about 3,000 tetrahedral elements. As far as the modeling of the workpiece is regarded, a “single block” approach is followed. In other words a continuum model (sheet blank without a gap) is used in order to avoid contact instabilities due to the intermittent contact at the sheet-sheet and sheet-tool interfaces. The rotating tool moves forward and welds a crack left behind the pin as it advances along the welding line. In figure 1 a sketch of the FEM model for a FSW aimed to obtain butt joints is shown. The sheet blank, 3mm in thickness, 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 sheet thickness. A non-uniform mesh with adaptive re-meshing was adopted with smaller elements close to the tool and a re-meshing referring volume was identified all along the tool feed movement (Marré et al., 2009). Experience in previous FEM simulation shows that a coarser mesh leads to incorrect results and a finer mesh results in unaffordable computation time without significant improvement of simulation results. A constant shear friction factor model 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. Finally in order to highlight the material flow due to the FSW processes, i.e. the nodes movements induced by the tool action, the node tracking option of the software DEFORM-3D^{TM} was utilized, highlighting for a set of nodes initially placed along the welding line, their final position after deformation.

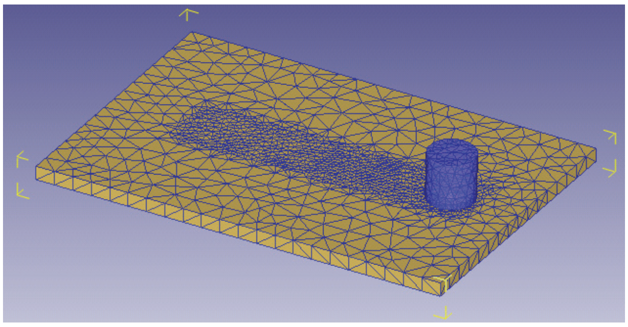

Fig. 1. *Sketch of the FSW FEM model*

3. THE FEM SIMULATION OF THE LFW PROCESS

As already pointed out, Linear Friction Welding (LFW) is aimed to extend the current applications for rotary friction welding to non axisymmetric components (figure 2). However, the two processes differ considerably in the mode of heat input and the stress field imposed on the plasticized layer (Vairis & Frost, 1998), and therefore existing mathematical models for rotary friction welding are not directly applicable to linear friction welding. The more uniform interfacial energy generation present in linear friction welding may account for the higher integrity welds associated with the process.

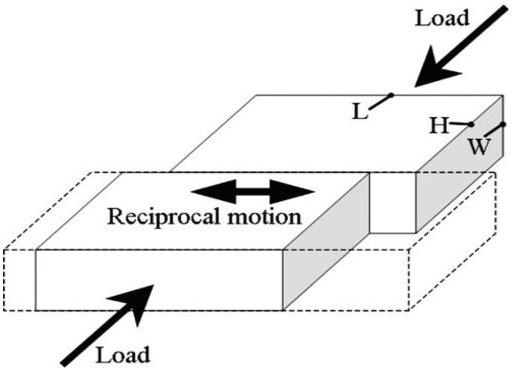

Fig. 2. *The LFW process*

As far as LFW is regarded, the evolutions occurring during the process can be described following four different subsequent stages (figure 3, see Vairis & Frost, 1999). During tile initial phase the two materials are brought in contact under pressure; at this stage, the two surfaces touch each other on asperities and the heat is generated from solid friction. Surface contact area is expected to increase throughout this phase with the reduction of asperities height.

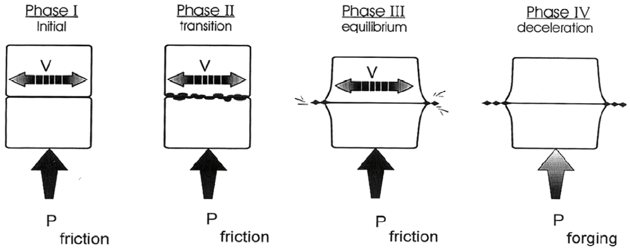

Fig. 3. *The LFW stages (Vairis & Frost, 1999)*

Although the shear force experienced is expected to rise as a consequence of the increase in contact area, it remains sensibly constant (Li et al., 2008a). This is thought to be due to the fact that the shear yield stress decreases as the temperature increases, which compensates for the increase of the true contact area. During such stage 1, called initial phase, if the speed at the interface is too low for a given axial force, insufficient heat will be generated and in this way no bonding will be reached. It should be observed that, if this condition is not achieved, the next phase will not follow and successful welding is not possible. In this way it is possible to experience threshold conditions of pressure and moving speed for each material or couple of materials to be welded.

Following stage 1, the so called transition phase is observed (stage 2 of the LFW process) and assuming that sufficient heat has been produced in order to reach material softening conditions, large wear particles begin to be expelled from the interface, and the heat affected zone expands. From stage 1 onwards the contact area is considered to be 100% and the soft plasticized layer formed between the two materials is no longer able to support the axial load. The shear force begins to increase although there is no evidence at this stage of axial shortening.

In the subsequent stage 3 – so called equilibrium phase – axial shortening of the two parts to be welded begins as result of the expelled material as flash. It is recognized in the few literature examples that the axial shortening varies approximately linearly with time (2-4). As process mechanics is regarded, it should be observed that in the plasticized layer formed at the interface between the two parts, the local stress system extrudes material from the interface into the flash in the direction of the oscillatory movement. At this stage, instabilities can appear due to non-uniform temperature distribution at the interface; in particular if the temperature increases at one part of the interface, the plasticized layer becomes thicker in that section, and more material is extruded in that side of the joint. This can result in a gradual rotation of the interface from the original plane: in other words the joint would become asymmetric. The origin of this unstable behavior could be attributed for instance to an initial misalignment of the specimens. This is a steady state extrusion stage, and the reaction force remains constant.

Finally, when the desired upset is reached (stage 4, the deceleration phase) the two materials are brought to rest very rapidly (in less than 0.1s) and forging pressure may be applied to consolidate the weld.

It should be observed that several parameters affect the described stages of the welding process. The pressure superimposed on the specimens to be welded, the frequency and the amplitude of oscillations of the specimens, the time length characterizing each of the formerly described phases are process parameters to be properly determined for each base material to be welded in order to maximize the mechanical performances of the developed joints. It should be observed that the cited parameters are not independent each other: for instance, it is expected that increasing the frequency of oscillation, a reduced amplitude is required in order to reach the welding conditions, assuming that the power input to be conferred to the rubbing interface remains constant.

Of course also the state of the surface of the specimens to be joined is relevant since it determines the frictional conditions and then the frictional forces at the interface between the two specimens.

Other relevant issues of the LFW process regard the metallurgical observation on the material microstructural evolutions in the welded joints (Li et al., 2008a; Mary & Jahazi, 2008; Dalgard et al., 2010). Actually an evolution of the average value of the grain size is observed and overall a thermo-mechanically affected zone (TMAZ) is observed close to the welding line and then moving towards the parent material on each side of the joint an heat affected zone (HAZ) is found out (Ceschini et al., 2010; Jun et al., 2010; Li et al., 2008b). What is more as joints made of two different materials are considered also the formation of inter-metallic structures must be considered, sometimes determining a brittle behavior of the joints, as it happens for aluminum-steel ones. Actually the metallurgical evolutions occurring in the material during the LFW strongly determine the mechanical performances of the obtained joints (Ceschini et al., 2010; Jun et al., 2010; Li et al., 2008b); in this way the former aspect is a crucial one in the engineering and design of LFW operations.

Another critical issue, probably the fundamental one in the wide diffusion of such solid state welding process, is related to the machine used for the process. Such device must provide oscillations characterized by frequency in typical range of 120-240Hz (but also an upper limit value of 1kHz should be considered) and amplitude of 0.5-5mm, and adjustable friction and pressure between the specimens to be welded. In literature a few approaches for the design and control of the LFW machines were proposed (Baynder & Ates, 2005; Vairis & Frost, 2006). Overall from the literature review appears that the design of the machine and its control must provide the possibility to vary process parameters within effective ranges of each variable in order to be able to carry out an effective engineering of the LFW process.

On the other hand, just rare examples attempting the modeling of the process are found out in literature. In Vairis and Frost (2000) the authors propose an analytical model of the heat flow, basing on a semi-empirical description of the material behavior. Just most recently FEM models of the LFW process have been proposed in literature up to now (Li et al., 2009; Ceretti et al., 2010; Sorina-Müller et al., 2010). Actually it should be observed that the numerical simulation of the process requires the overcoming of several numerical problems: first of all the self contact between the two parts to be welded must be faced. What is more a very refined mesh is required in order to "follow" the evolutions of the bodies (Ceretti et al., 2010; Sorina-Müller et al., 2010). Overall, an effective numerical simulation of the process represent a relevant step forward and a relevant tool for the engineering and best exploitation of the LFW processes. The numerical simulation of the LFW process was carried out using FE DEFORM 2D and 3D^{TM} commercial code. In fact, a two dimensional model, in plane strain conditions, is able to reproduce the actual process conditions occurring during the considered welding process. What is more, it should be observed that a fully three-dimensional model allows to take into account potential deformations in the third direction which could be relevant especially if specimens of small dimensions are considered. The LFW model is typically made of four objects, representing the two specimens to be welded during the process, a chuck used to clamp and make one of the two specimens oscillate during the process and a further chuck used just to clamp the other specimen as e.g. in figure 4.

The two specimens to be welded are defined as plastic, while the chucks are considered rigid in order to simplify the computation. Pressure is applied on the bottom side of the lower chuck (see again figure 4), while the oscillatory motion is given to upper specimen. The imposed oscillation of the upper specimen was given through a sinusoidal function characterized by a frequency and a maximum amplitude.

It should be observed that the proper modeling of the actual contact condition at the interface between the two specimens to be welded is a key factor of the FE analysis. What is more, frictional heat is generated only when parts of the contact surfaces are in contact. The shear factor model was used in order to model friction phenomena.

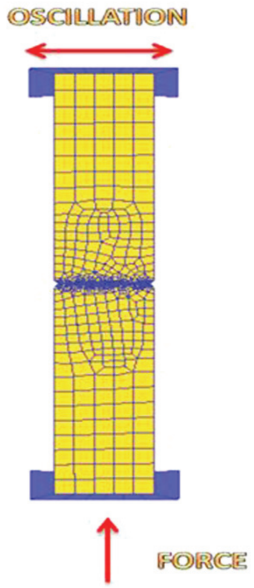

Fig. 4. The 2D LFW model

4. THE OBTAINED RESULTS

4.1. The FSW process

In the following some results regarding the FSW of butt joints of AA7075-T6 aluminum alloy blanks are shown. For the carried out numerical simulations the following values were utilized: thermal conductivity k = 180 [N/(s°C)] and thermal capacity c = 2.4 [N/(mm^2°C)] taken from literature; no variation of k and c with temperature was taken into account. This assumption makes the thermal problem linear speeding up the numerical solution at each time increment. A rigid-viscoplastic temperature and strain rate dependent material model was employed,

$$\sigma = K T^{A} \left(\dot{\bar{\varepsilon}}\right)^{B} \left(\bar{\varepsilon}\right)^{C} \text{ [MPa]} \qquad (1)$$

where $\dot{\bar{\varepsilon}}$ [s^{-1}] is the strain rate, T [Kelvin] is the temperature level, $\bar{\varepsilon}$ is the strain, while K = 2.69E10, A = -3.3155, B = 0.1324 and C = 0.0192, are material constants determined by a numerical regression based on experimental data. A constant interface heat exchange coefficient of 11 [N/(mm·s·°C)] was utilized for the tool sheet contact surface.

The sheet blank, 3 mm in thickness, was meshed in such a way to have about four element placed along the sheet thickness. A non-uniform mesh with adaptive re-meshing was adopted with smaller elements close to the tool and a re-meshing referring volume was identified all along the tool feed movement. 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. The tool was characterized by a shoulder of 12mm and a cylindrical pin with a diameter of 4mm and an height of 2.80 mm. Finally, as far as the process parameters are regarded a rotating speed (R) of 715 r.p.m. and an advancing speed of the tool V_f of 100 mm/s were used. A tilt angle of 2° was set and a tool sinking of 2.95 mm was reached. In the following Figures 5, 6 and 7 the distributions of the most relevant filed variables, namely temperature, strain and strain rate, are reported, with reference to a transverse section of the FSW butt joint taken just after the tool pin pass. The advancing side (A.S.) of the joint and the retreating one (R.S.) are highlighted in the figures.

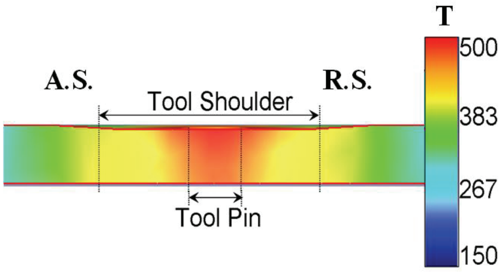

Fig. 5. The temperature distribution [T°] – transverse section of the joint just after the tool pin pass.

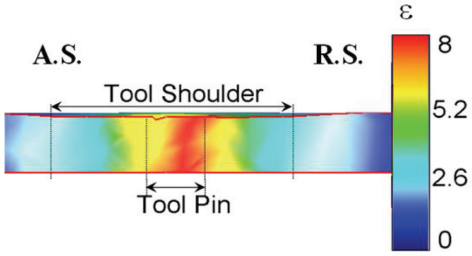

Fig. 6. The equivalent plastic strain distribution – transverse section of the joint just after the tool pin pass.

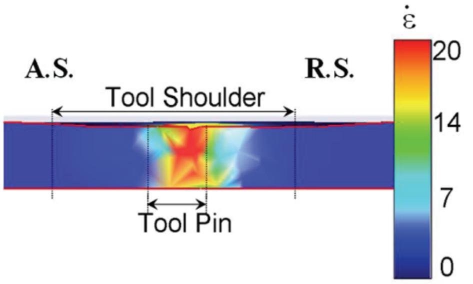

Fig. 7. The equivalent plastic strain rate distribution – transverse section of the joint just after the tool pin pass.

It should be observed that the above reported information typically are the basic input for the most common used bonding criteria. What is more, the strong gradients characterizing the investigated field variables are clearly visible in the reported figures. This is a peculiar characteristics of the FSW process; in this way the numerical models analyzing such joining by forming technique must be properly accurate. Another interesting information which can be used for further insights of the process is the distribution of the so called Zener-Hollomon parameter [19] (figure 8), since it is strictly related to the grain size evolution of the material during the welding process.

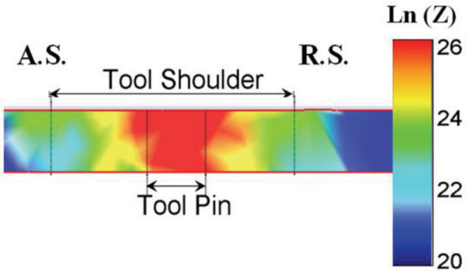

Fig. 8. The Zener-Hollomon parameter distribution – transverse section of the joint just after the tool pin pass.

Fig. 9. Top view of the FSW joint – position of the nodes initially placed along the welding line.

Finally using the node tracking option of the used commercial software, for a set of nodes initially placed along the welding line, their final position after deformation, was highlighted deriving relevant information regarding the actual material flow during the FSW process and in particular the fact that the bonding occurs in the advancing side (A.S.) of the joint (Fratini et al., 2006). The combination of a correct reproduction of the material flow occurring during the process and of the thermo-mechanical evolutions determining the local values of the field variables can allow to predict the bonding of the blanks and what is more, if an effective bonding criteria is implemented, to quantitatively evaluate the bonding itself.

4.2. The LFW process

In the present section a few results of a carried out FE model for the LFW of AISI 1045 steel specimens are reported. Conductive thermal phenomena were considered through a heat exchange coefficient of 11 w/mm^2/C. The material rheological behavior was introduced in the model through the following flow rule (1) taking into account strain, strain rate and temperature (Ceretti et al. 2010):

$$\sigma = 2000\varepsilon^{0.1}\,\dot{\varepsilon}^{\,0.06}T^{-0.23} \qquad (2)$$

where, again, $\dot{\bar{\varepsilon}}$ [s^{-1}] is the strain rate, T [Kelvin] is the temperature level, $\bar{\varepsilon}$ is the strain.

The imposed oscillation of the upper specimen was given through a sinusoidal function characterized by a frequency of 33 Hz and a maximum amplitude of 4 mm. The applied pressure was equal to 1.4 kN. The oscillation cycle (4 s) was subdivided into 4000 steps with a time step of 0.001s following the indications given in (Ceretti et al. 2010).

As far as the frictional heat is regarded, the shear factor (m) model was used: in particular for most of the process *m* = 0.8 was fixed while in the very early stages of the LFW process simulation and increasing value with time was introduced as indicated in (Ceretti et al. 2010).

In the next figure the temperature distribution in the top specimen are reported for four different steps of the modelled operation. It should be observed that the chosen steps recall the four stages of the LFW process, namely initial, transition, equilibrium and deceleration (see again figure 3).

Again, also for LFW operations, the FE models are able to furnish proper distributions of the field variables which are fundamental in order to investigate the actual contact conditions at the interface of the two specimens to be welded, especially as experimental bonding occurs.

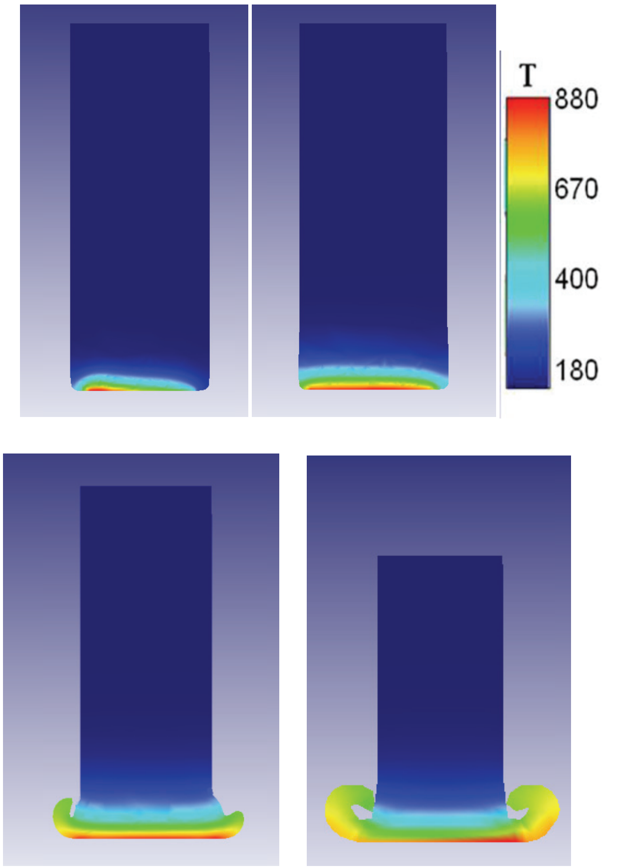

Fig. 10. *Temperature distribution at four stages of the investigated LFW case study (temperature scale is referred to last stage of the process).*

5. SUMMARY

Overall, it can be assessed that if a proper experimental campaign is associated and, what is more, if proper thermo-mechanical characterization of the materials to be welded are introduced, the FE models can be a very effective design tools in order to investigate the joining by forming process mechanics and to highlight the bonding conditions at the interface between the specimens to be welded.

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SYMULACJA METODĄ ELEMENTÓW SKOŃCZONYCH PROCESÓW FSW I LFW

Streszczenie

W artykule przedstawiono możliwości metody elementów skończonych (MES) w zakresie modelowania procesów spajania przez odkształcenie. Szczególny nacisk położono na procesy zgrzewania tarciem z mieszaniem zgrzewanych materiałów (ang. Friction Stir Welding – FSW) i liniowego spajania tarciem (ang. Linear Friction Welding – LFW). Liczba zastosowań procesów spajania w stanie stałym szybko rośnie, ze względu na liczne zalety tych procesów w przemyśle w stosunku do tradycyjnych metod spajania. Zaawansowane modele MES są potrzebne dla przeprowadzenia dokładnej analizy tych procesów i uzyskania ilościowych wyników, które są użyteczne dla zaprojektowania technologii spajania. Badania mechanicznych aspektów procesów spajania oraz płynięcia materiału w tym procesie są również istotne dla pełnego zrozumienia podstaw tych procesów i warunków łączenia się materiałów. W artykule omówiono procesy FSW i LFW i przedstawiono wyniki symulacji MES dla tych procesów. Zaprezentowane wyniki pokazują możliwości numerycznego modelowania w zakresie wspierania projektowania procesów spajania, ze szczególnym uwzględnieniem warunków łączenia się materiałów w strefie spajania.

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