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Using a neural network for predicting the average grain size in friction stir welding processes

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ABSTRACT

In the paper the microstructural phenomena in terms of average grain size occurring in friction stir welding (FSW) processes are focused. A neural network was linked to a finite element model (FEM) of the process to predict the average grain size values. The utilized net was trained starting from experimental data and numerical results of butt joints and then tested on further butt, lap and T-joints. The obtained results show the capability of the AI technique in conjunction with the FE tool to predict the final microstructure in the FSW joints.

1. Introduction

FSW of butt joints is obtained inserting a specially designed rotating pin into the adjoining edges of the sheets to be welded and then moving it all along the welding line [1–4]. The pin is characterized by a rather small tilt angle (θ) and as it is inserted into the sheets up to a proper tool sinking (Δh), the blanks material undergoes to a local backward extrusion process up to contact the tool shoulder. The tool rotation determines an increase of the material temperature due to the friction forces work decaying into heat. The material mechanical characteristics are then locally decreased and the blanks material reaches a sort of "soft" state; no melting is observed, a circumferential metal flow is obtained all around the tool pin and close to the tool shoulder contact surface.

As such material softening is reached, the tool is moved along the joint welding line avoiding excessive reaction loads which could lead the pin to fracture. The tool movement (tool feed rate V_f) determines heat generation due to both friction forces work and material deformation one. It should be observed that is now known in the scientific community that the largest amount of heat in FSW processes is given by the frictional forces at the tool shoulder–workpiece interface [5,6]. As indicated by Schmidt et al. [5] about the 86% of the thermal flux is due to the frictional forces work decaying into heat.

What is more, during the FSW process the composition of the tool spin vector (R) and of the feed rate vector (V_f) determines a metal flow all around the tool contact surface [7–9]. Considering a transverse section of the joint, an asymmetric metal flow is obtained and an advancing side and a retreating one are observed. The former is characterized by the "positive" composition of the tool feed rate and of the peripheral tool velocity; on the contrary, in the latter the two velocity vectors are opposite. Overall, the tool action determines the metal flow which allows the blanks welding [10,11]. In FSW of butt joints the material flows on the back of the tool from the retreating side of the joint towards the advancing one bonding in the advancing side with the undeformed material on an inclined surface.

Several researches have been presented in literature in the last years on some fundamentals of FSW and of its process mechanics: for instance on the microstructural evolutions occurring to the material [4,9], on physical and chemical possibility to obtain joints from dissimilar materials [12,13], on the occurring material flow and actual bonding [10,11], on the residual stresses resulting in the joint [14], or on the occurring fracture mechanics [15]. A wide research activity has been also focused on the mechanical performances – both static and dynamic – of the FS welded joints and on the influence of the most relevant process parameters on such performances [8,14,16].

In the recent past a few research activities were developed also on the numerical simulation of FSW processes. First of all, analytical thermal models were proposed [5,17] trying to highlight the temperature distribution nearby the rotating pin for given process parameters. Then finite element thermo-mechanical models were presented [18,19] with the aim to investigate the stress and strain distribution during the FSW process and to highlight the material flow, in terms of material circumferential speed all around the rotating pin.

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Nomenclature

FEM	finite element model	k	thermal conductivity [J/(m s °C)]
FSW	friction stir welding	c	thermal capacity [J/m^3 °C]
θ	tilt angle	Z	Zener–Hollomon parameter
Δh	tool sinking	Q	continuous recrystallization activation energy
V_f	tool feed rate	R	gas constant
R	tool spin vector	RP	rotational pitch
CDRX	continuous dynamic recrystallization	STC	specific thermal contribution
UTS	ultimate tensile strength	HAZ	heat affected zone
UTS_b	ultimate tensile strength of the base material	TMAZ	thermo-mechanically affected zone
LOM	light optical microscope	D_{CDRX}	average grain size due to continuous dynamic recrystallization
T	temperature [K]	D_0	initial grain size
ε	strain	MSE	mean square error
$\dot{\varepsilon}$	strain rate [s^{-1}]		

The authors presented a 3D fully coupled thermo-mechanical FEM model [20,21] in which the tool–workpiece interaction in FSW of butt joints was investigated. In particular in [21] the numerical model was improved considering the material microstructure evolution during the FSW process. An analytical model of grain size evolution due to recrystallization phenomena was linked as a subroutine to the FEM code. Actually in FSW processes a continuous dynamic recrystallization phenomenon (CDRX) [22,23] occurs at the core of the welding, in the so called nugget area, due to the tool pin disruptive mechanical action. The tool stirring action generates the formation of fine, equiaxed recrystallized grains and such new microstructure determines the local material mechanical properties and the overall joint resistance. In this way, an effective prediction of the material grain size is a fundamental step in the CAE of the FSW process.

It should be observed that the microstructural phenomena occurring in FSW process are quite complex and strongly depend on the distance from the welding line, i.e. from the tool pin. In other words, the material microstructural evolutions which take place in FSW processes can hardly be modelled through an analytical model referred to recrystallization phenomena. In this way the authors improved the capability of the numerical model to predict the local values of the average grain size using a properly trained neural network [24]. In particular with reference to AA6082-T6 and AA7075-T6 aluminum alloys, two neural networks were designed and properly trained on the basis of experimental tests data and numerical calculations. The developed artificial intelligence tools were then linked to the 3D FEM model and permitted to predict the grain size evolution in further investigated case studies for the two considered materials. The NNs permitted to set up a correlation between field variables occurring in the transverse section of FSW joints and the final average grain size of the material. Through the AI tools, no relevance is given to the occurring microstructural phenomena, both static and dynamic and, what is more, no specific reference is done to the FSW process parameters. The process and its metallurgy is assumed as a black box: the inputs of the problem are the local values of the field variables given by the FE code and the output is the obtained microstructure, in terms of average grain size. In [24] the authors highlighted the obtained improvement with the NNs in the prediction quality with respect to analytical models.

In the present paper, taking into account 2xxx series aluminum alloys, a further relevant extension of the approach based on NNs is proposed. The AI tool was designed and properly trained for the prediction of the average grain size in the transverse section of butt joints obtained by FSW. A first test stage of net was then developed on further case studies, i.e. on further FSW of joints welded with different process parameters. Furthermore the NN was applied to prediction of the final local values of the grain dimension in FSW of lap and T-joints of the same material. The obtained numerical results were compared with the experimental evidences, i.e. the measured grain sizes for such new welding configurations. Even in such extended conditions the AI tool demonstrated its capabilities and good performances were obtained if compared to the ones for butt joints. In this way a complete predictive tool was developed, able to be used in every FSW process configuration once trained and tested for the basic one, i.e. the butt joint.

2. The FSW processes

The FSW between 3.2 mm thick AA2139-T8 blanks were considered for the three joint configurations proposed. The utilized alloy was characterized at room temperature by a yield stress of 440 MPa and an ultimate tensile stress (UTS_b) of 480 MPa. At room temperature the blank material showed a microhardness equal to 155 HV and grains of about 50–60 μm (D_0). Specimens of 100 × 70 mm edges were jointed. In the next Table 1 the chemical composition of the AA2139-T8 is reported.

The material was furnished in the T8 condition, namely after a solubilization at 530 °C for 4 h, a cooling in water and an artificial aging at 175 °C for 8 h, the blanks were cold stretched [25]. A proper clamping fixture was designed and developed for each of the considered joints in order to fix the blanks to be welded on the working table of a milling machine.

In the next Figs. 1–3 the sketches of the three processes are reported.

The utilized tools were made of H13 steel quenched at 1020 °C, characterized by a 52 HRc hardness. Three different welding configurations were considered, namely the butt, lap and T-joints. In the next Table 2 the geometrical data of the three used tools are summarized.

All the geometrical parameters were chosen on the basis of preliminary experimental campaigns aimed to obtain effective joints without defects, such as tunnels in the transverse section.

As far as the process parameters are regarded the influence of the tool rotating speed (R) and of the tool feed rate (V_f) were investigated. In the next Fig. 4 the experimental plan carried out for the FSW of butt joints process is shown. For all the considered case studies, namely FSW1-9, three different replicas were developed and the average values of the grain size were considered for each measurement locus.

As far as the lap and T-joints are regarded, one test for each configuration was developed as reported in the next Table 3. It should be observed that, again, three different replicas were developed for