Int J Adv Manuf Technol (2017) 88:2899–2908
DOI 10.1007/s00170-016-9007-4

ORIGINAL PAPER

Temperature measurements during friction stir welding

A. C. F. Silva [1] · J. De Backer [1] · G. Bolmsjö [1]

Received: 16 March 2016 / Revised: 28 May 2016 / Accepted: 1 June 2016 / Published online: 9 June 2016

Abstract The increasing industrial demand for lighter, more complex and multi-material components supports the development of novel joining processes with increased automation and process control. Friction stir welding (FSW) is such a process and has seen a fast development in several industries. This welding technique gives the opportunity of automation and online feedback control, allowing automatic adaptation to environmental and geometrical variations of the component. Weld temperature is related to the weld quality and therefore proposed to be used for feedback control. For this purpose, accurate temperature measurements are required. This paper presents an overview of temperature measurement methods applied to the FSW process. Three methods were evaluated in this work: thermocouples embedded in the tool, thermocouples embedded in the workpiece and the tool-workpiece thermocouple (TWT) method. The results show that TWT is an accurate and fast method suitable for feedback control of FSW.

Keywords Friction stir welding · TWT method · Temperature · Aluminium · Thermocouples

✉ A. C. F. Silva
ana.silva@hv.se

J. De Backer
jeroen.debacker@hv.se

G. Bolmsjö
gunnar.bolmsjo@hv.se

[1] University West, Trollhättan, Sweden

1 Introduction

Friction stir welding (FSW) is a solid-state welding process developed by TWI Ltd. in 1991 [1]. Nowadays, many industrial sectors have demonstrated successful application of the FSW process, including aerospace, marine, railway and automotive. In this process, a non-consumable rotating tool is plunged into the material to be welded. The friction between the tool and the workpiece generates heat, softens the material and enables the material plastic deformation. The tool advances, under continuous rotation, generating a complex material mixture and thereby creating a solid-state joint [2, 3]. Figure 1 presents a schematic representation of the FSW process. The low temperatures during FSW avoids several of the defects typically observed in fusion welding processes such as porosities and cracks, hence presenting good mechanical properties over arc welding [2, 3]. Furthermore, the reduced heat input results in lower deformation. FSW was initially developed for aluminium alloys but also for other materials such as magnesium, steels, titanium and nickel copper alloys, and dissimilar materials can also be welded [2, 3].

Guaranteeing a void-free weld with consistent mechanical properties is crucial for industrial applications and permits minimal post-weld inspection. This is especially important for FSW since in-process non-destructive monitoring and testing are less developed for FSW than for fusion welding processes. As the industrial demand for lightweight products with increased geometrical complexity rises, there is a need for better process control, in order to guarantee a consistent weld quality. Furthermore, feedback of process variables during welding allows a systematic approach for weld parameter window development, instead of the trial-and-error approach which is often adopted [4].

Previous studies have demonstrated a direct effect of weld temperature on the mechanical properties of a FSW joint. The

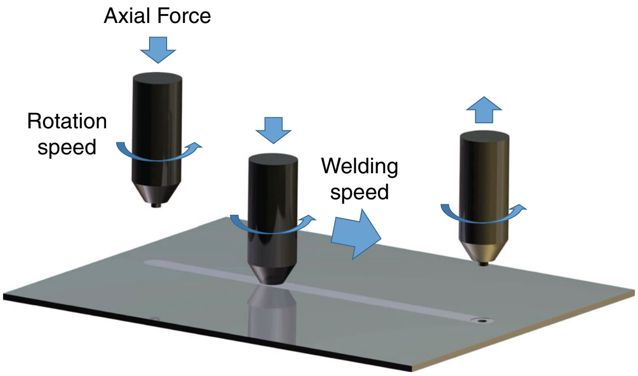

Fig. 1 Friction stir welding process

weld temperature distribution as well as the material flow during welding determine the defect development, microstructure evolution and, consequently, the resulting joint's mechanical properties. The weld parameters, material thickness, the alloy to be welded and the tool design strongly affect the weld temperature [2, 3, 5], and the backing bar material has also been reported to have an influence [5, 6]. The implementation of temperature control for FSW allows optimisation of the process and is in some applications essential to obtain sound welds [2–5, 7]. A welding parameter's window based on "hot" and "cold" weld boundaries is usually adopted to achieve sound welds. The combination of high rotation speed and low traverse speed, in literature often denoted "hot welds", leads to flash formation and microstructure modifications. Cold welds, achieved by the use of low rotation speed and high traverse speeds, result in void formation and can lead to the tool fracture [3]. A minimum weld temperature is required in order to obtain sufficient material mixing [5]. This means that the weld temperature during FSW should remain within a certain temperature range in order to obtain sound welds [3]. Thermal disturbances induced by variations in heat dissipation affect the weld properties and may result in a weld temperature outside the allowable range. By controlling the welding parameters such as rotational speed or axial force, it is possible to maintain the weld temperature within the allowable range, avoiding defect formation. This can be achieved through online feedback control of the welding process, such that the temperature is controlled to a predefined value [5, 7–9].

Although it is commonly agreed within the scientific community that temperature information can be used to control the process and thereby improve weld quality, there is no agreement regarding an optimal weld temperature [3]. Some researchers claim that the material temperature around the pin achieves the solidus temperature (T_S), with the occurrence of local melting. In this case, a self-limiting system is achieved, where the material at the tool-workpiece interface transfers from a stick-to-slip phase as the T_S is reached, decreasing the heat generation due to the reduction on friction [2, 3, 10]. The weld temperature to achieve sound welds has been reported just below the T_S measured in centigrade, in the range of 80 % T_S [6], 60–90 % T_S [2] or 80–90 % T_S [4].

Weld temperature measurements through experimental validation are difficult to perform due to the intense plastic deformation at the workpiece-tool interface, which is considered the hottest area in the weld [3, 11]. The passage of the rotating pin makes it difficult to measure the temperature on the stir zone; therefore, acquiring peak temperature measurements from thermocouples inside the workpiece is problematic [2]. For this reason, standard temperature measurement methods often lack the required repeatability, accuracy or speed for industrial use.

In this paper, an overview of existing temperature measurement methods is presented and some methods are compared and experimentally verified.

2 FSW temperature measurement methods

Temperature measurement during FSW has been explored by several researchers, and different methods have been applied in order to measure or predict the weld temperature, for example, thermocouples embedded in the workpiece or in the FSW tool, thermal cameras, correlation with the microstructure, simulation models and temperature measurement methods based on ultrasound and neutron source. Table 1 presents some temperature values described in literature using the different methods.

Stir zone temperatures are preferably measured close to the transition from the probe to the shoulder, as this is considered the hottest point inside the weld [7]. The use of embedded thermocouples located inside the workpiece and close to the rotating pin area has been the most common temperature measurement method found in the literature [2, 19–21]. In several studies, the maximum temperature through the use of thermocouples in the workpiece is close to 500 °C for aluminium alloys [3]. However, the thermocouple measurements are very sensitive to its location and its data should be interpreted with caution. The exact thermocouple location is uncertain due to the rotating pin and the strong plastic deformation in the stir zone. For this reason, the temperature values may be also uncertain [3]. Some researchers reported that the thermocouple at the joint line may be destroyed when the pin passes by [7]. It has also been reported that the pin passage does not destroy the thermocouple at the weld centre but may change its position due to the intense material flow [2]. However, temperature measurements further away from the stir zone do not provide a good estimate of the quality of the weld. The maximum temperatures have been reported close to the stir zone border and present a decrease with increasing distance from the joint line [2, 11]. Due to the complex geometry, material tolerances, clamping and backing of production parts,

Table 1 Temperature values obtained using different methods as found in literature

Measurement method	Material	$T_{Solidus}$ (°C)	Weld temperature peak (°C)	Reference
Thermal camera	SSA038-T6	–	363–490	[10]
Equation	SSA038-T6	–	346–390	[10]
Simulation model	AA7050	490	422	[4, 12]
Microstructure evaluation	AA7075-T651	475	400–480	[2, 12]
TTC-Shoulder	AA7075	475	378–478	[12, 13]
TTC-Probe	AA7075	475	371–507	[12, 13]
TTC-Root	AA7075	475	371–480	[12, 13]
Microstructure evaluation	AA6061	582	400	[2, 5]
Simulation model	AA6061	582	443	[4, 5]
TTC-Shoulder	AA6061-T6	582	533	[5, 7]
TTC-Probe	AA6061-T6	582	482	[5, 7]
WTC and regression analysis	AA6061-T6	582	365–390	[5, 14]
WTC	AA6061-T651	582	475	[5, 6]
WTC	AA6061-T6	582	450	[2, 5]
Simulation model	AA6061-T651	582	524	[5, 6]
Neutron diffraction	AA6061-T6	582	362	[5, 11]
Microstructure evaluation	AA6082-T6	580	400	[2, 15]
WTC	AA6082-T6	580	189–474	[15, 16]
TWT	AA6082-T6	580	525	[15, 17]
Simulation model	AA6082-T6	580	536–567	[15, 18]
Microstructure evaluation	AA6063	615	402	[2, 12]
TTC-Shoulder	AA5083-H111	574	>518	[5]
TTC-Probe	AA5083-H111	574	>479	[5]
WTC	AA5083-O	590	550	[2, 12]

TTC tool thermocouple, *WTC* workpiece thermocouple, *TWT* tool-workpiece thermocouple

it is in practice impossible to predict the temperature in the joint line from measurements elsewhere. The thermocouple's vertical position inaccuracy may also lead to temperature inaccuracy, which reflects the vertical heat dissipation towards the backing bar. Thermocouples located at the top of the workpiece to be welded measure a higher temperature than those located in the bottom, especially when high thermal conduction material is used as backing bar [2, 6]. Hence, different thermocouple locations may be found in different studies making it challenging to compare with each other. In order to forecast the peak temperature, regression analysis from temperature data acquired using thermocouples at various locations has been applied to extrapolate a weld temperature as function of the distance to the joint line [14, 22]. The use of thermocouples embedded in the workpiece material is a demanding and time-consuming task with significant post-weld data analysis. In addition, this method cannot provide online measurements and the thermocouples cannot be reused [7]. Furthermore, the method cannot be used for weld inspection purposes in production since the thermocouple cannot be removed without damaging the welded part.

The use of thermocouples embedded in the tool has been investigated in several studies. Cederqvist et al. have implemented this method in order to perform online weld control on large copper canisters. A tool with three thermocouples, located on the centre of the probe, at the internal shoulder diameters and at the external shoulder diameter, was used. A slow time response of the thermocouple on the probe was reported [23], and the thermocouple located on the internal shoulder diameter reacted faster to disturbances in the weld. This was due to the thermocouples in the shoulder being closer to the stir zone, as well as the shoulder material having a higher thermal conductivity than the probe material. The thermocouple on the shoulder internal diameter was selected to be used by the controller as it provided the quickest time response [24]. Fehrenbacher et al. have used a tool with one thermocouple embedded in the shoulder and another in the centre of the probe [5]. The thermocouples were located as close as possible to the tool-workpiece interface. In order to minimize the thermal delay and dead time, a finite element method model was used to define the thermocouple locations to obtain the temperature peak [7]. However, due to the dynamic response of the thermocouple, the temperature readings are not as expected on the tool-workpiece interface. The dynamic response of the embedded thermocouple was measured using the laser flash method, and the true tool-workpiece interface temperature was calculated. In this way, it was possible achieving accurate tool-workpiece temperature readings. A wireless system was used for data transmission [9]. A decrease of instrumentation effort per weld as well as accurate and fast readings were reported [7]. This method was used for online temperature control [5]. However, embedded thermocouples present some limitations such as the difficulty to apply on small FSW tools, as it requires a pre-drilled hole which makes the tool costly. Finally, a risk of thermocouple failure by breakage during welding is inherent to the method due to the thermocouple being close to the tool-workpiece interface. Fehrenbacher et al. successfully welded over 7 m length using a single set of thermocouples without failure [9]. The thermocouples need to be assembled as close to the tool-workpiece interface as possible, enabling a very quick response to weld variations [5, 7]. However, the temperature distribution is varying throughout the tool and the validity of single point measurement is questionable [3]. Fehrenbacher et al. reported higher weld temperature readings in the shoulder interface than in the probe interface, with a difference of about 20 °C. Welds in AA6061 reportedly produced defects when shoulder temperatures were below 520 °C. Welds above T_S resulted in a decrease of mechanical properties, suggesting occurrence of local melting. The welds performing at a shoulder temperature of 533 °C during the weld were reported to provide high quality [5].

Thermographic equipment such as pyrometers and thermal cameras have been tested for FSW temperature measurements. However, their repeatability is compromised by other possible radiation sources; for example, the FSW tool has similar temperature magnitudes and large temperature gradients. Also, the high reflectivity of the aluminium makes the measurements difficult [7]. This method is limited to the shoulder edge temperature and can thus not register the temperature peak, causing a slow time response to changes in the FSW temperature [7].

Relations between the temperature and the microstructure evolution have been used to estimate the weld temperature. The temperature distribution affects the weld microstructure, namely, grain size, grain boundary, coarsening and dissolution of precipitates [2, 25]. Microstructure analysis rarely suggests the occurrence of melting at stir zone and the thereby associated liquation cracking [2, 3]. The maximum temperature at the stir zone is believed to be below the melting point of the alloy due to no melting being observed and due to the dynamic recrystallization characteristic of this process [2, 14]. Temperature has been estimated from the secondary phase dissolution, suggesting a peak temperature between 425 and 500 °C [2, 3, 25]. For example, Su et al. [26] studied microstructural development during FSW in AA7050-T651. The results indicate that the TMAZ region bordering with the stir zone reaches the solution heat-treatment temperature allowing η precipitates to dissolve and re-precipitate. Temperatures higher than 400 °C were estimated to be reached on this region [25, 26]. A relationship between the stir zone grain size and the maximum weld temperature was studied performed by Sato et al. [27]. The study revealed that an increase of temperature leads to larger grain size [25, 27]. The microstructure study only offers an estimate of the temperature during the process and is only possible by destructive testing of the joint.

Numerical models of FSW have proven to be a great tool for a better understanding of the process. Prediction tools for temperature distribution and material flow during the weld, as well as the residual stresses and microstructure evolution, have been developed in recent years [7]. Other simulations attempted to predict the energy input per weld length, peak temperature and temperature field. However, verification of thermal models requires accurate experimental temperature data from the welding process which is difficult to obtain. Also, due to the limited number of temperature data acquired during experiments, it is difficult to acquire a high spatial and temporal resolution, which is needed as input for the models [7]. The backing bar effect is typically not represented as an actual heat loss on the non-welded zones. Khandkar et al. studied the backing bar effect through numerical simulation. The model predicted temperatures above the melting point, in the vicinity of the tool for the simulation using an insulated backing plate i.e. by setting the heat transfer coefficient to zero [6]. Numerical models are based on well-known boundary conditions, but in the industrial environment unpredicted circumstances such as clamping force, tool wear, preheating or variations in material properties and geometry may affect the predictions [28].

Other less conventional temperature measurement methods have been presented such as ultrasonic time of flight. This method is based on the physical phenomenon where the speed of a sound wave through a medium relates to the temperature of the medium. This method presents good temperature measurements but requires a flat surface, which makes it unsuitable for welding of complex geometries. It is also a complex technology and difficult to calibrate since it depends on the material state [28–30]. Another temperature method tested in FSW is the neutron source method, which is based on the use of in situ time-resolved neutron diffraction [7, 11]. With this technique, temperature and stress fields of the weld can be acquired simultaneously [11].

The tool-workpiece thermocouple (TWT) method is a temperature method for FSW recently developed by De Backer et al. [28]. The TWT method measures the temperature at the interface of the FSW tool and the workpiece. It is based on thermoelectric effect where the electric potential generated between the FSW tool material and the aluminium workpiece relates to the weld temperature, as illustrated in Fig. 2. The temperature value obtained by this method is an average of the entire contact area. The use of the thermoelectric effect for temperature measurement has been successfully applied

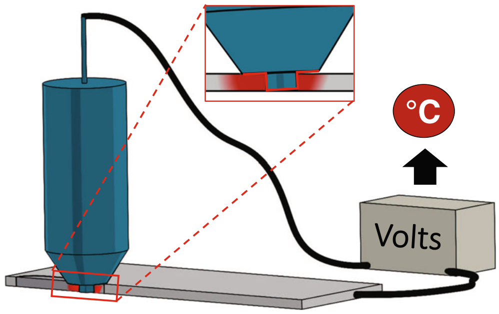

Fig. 2 Tool-workpiece thermocouple (TWT) method

previously in machining applications [31]. The voltage measured will depend on the tool and workpiece material properties [28, 32, 33]. Therefore, each tool-workpiece material combination requires a calibration of the voltage-temperature relation [17]. The TWT method has demonstrated to acquire accurate and fast measurements using a simple setup. This method is also suitable for feedback control of the process and for application in the industrial environment [28, 32, 33].

The overall goal of this study is to identify the most suitable temperature measurement method for temperature feedback control of thin-section FSW. Due to the already proved inaccuracy and instrumentation limitation, most of the methods discussed previously could not be verified within the scope of this work. Hence, the work was limited to three methods. The thermocouples inserted in the tool and the TWT method were selected due to the possibility for online data acquisition. The thermocouples embedded on the workpiece are included to verify the accuracy of the other methods. For the acquisition of truthful data with these, a careful care on it pre- and post-weld local identification was performed. The results were compared and presented in this work.

3 Materials and methods

Bead-on-plate FSW trials were performed in 3-mm-thick AA6082-T6. A FSW tool design with 12-mm scrolled shoulders and 5-mm-diameter scrolled probes was used. The probe length was 2.8 mm. Uddeholm QRO90 supreme steel was used as tool material. A stainless steel backing bar with 8 mm thickness was used. All the welds were performed using an ESAB Rosio™ robot located at the Production Technology Centre in Trollhättan, Sweden [33]. The robot is equipped with force feedback control. The system is limited to 12 kN axial force, a welding speed of 2500 mm/min and a rotation speed of the spindle of 4500 rev/min and a stall torque of 30 Nm. ABB RobotStudio and the LabVIEW-based ContRoStir software were used to control the system and register the temperature, rotation speed and axial force data. The temperature and voltage measurements were acquired by a National Instruments DAQ system at 15 Hz.

In order to study the temperature during the FSW process, three methods were used and compared: the TWT, a thermocouple inserted on the tool (TTC) and thermocouples inserted on the workpiece to be welded (WTC).

The TWT method was applied to all welds performed in this work. Its calibration to the aluminium alloy used has previously been reported [17]. Two Omega thermocouples type N with 1.5 mm diameter (TJC100-NNXL-M150G-450) were inserted in two equal FSW tools. Due to the tool size and limited connection channels, these could not be used at the same time. Figure 3 presents the thermocouple position on each tool. One thermocouple was placed in the probe centre of one tool (TTC-Probe), about 1.5 mm above the tip of the probe. The second thermocouple was placed in the shoulder (TTC-Shoulder) approximately 1 mm away from the outer diameter of the probe and in direct contact with the workpiece material. A slip ring was used to transmit the signals from the rotating spindle to the stationary measurement modules. The welding parameters used for these experiments were as follows: 3500 N axial force, 1000 rev/min rotation speed, 5 mm/s welding speed and 1° tilt angle. The step responses of the TWT and the TTC were calculated for welding variations in rotation speed (800–1400 rev/min) and axial force (3500–5500 N).

Several type-K thermocouples with the exposed connection were inserted into the material to be welded. These cannot be used for online control of the process but are used for verification of the temperature readings from the other temperature measurement methods. These thermocouples were placed in two different ways (see Fig. 4). Case 1: The thermocouples were placed horizontally inside 1.5-mm-diameter drilled holes at a height of 1.5 mm, i.e. half of the material thickness. Case 2: The thermocouples were inserted vertically inside a 1.5-mm diameter hole, drilled through the entire plate thickness. The thermocouple measurement point was located on the top plate surface. In both cases, the thermocouples were positioned at six different distances from the weld centre at 5, 4, 3, 2, 1 and 0 mm, both on the advancing and retreating side. In order to not damage the thermocouple, a lower axial force (3000 N) was used for the set of experiments in case 2. In

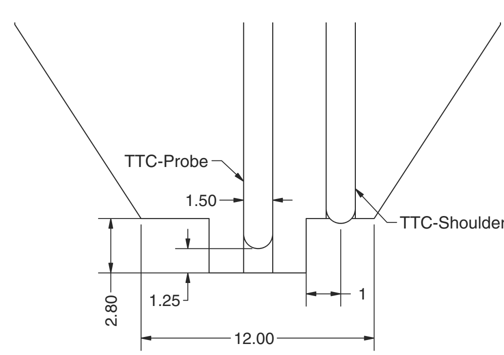

Fig. 3 Thermocouples positions on the FSW tools

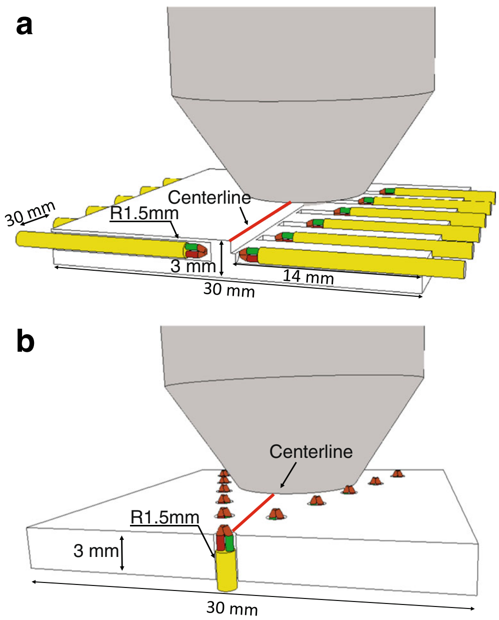

Fig. 4 Schematic representation of the thermocouples location. **a** The thermocouple is placed horizontally and perpendicular to the welding direction-case 1. **b** The thermocouple is inserted vertically through the plate-case 2

order to obtain the exact location of the thermocouple after welding, X-rays analysis was performed on all the welds.

4 Results and discussion

The experimental results of the temperature measurement performed using different methods are presented and compared in this section. Section 4.1 shows the result of the thermocouples inside the FSW tool and compares them with the TWT measurements performed on the same welds. In Sect. 4.2, the temperature measurements using thermocouples placed along the lateral direction of the workpiece are presented and analysed. Section 4.3 presents the results related to the temperature measurements by thermocouples placed through the workpiece thickness. In both cases, the measurements are compared to the TWT and TTC measurements.

4.1 TWT versus thermocouple inside the tool

Figure 5 presents the temperature data from TWT method and the thermocouple embedded in the tool. Two different welds were performed: (1) using a tool with a thermocouple embedded in the shoulder and (2) using a tool with the thermocouple embedded in the probe.

Values obtained using the TWT method are higher than the values read by both thermocouples. In the case of the thermocouples, both present lower temperature readings. The surrounded mass of steel around the thermocouples as well as the ceramic coating from the thermocouples may lead to lower temperature values. The weld temperature difference between the TWT and the thermocouples are 125 and 70 °C for the shoulder thermocouple and the probe thermocouple respectively. A probable explanation for the lower values of the thermocouple on the shoulder may be that the thermocouple is not located close enough to the stir zone when compared to the thermocouple in the probe, which is located in the weld centre.

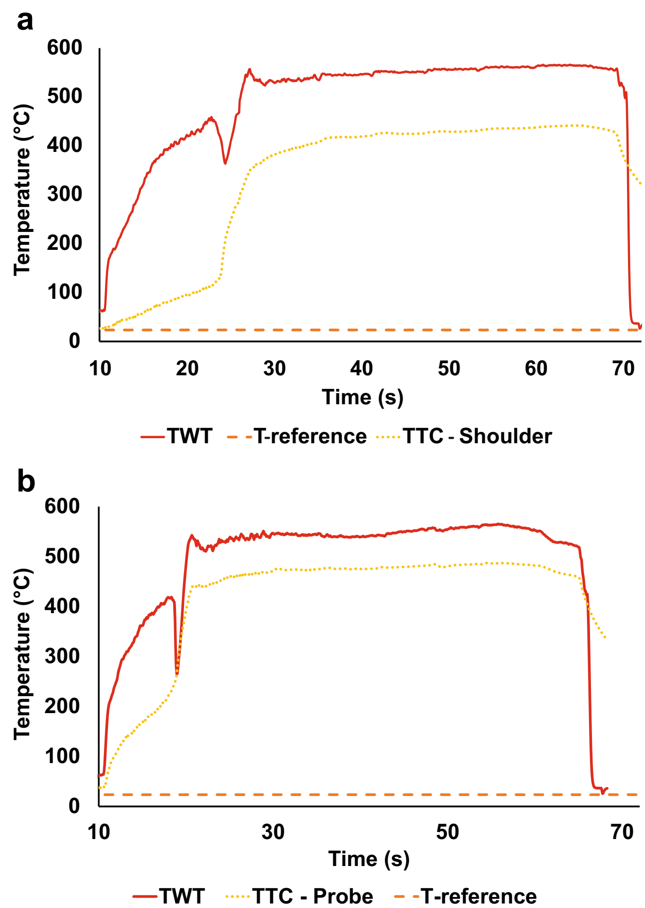

Fig. 5 Temperature data for two welds at 525 °C. **a** Tool with the thermocouple on the shoulder, TTC-Shoulder. **b** Tool with the thermocouple on the probe, TTC-Probe

Different behaviours were observed during the plunge stage. Both thermocouples present a slower time response when compared to the TWT method. However, an interesting characteristic is found during the plunge for TWT measurements. When the shoulder comes in contact with the workpiece material, a dip, followed by a quick increase in temperature, can be observed. This can be explained by the fact that the TWT temperature is initially only based on the probe-workpiece interface, until the relatively cold shoulder touches to the workpiece surface. This will cause a sudden drop in the average temperature, which quickly recovers as the friction between the shoulder and the workpiece starts contributing to the heat generation. In the case of the thermocouple data, this temperature drop could not be observed. However, it is still possible to identify a sudden increase in the heating rate as soon as the shoulder touches the surface.

The time response to variations in rotational speed and axial force are presented in Fig. 6 for both the TWT method and the thermocouple inside the probe. A sudden increase or decrease in rotation speed resulted in a quick response for both methods, where the TTC-Probe was approximately 5 % faster than TWT. However, for the axial force variations of 2000 N, the TWT was approximately 35 % faster than TTC-Probe. The probe thermocouple is located close to the weld centre which is to a larger extent influenced by rotational speed variations than the axial force. The TWT method, however, represents an average of the interface temperature, which will be strongly affected by temperature variations on the shoulder due to its large area. The increase of the force leads to higher pressure on the shoulder area increasing the heat generation by friction and plastic deformation.

4.2 Horizontally inserted thermocouples inside the workpiece

In order to verify the TWT method, different welds were performed with thermocouples embedded in the workpiece. In this section, temperature measurements from the horizontally inserted thermocouples inside the workpiece are shown and discussed (see Fig. 7).

In order to obtain precise data, X-ray images were taken and the thermocouple locations were measured. Displacement of the thermocouples close to the weld zone could be observed. This displacement was higher for the thermocouples placed on the retreating side. A possible explanation for this situation is the extreme plastic deformation associated with the FSW, causing the thermocouple to be pushed away from the original position. Therefore, only few temperature samples were acquired closed to the stir zone.

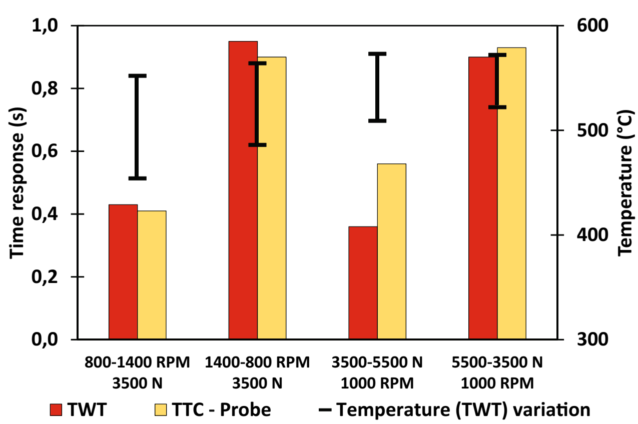

Fig. 6 Time response of TWT method and thermocouple on the probe (TTC-Probe) to fast increase and decrease of the rotation speed and the axial force. The temperature variation is presented. (Color figure online)

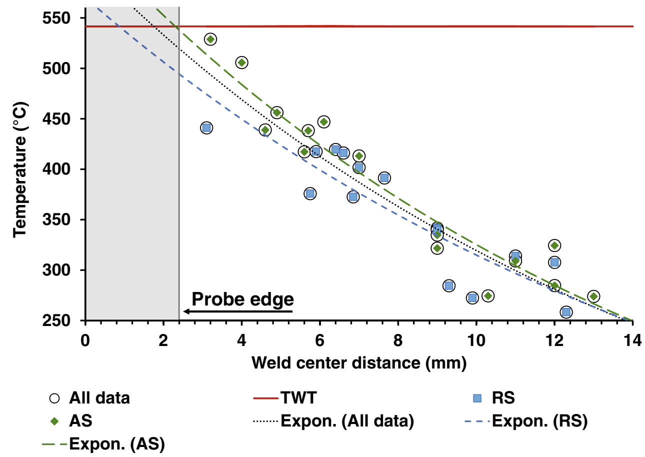

Fig. 7 Temperature data acquired by the thermocouples perpendicular to the joint line (lateral direction)

Also presented in Fig. 7 are the TWT values, corresponding to the average stir zone temperature, obtained on the same time than the WTC data. The TWT values are consistent at 540 °C, meaning that the temperature values acquired by the thermocouples embedded in the workpiece at different positions can be compared.

Regression analysis was performed for (a) the advancing side, (b) the retreating side and (c) all data. The retreating temperature curve has a similar shape as the advancing side curve, but is consistently at a lower temperature. The advancing curve and the retreating curve predict temperatures on the probe edge of 535 and 474 °C, respectively. The probe edge on the advancing side, usually considered the hotter point [6], differs only by 5 °C from the TWT measurements. This temperature difference may be caused by the positioning of the thermocouples, which is not just below the top surface, leading to slightly lower temperatures than the expected peak temperature.

4.3 Vertically inserted thermocouples inside the workpiece

In order to acquire higher temperature readings, thermocouples were inserted vertically through the plate thickness, aiming the thermocouple connection to be positioned at the tool-workpiece interface just below the tool shoulder. The temperature data was acquired by the TWT method, by the TTC in the probe and by the thermocouples embedded in the workpiece at different distances from the weld centre, on the advancing and retreating side of the weld. Figure 8 presents temperature data for a weld with thermocouples embedded at 2 and 3 mm from the weld centre.

The temperature measurements from the thermocouples inserted vertically inside the workpiece were consistently higher when compared to the previous setup. However, several thermocouples still measured lower reading than expected. This may be explained by the difficulty to accurately

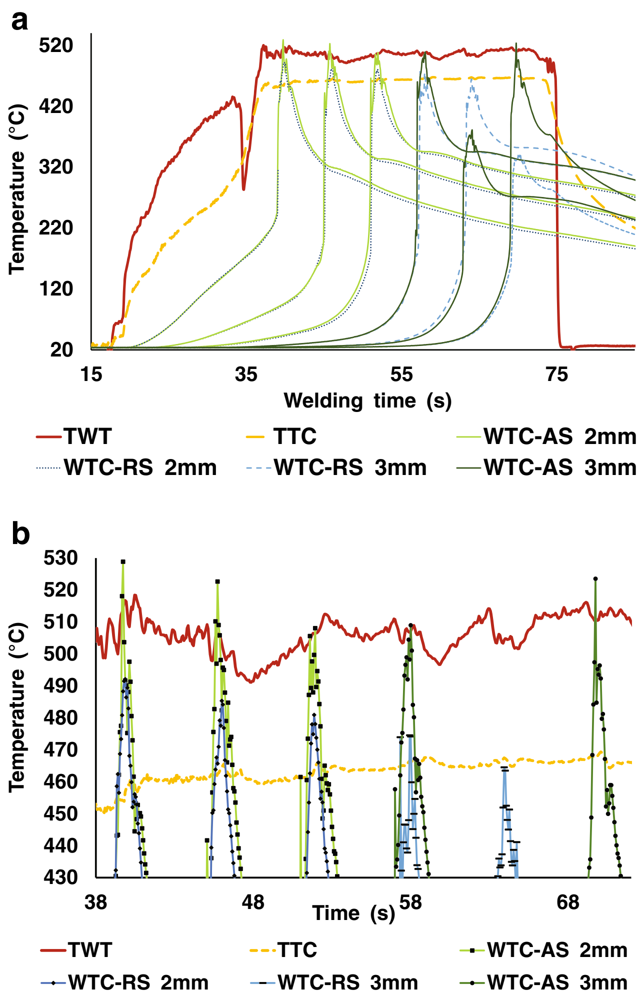

Fig. 8 Temperature data obtained by TWT method, thermocouple on the probe (TTC) and the thermocouples embedded on the workpiece on the vertical position (WTC) at 2 and 3 mm distances from the joint line. On **b** is presented the peak measurements of this data

position the thermocouple, as well as by the extreme plastic deformation, pushing the thermocouple out of position. It was also verified that thermocouples positioned on the advancing side at approximately 2–3 mm from the joint line showed higher readings than the TWT method, see Fig. 9. A possible explanation is that the TWT measurement is an average of the temperature on the contact area. This means that the TWT will depend on the temperature gradient across the whole contact area, so the temperature peak might be slightly higher than the TWT value measured. Another possible explanation is that the thermocouple is in direct contact with the shoulder and is also subjected to friction. Hence, the thermocouple material itself may increase the friction and increases also the temperature at the measurement point. A higher sampling frequency could also provide a better understanding of the moment when the tool contacts the thermocouple. This will be subject to future

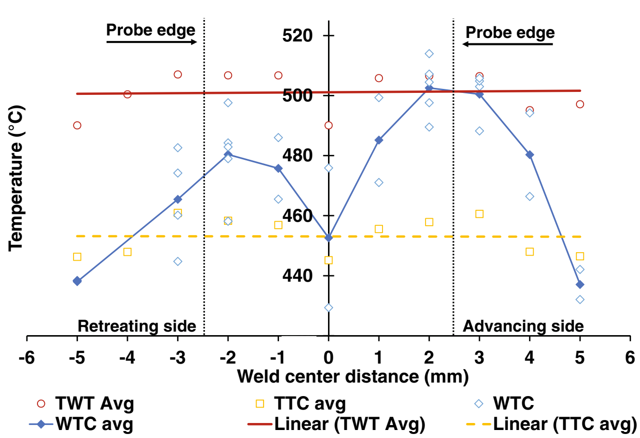

Fig. 9 Temperature data from different welds obtained by TWT method, thermocouple in the probe (TTC) and the thermocouples embedded in the workpiece (WTC) at different distances from the weld centre

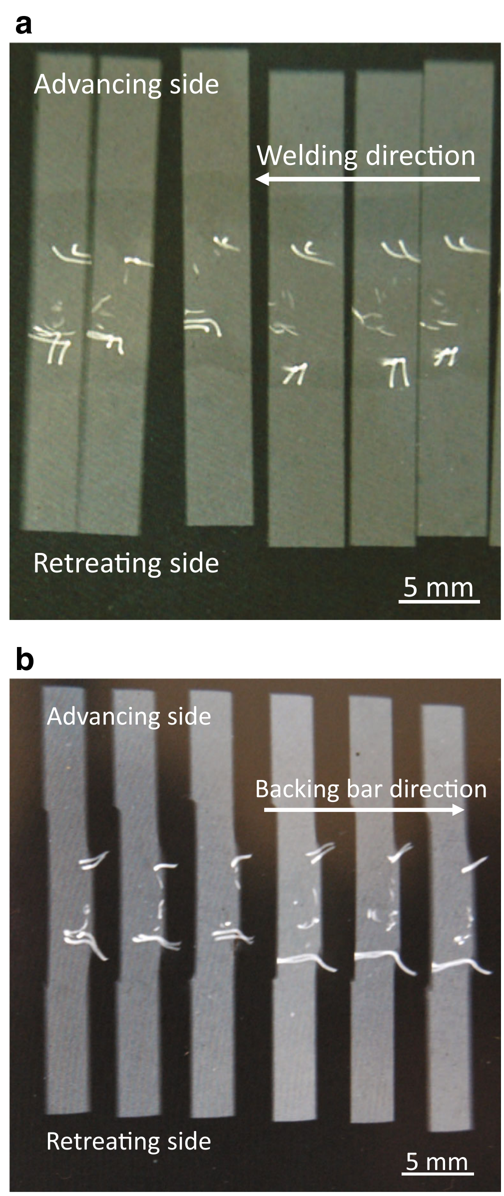

Fig. 10 X-ray from weld with thermocouple on the vertical position at 2 and 3 mm distances from the joint line. **a** Top view. **b** Side view

work and will enable higher accuracy of the methods demonstrated. The results show a low repeatability of the thermocouples embedded on the workpiece. This method is not applicable for production use due to its lower repeatability and demanding setup. However, when carefully prepared in a laboratory environment, it is a valuable method for verification of other methods such as TWT. Furthermore, the thermocouple remained in the workpiece after welding compromising its performance.

A difference temperature between the retreating and advancing side is confirmed in Fig. 9. The thermocouples placed on the advancing side present approximately 20–25 °C higher temperature readings than the ones on the retreating side. The temperature decreases with the increase of distance from the joint line, as expected, due to the heat dissipation away from the joint line.

The temperature data acquired from the TWT and the TTC show a slight temperature decrease around the thermocouples, due to the thermal variation caused by the predrilled holes. The TTC readings are in most cases lower than TWT and WTC values. Very similar readings are found at the stir zone by TWT and WTC. This proves that the TWT measures temperatures closer to the peak temperature, as measured by the TTC method.

Through X-ray analysis, it could be verified that the thermocouples on the advancing side had deformed with the material plasticization and were bent down in the weld direction, measuring the temperature of the material while it was still heating and plasticizing, i.e. at the leading edge of the tool. The thermocouples on the retreating side deformed and bent down to the opposite direction measuring the temperature of the material towards the trailing edge, see Fig. 10. This influenced the temperature measurements acquired by the thermocouples inside of the workpiece.

5 Conclusions

The presented work aimed to evaluate temperature measurements applied in FSW process. The further objective is the application of these methods for online control of the process. A literature review on suitable temperature measurement methods for FSW was presented. Three different temperature methods were selected and experimentally verified. The time response, accuracy and industrial practicality of three methods were evaluated:

- Thermocouples were embedded in the tool at two different locations. The thermocouple located inside the probe presented a faster response and higher temperature readings than the thermocouple on the shoulder. This method presented acceptable temperature readings and reaction to welding variations. However, it is strongly depending on the thermocouple location and both thermocouples presented low temperature readings and lower time response during plunge operation when compared to the TWT method.
- Thermocouples embedded in workpieces cannot be used for online control, but were valuable for verification of the temperature reading from TTC and TWT methods. The measurements from thermocouples inside the workpieces strongly depend on their location, which led to unrepeatable temperature readings.
- The TWT temperature presents accurate measurements and fast time response during the plunge operation and could quickly detect both force and rotation speed variations. Experiments demonstrated repeatable results.

The TWT method is a suitable method for temperature measurement during the friction stir welding process and capable to be used for process feedback control in an accurate and fast away.

Acknowledgments The authors acknowledge the support from Swedish Agency for Economic and Regional Growth through European Regional Development Fund under contract 20200328 and the County Council for West Sweden under contract RUN 612-0254-15.

References

1. Thomas W et al (1991) Patent - Friction stir butt welding, T.W. Institute, Editor
2. Mishra RS, Ma ZY (2005) Friction stir welding and processing. Mater Sci Eng R Rep 50(1–2):1–78
3. Threadgill PL et al (2009) Friction stir welding of aluminium alloys. Int Mater Rev 54:49–93
4. Qian J et al (2013) An analytical model to optimize rotation speed and travel speed of friction stir welding for defect-free joints. Scr Mater 68(3–4):175–178
5. Fehrenbacher A et al (2014) Effects of tool–workpiece interface temperature on weld quality and quality improvements through temperature control in friction stir welding. Int J Adv Manuf Technol 71(1–4):165–179
6. Khandkar MZH, Khan JA, Reynolds AP (2003) Prediction of temperature distribution and thermal history during friction stir welding: input torque based model. Sci Technol Weld Join 8(3):165–174
7. Fehrenbacher A et al (2014) Measurement of tool-workpiece interface temperature distribution in friction stir welding. J Manuf Sci Eng 136(2):021009
8. De Backer J, Bolmsjö G, Christiansson A-K (2014) Temperature control of robotic friction stir welding using the thermoelectric effect. Int J Adv Manuf Technol 70(1–4):375–383

9. Fehrenbacher A et al (2014) Combined temperature and force control for robotic friction stir welding. J Manuf Sci Eng 136(5–8): 021007
10. Hamilton C, Dymek S, Sommers A (2010) Characteristic temperature curves for aluminum alloys during friction stir welding. Weld J 89
11. Woo W et al (2007) In situ neutron diffraction measurements of temperature and stresses during friction stir welding of 6061-T6 aluminium alloy. Sci Technol Weld Join 12(4):298–303
12. Properties and selection: nonferrous alloys and special-purpose materials. Vol 2. ASM international 3470
13. Covington JL (2005) Experimental and numerical investigation of tool heating during friction stir welding. In: Department of Mechanical Engineering, Brigham Young University
14. Hwang Y-M et al (2008) Experimental study on temperature distributions within the workpiece during friction stir welding of aluminum alloys. Int J Mach Tools Manuf 48(7–8):778–787
15. Huang C, Kou S (2004) Liquation cracking in full-penetration Al-Mg-Si welds. Weld J 83(4)
16. Silva ACF et al (2014) Friction stir welded butt joints optimization. Mater Werkst 45(11):1010–1017
17. Silva ACF, De Backer J, Bolmsjö G (2015) TWT method for temperature measurement during FSW process. In: FSWP 2015 International Conference. Ordizia, Spain. p 95–98
18. Buffa G et al (2006) Solid state bonding in extrusion and FSW: process mechanics and analogies. J Mater Process Technol 177(1–3):344–347
19. Silva ACF, de Figueiredo MAV, Moreira PMGP (2013) Optimização Do Processo SFL Aplicando a Metodologia Taguchi—Efeitos dos Parametros na Temperatura. APAET Rev Associação Port Análise Exp Tensões 22:35–40
20. Rosales MJC, Alcântara NG, Dos Santos JF (2009) Influência do Material do Backing no Fluxo de Calor e na Formação de Zonas Deformadas pelo Processo FSW em Ligas de Alumínio. Tecnol Metal Mater 5(3):167–172
21. Upadhyay P, Reynolds AP (2010) Effects of thermal boundary conditions in friction stir welded AA7050-T7 sheets. Mater Sci Eng A 527(6):1537–1543
22. Ghetiya ND, Patel KM, Patel A (2015) Prediction of temperature at weldline in air and immersed friction stir welding and its experimental validation. Int J Adv Manuf Technol 79(5–8):1239–1246
23. Cederqvist L (2011) Friction stir welding of copper canisters using power and temperature control. In: Department of Design Sciences, Lund University
24. Cederqvist L et al (2012) Cascade control of the friction stir welding process to seal canisters for spent nuclear fuel. Control Eng Pract 20(1):35–48
25. Heidarzadeh A et al (2014) 3 - Microstructural evolution. In: Advances in friction-stir welding and processing. Woodhead Publishing. p 65–140
26. Su JQ et al (2003) Microstructural investigation of friction stir welded 7050-T651 aluminium. Acta Mater 51(3):713–729
27. Sato YS, Urata M, Kokawa H (2002) Parameters controlling microstructure and hardness during friction-stir welding of precipitation-hardenable aluminum alloy 6063. Metall Mater Trans A 33(3):625–635
28. De Backer J, Bolmsjo G (2013) Thermoelectric method for temperature measurement in friction stir welding. Sci Technol Weld Join 18(7)
29. Shahdan M Temperature measurement method of friction stir welding using ultrasonic time of flight. In: Mechanical Engineering. Vanderbilt University p 40
30. Shahdan MAM (2012) Temperature measurements of weld during friction stir welding using ultrasonic time of flight. In 9th international conference on trends in welding research. ASM International.
31. Ghodam SD (2014) Temperature measurement of a cutting tool in turning process by using tool work thermocouple. Int J Res Eng Technol 03(04)
32. De Backer J, Bolmsjö G (2014) Self-tuning algorithm for friction stir welding using temperature feedback. In: 10th International Friction Stir Welding Symposium
33. De Backer J (2014) Feedback control of robotic friction stir welding. In: Production Technology. University West p 134