Designs of Temperature Measuring Device for a Re-Configured Milling Machine

Esther T. Akinlabi, Stephen A. Akinlabi

Abstract**—**The design of temperature measuring approach for a re-configured milling machine to produce friction stir welds is reported in this paper. The product design specifications for the redesigning of a milling machine were first outlined and the ranking criteria were determined. Three different concepts were generated for the temperature measurement on the reconfigured system and the preferred or the best concept was selected based on the set design ranking criteria. Further simulation and performance analysis was then conducted on the concept. The Infrared Thermography (IRT) concept was selected for the temperature measurement among other concepts generated because it is an ideal and most effective system of measurement in this regard.

Keywords**—**Clamping system, Friction Stir Welding, Reconfiguration, Support systems.

I. Introduction

A fairly modern technique of welding materials together has established itself as an increasingly popular procedure in the manufacturing industry. This method of welding is formally known as Friction Stir Welding (FSW). FSW has shown great results for joining metals without significantly altering the original properties of the parent metals. FSW is a solid-state joining process which is applicable to all metals and plastics. It is a variant of friction welding that produces a weld between two or more workpieces by the heating and plastic material displacement caused by a rapidly rotating tool that traverses the weld joint [1]. Due to its many advantages over the conventional welding methods, friction stir welding has gathered widespread of interest in numerous applications in the automotive, aerospace, construction and the electrical industries. The process was invented at The Welding Institute (TWI) in the United Kingdom and it was initially applied to aluminum alloys [1]. The tool serves three primary functions, namely; the heating of the workpiece, the movement of material to produce the joint and the containment of the hot metal beneath the tool shoulder. Furthermore, heating is created within the workpiece by both friction between the rotating tool pin and shoulder and severe plastic deformation of the workpiece. The localized heating softens the material around the pin and combined with the tool rotation and translation, leads to movement of material from the front to the back of the pin, thus filling the hole in the tool wake as the tool moves forward. The tool shoulder restricts metal flow to a level equivalent to the shoulder position [2]. As a result of the tool action and influence on the workpiece, when performed properly, a solid-state joint is produced. Because of the various geometrical features on the tool, material movement around the pin can be complex, with gradients in strain, temperature, and strain rate [3].

In order to achieve a weld with sound joint integrity, a good understanding of the factors influencing the success of producing friction stir welds is required. The frictional heat generated during the process together with the rotating and traversing of the welding tool softens the material and produces plastic flow that effectively stirs the material from the sections of both parent materials and fuses them together to create a weld. It is thus essential that the temperature during the process is monitored. It is known that temperature versus the weld integrity is somewhat a parabolic function [4] – too little or too much heat generation will result in weak welds. Hence, it is very important to have an insight into the welding temperature. The temperature generation can be calculated during a FSW procedure and is mainly a function of the rotational speed and the interfacial pressure. The heat flow through the material is also dependent on the friction coefficient of the welding material and geometrical aspects of the rotating FSW tool.

The heat input to the weld in FSW process is an important quantity, due to its influence on the resulting properties of the weld. Heat generation during FSW arises from two sources: friction at the surface of the tool and the deformation of the material around the tool. The heat generation is often assumed to occur predominantly under the shoulder, due to its greater surface, and to be equal to the power required to overcome the contact forces between the tool and the workpiece [5]. Average heat input in FSW has been proposed by many authors in the context of simple energy models [6-7]. Although, this is only an estimate of the heat input since there may be loses that depend on the input parameters; for example, the rate of heat loss through radiation or by conduction of the anvil and the tool, may change based on the weld parameters. Hence, the heat input (j/mm) from the shoulder of the tool in FSW determined through the spindle torque measurements is constant once the thermal equilibrium is reached and is given by [6]:

$$Q = \eta \frac{2\pi\omega T}{f} \tag{1}$$

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where Q= heat input (J/mm), η= efficiency factor, ω= rotational speed (rev/min), T= torque (Nm) and f= feed rate (mm/min).

Specialized FSW machines are capable of monitoring the underlying factors during the welding process. This then allows for the formation of welds with optimum integrity but due to the high cost and demand for friction stir welding machines, there has been a move towards adapting milling machines to produce friction stir welds [8], [9] but these reconfigured milling machines have limitations. It is therefore essential that measurement features such as temperature measuring devices are incorporated into the specialized reconfigured machines to allow for the production of friction stir welds with good joint integrity thus expanding the capability of the equipment. This paper therefore reports on the detailed design of temperature measuring device to be incorporated into a milling machine to produce friction stir welds.

II. Design Criteria

A Product Design Considerations

The Product Design Considerations (PDC) for the redesigned milling machine that will effectively produce friction stir welds of high quality integrity with a temperature monitoring device include the following but not limited to it: can be adapted to fit on most milling machines and have a tool temperature / weld monitoring and control system, provide accurate readings and easy to use.

B. Ranking of the Criteria

The main criteria were selected according to the PDC and these were compared against each other in order to identify the weighting of each of the criteria. This was also used to establish how each of the alternatives performs in different criteria. The different criteria are denoted by C_1, C_2, C_3, C_4 and C_5 respectively and presented below:

C_1 = Safety, C_2 = Cost Effectiveness, C_3 = Energy Efficiency, C_4 = Flexibility and C_5 = Simplicity.

All these criteria were compared against each other to identify the importance of each as shown below in Table I. The weighting is calculated by dividing each of the respective criteria total by the sum of the criteria total. This was effectively done by obtaining the fraction of each criterion with respect to the overall total criteria. As presented in Table I the total of the weighting is equal to 1. Therefore, the weighting of each criterion are as follow:

TABLE I
Design Criteria

Criteria	C_1	C_2	C_3	C_4	C_5	Total	Weighting
C_1	x	1	1	1	1	4	0.4
C_2	0	x	1	0	0	1	0.1
C_3	0	0	x	0	1	1	0.1
C_4	0	1	1	x	1	3	0.3
C_5	0	0	0	1	x	1	0.1
Total						10	1

From Table I, we obtain: C_1 = 0.4, C_2 = 0.3, C_3 = 0.1, C_4 = 0.2 and C_5 = 0.0

As shown, the most important criterion is safety. This should generally be the criterion with the highest weighting. It is expected that the temperature monitoring device must be safe to use. Followed by safety in descending order are; flexibility, energy efficiency, cost effectiveness, and simplicity are ranked equal in this regard. This is reasonable as the temperature monitoring system could be expensive. The major objective in this design is to allow for a reconfigured milling machine that can be used to produce friction stir welds. The weighting of these criteria should result in increased studies being conducted on FSW which may allow the industry to gain further insight into the capabilities and mechanisms of FSW. Together with these criteria weighting, a similar method is used to conduct a simple analysis on selecting the most appropriate concept for the design.

III. Concept Generation and Selection

From the Product Design Considerations (PDC), several ideas were brainstormed and noted for consideration. Consideration was then given to the most viable concepts and then a final concept was selected based on the ranking criteria. Temperature monitoring and control is essential during the friction stir welding process as such, incorporating a temperature measuring system into the re-configured FSW milling machine is key and very important in this regard. Various concepts were generated to design such a system which can actively measure and record the temperature distribution and heat flow patterns in the apparatus in order to optimize the FSW process and the success of defect free welds. Finally, the most viable concept was selected and the performance analysis and simulation was conducted. Temperature being a vital factor to control during the welding process, successfully plasticizing and stirring of the materials will only be achieved at a certain percentage of the materials melting point.

It is important to note that the rising of temperature within a material causes the material to expand. It was considered to use a strain gauge. A strain gauge bonded to the expanding material will also expand and a strain measurement can be obtained (via a change in the resistance of the gauge). This strain measurement can be used to calculate the temperature change, (ΔT) assuming the thermal coefficient of expansion of the relevant material is known. However, due to the nature of this design, the method of strain gauging may not give a perfect and the desired result. This is because many other strain effects are developed during the process of friction stir welding. This implies that all location marked out for temperature measurement would also be under the effect of either torsional or shear stress, bending moments, axial compressive stress or combination of these. All of these in effect will influence the strain gauge result; although these effects can be separated and filtered but a more practical approach could be to employ the use of thermocouples which are only sensitive to temperature. If these can be installed near temperature critical locations, then an adaptive design can be made to successfully monitor the temperature during the FSW process.

A general trend of temperature distribution through the FSW rotating tool during welding process is shown in Fig. 1, illustrating the animated Computational Fluid Dynamics (CFD) model of the hypothesized heat distribution through the workpieces and FSW tool during an intermediate moment in time while FSW is being conducted. This also serves as insight as to where the ideal locations for continuous temperature monitoring would be. Some of the concepts considered are hereby presented.

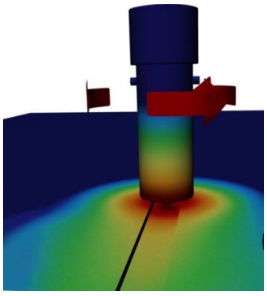

Fig. 1 Schematic of temperature distribution during FSW

A. Concept One

The concept presented in Fig. 2 makes use of a thermocouple imbedded into the friction stir welding tool. This enables the user to determine the average and maximum temperatures in the tool.

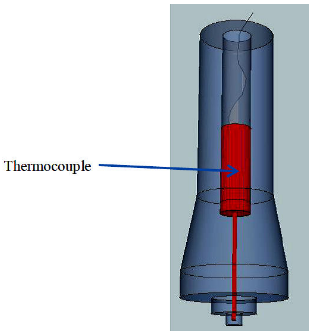

Fig. 2 Temperature measurement design for concept one

The measurement and monitoring of the tool temperature will determine the success of welding high strength alloys without causing damage to the tool due to the excessively high temperatures. The thermocouple is electrically excited and becomes sensitive to temperature changes. The measurements are then sent to a data acquisition system and then converted by the software to a readable data required by the user. This concept is ideal for tool temperature measurement however it is not conveniently suited for workpiece temperature measurement. Heat analysis is consequently conducted from the obtained data readings to determine the heat input into the actual welding process.

B. Concept Two

This design involves temperature measurement by capturing the temperature profile across the workpiece. Concept two is presented in Fig. 3, showing the thermocouples imbedded into the backing plate. This enables the user to determine the temperature distribution along the lengths of the workpieces.

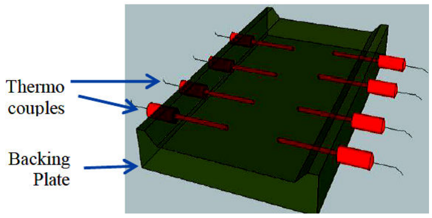

Fig. 3 Temperature measurement design for concept two

The thermocouples are electrically excited and become sensitive to temperature changes. The measurements are then sent to a data acquisition system similar to concept one. This design allows close monitoring of the workpiece temperature. Using a feedback control system, the rotational speed of the tool can be adjusted so that the optimum temperature for the specific welding material to be achieved. This concept is not ideal for tool temperature monitoring as the mechanism of heat transfer between the tool and the workpieces may be complex. However, highly relevant data can be obtained from the heat increase within the workpieces.

C. Concept Three

Concept three uses a more manual method of capturing and interpreting the temperature measurement data. A modern technique known as Infrared Thermography (IRT) has been suggested in the design. Infrared thermography, thermal imaging, and thermal video are examples of infrared imaging science. Thermal imaging cameras detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation, called thermograms. An infrared thermometer measures temperature by detecting the infrared energy emitted by all materials which are at temperatures above absolute zero. The amount of radiation emitted by an object increases with temperature; therefore, thermography allows one to see variations in the temperature. Infrared thermometers for non-contact temperature measurement are highly developed sensors which have wide-spread application in industrial processing and research. A typical example is illustrated in Fig. 4 showing the IRT being used to monitor the bearing temperature of an electric motor.

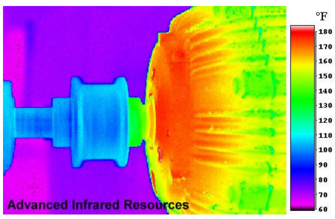

Fig. 4 Thermograph of an electric motor [10]

The most basic design consists of a lens to focus the Infrared (IR) energy on the detector, which converts the energy to an electrical signal that can be displayed in units of temperature after being compensated for ambient temperature variation. This configuration facilitates temperature measurement from a distance without contact with the object to be measured. As such, the infrared thermometer is useful for measuring temperature under circumstances where thermocouples or other probe type sensors cannot be used or do not produce accurate data for a variety of reasons. In this concept, an IRT camera is attached to the milling machine to monitor the critical welding location while the XY table is traversed. Fig. 5 illustrates this concept applied to the reconfigured milling machine.

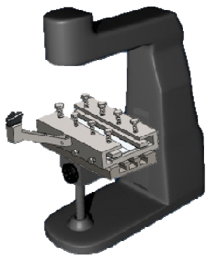

Fig. 5 Temperature measurement design for concept three

In order to successfully select the most viable concept a comparison between the advantages and disadvantages of each concept were evaluated with respect to the design criteria and concept three was considered as the best concept compared to the other concepts generated. The concept three allows for instant temperature measurement across the entire spectrum of the relevant FSW apparatus at every point in time. It is simple and user friendly; monitors the welding procedure at every point in time and can monitor temperature in all the FSW apparatus. The effort of designing a support system for the IRT camera being a delimitation is insignificant when compared to the laborious exercise of heat transfer analysis that may be required for the first two concepts. The technology of thermography is ideal in this design and hence seems to be the most viable concept.

IV. Performance Simulation and Analysis

The Infrared Thermography (IRT) concept was selected; hence the performance analysis was conducted. The major effort regarding this system lies with the selection, purchase, installation and set-up of the required components. Testo specializes in the manufacturing and development of thermographic cameras and imagers [11]. For this design, the use of the Testo 890 Thermal Imager was recommended and simulated. A 3D model of the device is shown in Fig. 6.

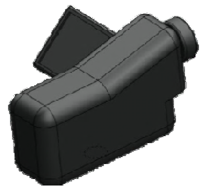

Fig. 6 3D model of Testo 890 thermal imager

"The heart of a thermal imager is the detector". With the Testo 890, the highest level of image quality can be achieved due to the 640 x 480 pixel detector in combination with high-quality Germanium optics [11]. Because the more measurement points there are in the thermal image, the more details can be recognized and analyzed. "With the Testo 890, thermal processes can be recorded in real time. Via the USB 2.0 interface, all data from the thermographic recording are directly transferred to the PC, and can be stopped and analyzed at any point. The settings for the video are carried out using the IRSoft from a PC. This makes the Testo 890 optimum for the examination of heat development in development processes [11]." A mechanical support system is required to support this camera in such a manner that it views the necessary apparatus during the FSW process. The camera is to record digital thermographic images of the tool and workpieces throughout the FSW operation.

The camera support system is designed such that it does not hinder the operation of the re-configured milling machine. The length of the camera support needs to be determined based on the Field of View (FoV) of the camera. The FoV is described as the area visible by the thermographic camera. It is not possible to obtain actual experimental data and Thermographic images without conducting an actual FSW procedure with the thermographic monitoring. A simulation of the expected result is depicted in Fig. 7.

Note that the color scale shown on Fig. 7 does not depict actual temperature variations during a FSW process. These values are assumed and only serve to present an example of the expected visual results of the temperature monitoring system.

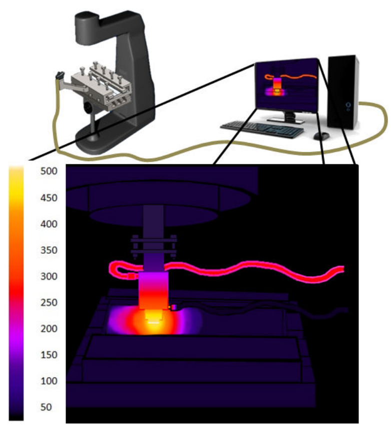

Fig. 7 Simulated thermographic image during FSW

V. CONCLUSION

The selected design concept for the temperature measurement on a reconfigured milling machine was suggested for design considerations. The detailed performance analysis and simulation showed that the concept of employing an Infrared Thermography will be suitable for the temperature monitoring system of Friction Stir Welding using a typical reconfigured milling machine. The Infrared Thermography (IRT) concept was selected for the temperature measurement among other concepts because it is an ideal and very effective system. Although, may be expensive but promises accurate results and user friendly. The relatively inexpensive milling machine adaptations will make the reconfiguration of milling machines to produce friction stir welds ideal for research purposes and applications. Furthermore, the redesign of a milling machine to produce friction stir welds with temperature monitoring system will enhance the capability of such machines.

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