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Review on the Thermal Characterizations of Rotary Friction Welding

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ABSTRACT:

Rotary friction welding is a solid-state technique for combining two materials together by using the heat energy generated by the friction at the interface region between them with help of an external axial force. The main goals of this work-study were, to look to the researches works that studied RFW, to understand their thermal models of the RFW process, see mathematical, simulation models and the assumptions taken into account, and compare with the experimental results of their works if exist. The results we obtained from previous researches were as follows: The rise in the temperature of materials during the welding process leads to a change in their properties, so the heat generated during the process is not constant. The heat generated is divided into two parts, heat generated by rotating and sliding friction, and heat generated during plastic deformation. With the temperature rising, the yield stress reduces until it became less than flow stress, and then the plastic deformation starts. The heat transfer throw the solid work pieces is analyzed by Fourier heat conduction law. Compared the simulation results with the experimental results of the researches we can say that, the welding process can be represented numerically through software programs.

Keywords:

Rotary friction welding; Finite element analysis; Temperature distributions; Heat generation.

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1. INTRODUCTION

Rotary friction welding (RFW) is a solid-state method that joins materials without melting them. It's one of the most effective processes for combining identical and dissimilar materials with extremely high joint strength, sometimes exceeding the base material's strength [1]. RFW is a pressure variation method in which the welded connection is established by joint plastic deformation of the components to be welded without melting the metal, due to the friction that generates heat. Friction welding is a thermo-mechanical process that refines the grain structure of the weld zone. Friction welding has a minimal heat requirement, is simple to use, and saves material. RFW is used to join various shapes such as rods to rods, rods to plates, and so on. [2].

The friction of the surfaces generates heat in the RFW process, which plasticizes the material at the interface region. The compression force causes the plasticized material to move from the interface, expelling the oxide surface coatings and other impurities, as well as surface interlocking connecting mechanisms, and encouraging metallurgical. The work components lose length in the direction of the compression force as a result of this plastic deformation process, which forms a collar. This shortening is known as axial shortening, and after it has reached the appropriate length, the friction movement is stopped, and a forging force is retained, or increased, for a period of time to assist consolidate the weld. [3][4].

In RFW, one part of the work piece is held fixed while the other rotates at the required high speed to give energy to the weld interface. There are two mechanisms for RFW: continuous drive friction welding (CDFW) and inertia friction welding (IFW). The spinning portion is driven by a spindle motor at a consistent speed during the welding process in CDFW while in IFW, the rotating part is connected to the flywheel, which is disconnected from the thrust motor after the required rotational speed is obtained, then the work piece is engaged, and the flywheel delivers power to the interface; the rotational speed steadily drops till stopping throughout this method. Both mechanisms of RFW are shown in Fig. 1[5].

The main goals of this work-study were, to look to the researches works that studied RFW, to understand their thermal model of the RFW process, see mathematical, simulation models and the assumptions taken into account, and compare with the experimental results of their works if exist.

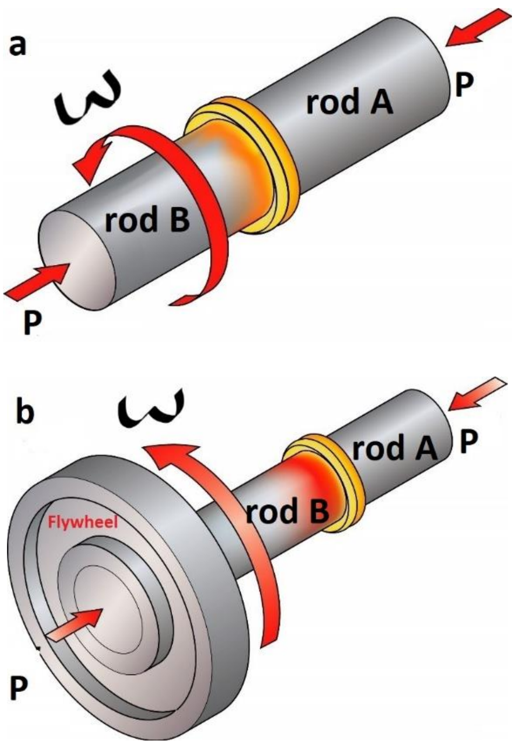

Figure 1: (a) Continuous drive friction welding and (b) inertia friction welding. [5]

2. RFW STAGES:

RFW is divided into three stages. Two relatively moving components come into contact with each other in the first stage (known as the heating stage), and axial pressure is applied. Frictional heat generation raises the temperature of the interface's surface, resulting in a reduction in the material's flow stress. The material cannot survive the imposed pressure in the second stage, and the plastic flows outward, forming flashes and carrying oxides and impurities. This stage is known as the burn-off stage, and flashes will form. Finally, in the third stage (also known as the forging stage), the welding process is completed by stopping relative movement and applying a higher compressive axial pressure to help consolidate the weld. [6].These stages are shown in Fig. 2.

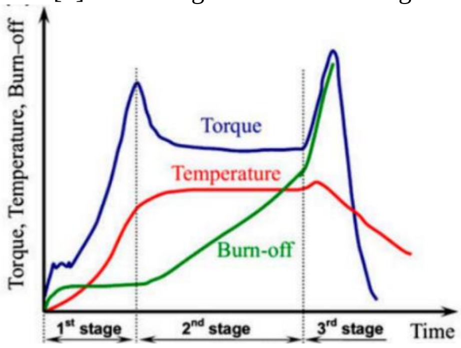

Figure 2: Stages of RFW process. [6]

3. PERVIOUS RESEARCHES

Several researchers have looked at the RFW process for various reasons and in various methods. The major objectives of this research are to comprehend the thermal model of the RFW process, to examine mathematical, simulation models, and assumptions that have been taken into account, and to compare the experimental findings of their works, if any exist.

3.1 Researches, that assumed that the properties of the material are constant

In this sub, the researchers assumed that the mechanical properties like (young modulus, yield stress, etc.) and thermal properties like (thermal expansion, thermal conductivity, etc.) of the materials are constant and do not vary with temperature.

Raviteja and Reddy [7] used ANSYS program (thermal analysis-static structural analysis) to perform numerical welding of rotary friction welding for UNS C23000 brass/AISI 1021 joint. The rod had a diameter of (25.4 mm) and a length of (100 mm). They used Taguchi technology to optimize process parameters. Their results show that if the operating conditions are: (friction pressure (60 MPa), friction time (4 sec), speed (1500 rpm), and forging pressure (62.5 MPa)), the welding efficiency is good.

Kumar and Reddy [8] used ANSYS program (thermal analysis-static structural analysis) to perform numerical welding of rotary friction welding for 2024Al alloy/AISI 1021 steel joint. The rod had a diameter of (25.4 mm) and a length of (100 mm). They used Taguchi technology to optimize process parameters. Their research shows that if the operating conditions are (the friction pressure (35 MPa), the friction time (3 sec), the speed (1500 rpm), and the forging pressure (37.5 MPa)), the welding efficiency is good.

The research studies [7] and [8] contain a number of flaws, including the fact that they did not address the assumptions or physical laws that control the welding process, and they totally relied on the software.

Hynes et.al. [9] They investigated through experiments and numerical simulations, the temperature influence in the friction welding process of low carbon steel/ aluminum joints. They took temperature readings with a non-contact infrared thermometer and plotted a time-temperature curve. The cylindrical work piece was modeled with a diameter of (12 mm) and a length of (45 mm). The range of process parameters were: friction pressure (2-4 bar), friction time (2-6 sec), forging time (3-10 sec), forging pressure (2-6 bar) and speed (800-1600 rpm). The maximum error between the experimental and numerical welding temperature at the interface region at (4 bar) and (1600 rpm) reaches to (15.7%).

Thien et.al. [10] They use ANSYS software to simulate the unsteady heat transfer and the welding process. The power consumed against the frictional force was converted to thermal energy at the interface in their research, AISI 1020/AISI 304 joint were studied. The rode was (20 mm) radius and (150 mm) length, the selected welding temperature was (1150 °C), and they found that the simulation temperature result at the welding interface was (1169 °C). This temperature value is sufficient to heat the workpiece to a plastic state, dissimilar materials diffuse each other under pressure, and the weld is formed well. AISI 1020 longitudinal heat affected zone (HAZ) was wider than AISI 304 (HAZ). They found that by increasing the heat they could reduce the friction time. This means that the speed or the friction or both must be increased to reduce the friction time.

Dawood et.al. [11] Were studied the thermal effect in the friction welding process of AA1050 Aluminum alloy/AISI 304 austenitic steel joint and AISI 304 austenitic Steel/AISI 304 austenitic steel joint through experiments and numerical simulations. A two dimensional model was generated on COMSOL Multiphysics and the thermal and structural modules were used to plot the temperature curve. The cylindrical work pieces for similar and dissimilar joint was (14.8 mm) in diameter and (100 mm) in length. The parameters for dissimilar joint was: friction pressure (2.1 MPa), friction time (60 sec), forging pressure (1.4 MPa), forging time (60 sec) and rotational speed (3200 rpm). Their results show that, the peak temperature for the simulation was (332.9 °C) and for the experimental were (261.1 °C) both was at (57.7 sec). The parameters for similar joint was: friction pressure (131 MPa), friction time (3 sec), forging pressure (100 MPa) forging time (1 sec) and rotational speed (1410 rpm). Their results show that, the peak temperature for the simulation were (1002 °C) at (2.8 sec), and for the experimental were (931 °C) at (2.9 sec).

Yohanes et.al. [12] Were investigate the friction welding of similar low carbon steel joint by three dimentional model using SOLIDWORKS and ANSYS softwars. The 3D model of mild steel bar had a diameter of (8 mm) and a length of (90 mm). The heat flux and temperature were derived from the thermal analysis process parameters. They assumed that, all of that kinetic energy was converted to thermal energy, and that was used to generate heat for the welding process. There were three different friction times and three different speeds for friction welding (2000, 2500, and 3000 rpm) (150, 200 and 250 sec). They take the melting temperature of low carbon steel as (1350°C). Their study found that as the shaft rotates faster, the temperature rises, the heat flux rises, and the length reduces. The influence of friction time, on the other hand, reveals that the lower the friction time, the lower the temperature created, the lower the heat flow generated, and the smaller the loss in length value.

3.2 Researches that have taken into account that the properties of materials are variable

In the following research work they taken into account that the properties of the selected materials vary with raising temperature. Heat generation in RFW consisted of two parts: heat generation at the interface due to the friction at the interface region and heat generation during plastic deformation, which occurs when the welding temperature is raised above the equivalent flow stress, causing the yield stress to be lower than the equivalent flow stress, causing internal heat generation.

Maalekian et.al. [13] They investigated how much heat was generated during the orbital friction welding of a rectangular bar steel/steel connection. A three-dimensional finite element (FE) analysis based on the reverse heat conduction method and constant-coefficient friction method was made with a cross-sectional dimension of (88 × 20 mm). They compared the calculated temperature curve with experimental results. The temperature change process during friction welding was measured by several connected thermocouples (2.5, 5.0, and 7.5 mm) away from the friction surface. Their results show that the reverse heat conduction method can accurately predict the heat generation rate, while the constant friction coefficient method leads to the most accurate temperature profile. Due to the short friction heating cycle and uniform interface heating rate, they found that the heat generation due to plastic deformation is very small compared with the heat generation due to friction and it can be ignored.

Seli et.al. [14] In their research work, the mechanical properties of a low carbon steel/aluminum joint were assessed in order to understand their thermal implications, and an explicit one-dimensional finite difference approach was utilized to estimate the low carbon steel/aluminum joint's heating and cooling temperature distribution.The rod has a diameter of (10 mm) and a length of (50 mm). The friction welding parameters were: rotational speed (900 rpm), friction pressure (15 MPa), friction time (3.15 sec), upsetting time (0.86 sec), and upsetting pressure (25 MPa). Their found that the welding material has a lower hardness than its parent material, and the weld joint has a lower tensile strength than the base material.

Xiong et.al. [15] They used analytical models to study (CDFW) of similar aluminum/ aluminum joint tubes. The outer and inner tube diameter were (20 and 16 mm) respectively and the length were (60 mm). The range of process parameters were friction pressure (29.2-40.7 MPa), friction time (3-6 sec), forging time (1-4 sec), and rotational speed were (800-1800 rpm). The analytical model was rigorously analyzed by comparing the analytical solutions of plastic zone thickness, welding power, and average temperature with the corresponding aluminum tube CDFW experimental data. The model's versatility was also tested by comparing the CDFW's steady-state forecast with the measured average temperature of 10 alloys' plastic flow. The comparison's consistency demonstrates that the analytical model can accurately and thoroughly capture the thermodynamic behavior of steady-state CDFW.

Asif et.al. [16] In their research work, a three-dimensional nonlinear finite element model was developed to describe RFW of UNS S31803 steel/ UNS S31803 steel joint. In their investigation a rod of (16 mm) in diameter and (100 mm) length was chosen. The range of process parameters were: friction pressure (30-50 MPa), friction time (3-5 sec), forging time (2-4 sec), forging pressure (60-80 MPa) and the rotational speed was constant at (1500 rpm). The software tool ANSYS was used to predict the thermal history and the axial shortening curve. The numerical model was verified by the experimental results. Their temperature distribution, peak temperature and axial shortening simulation results are basically consistent with actual experimental results, and infrared thermometers are used for temperature measurement. They found that the temperature raised the most during the friction heating stage. The peak temperature range was (840-920 °C), which is far below the melting point of the material (1390 °C). The axial shortening that happened in the forging stage was larger compared with the axial shortening that happened in the heating stage.

Li et.al. [17] They proposed an analytical heat generation model of rotary friction welding for similar mild steel joint tube based on the slide friction method. The rotational speed was (1900 rpm), the frictional pressure was (30 MPa), the forging pressure was (40 MPa), the outer and inner tube radius were (10.75) and (7.75) mm, respectively, and the tube length was (22 mm) the highest temperature of the friction interface confirms the model's accuracy. They discovered that the region between (0 sec) to (0.5 sec), have the highest temperature distribution error between measurement and calculation and it was (6%).

Łukaszewicz [18] He had proposed a mathematical model to study the temperature field caused by RFW for AISI 1040 steel/ AISI 1040 steel joint. He looked at how the two heat generating mechanisms (friction and plastic deformation of the contact surface) affected the sample's temperature field. He assumed that the friction coefficient, yield limit, and thermal properties of the specimen's material are all temperature dependent. The finite element approach was used to provide the numerical solution to this problem using (COMSOL software). Two samples of AISI 1040 steel were subjected to numerical analysis. The radius of the rode were (6 mm) and the length were (30 mm). The process parameters were friction pressure (75 MPa), friction time (7.45 sec), forging time (4 sec), forging pressure (80 MPa) and rotational speed were (146.6 rad/s). His findings reveal that, when compared to plastic deformation heating, friction heat has a greater impact on the maximum temperature of the interface region.

3.3 Researches with the practical side only

Misirli et.al. [19] They investigated the temperature distributions at the interface region for AISI 304 steel/aluminum joints by anchoring four thermocouples with varying distances from the center point. The rod were (10 mm) in diameter and (50 mm) in length. The welding Parameters were: rotational speed (1410 rpm), friction time (4 sec), friction pressure (30 MPa), upset time (12 sec) and upset pressure (60 MPa). Their results shows that during heating stage the temperatures decrease when you move away from the center point and the maximum value during this period was (500 °C) at time (4 sec) in center point.

Alves et.al. [20] Their research focusesd on using multi thermocouples to conduct an experimental thermal investigation of an (AA6351 T6 aluminum/AISI 304L stainless steel) joint during RFW. The rod were (14.8 mm) in diameter and (100 mm) in length. The welding Parameters were rotational speed (3200 rpm), friction time (5 sec), friction pressure (300 MPa), upset time (2 sec) and upset pressure (1200 MPa). The system of thermocouples were in both radial and axial direction. Their results show that, the largest temperature rise occurs in the first three seconds of the process. The temperature was maximum at the center of interface and decrease by moving away from interface in both radial and axial direction.

4. DISCUSSIONS

We observed that the heat generated during the welding process can be divided into two parts: heat generated at the interface region due to rotating and sliding friction, and heat generated due to plastic deformation, based on previous study. Due to the low value of plastic heat generation compares with friction heat generation and the difficult of calculation, many researchers were neglected it. The Fourier heat conduction law was used to examine heat transport through solid work components. The material's thermal and mechanical properties change as the temperature changes during the welding process. The Mathematical model were imprecise in some researches but were good in researches works done by: Asif [16], Maalekian [13], Li [17] and Seli [14]. The analytical programs used by previous researchers give good results for temperature distribution during the welding process, in many of this researches, , but they do not give results for the plastic deformation and axial shortening that occurs during the process, except research work that done by Asif [16] who give good deformation results.

5. CONCLUSION

From previous researches, the most prominent results obtained were as follows:

1. In general, with increasing of welding parameters (axial pressures, rotational speed and welding time…etc.), the welding temperature at the interface region and the axial shortening of the workpiece will increases.
2. By increasing the frictional pressure or the rotational speed we can reduce the frictional time.
3. The heat generated during the welding process can be divided into two parts: heat generated by plastic deformation and heat generated at the interface region duo to rotating and sliding friction.
4. With the temperature rising at the interface region the yield stress reduces until it became less than flow stress, and then the plastic deformation starts.
5. The heat generation duo to plastic deformation compares with the heat generation duo to the friction is very small and it difficult to calculate, so many researchers were neglected it.
6. The heat transfer throw the solid work pieces can be analyzed by Fourier heat conduction law.
7. The thermal and mechanical properties of the material vary with variation of temperature during the welding process.
8. Compared the simulation results with the experimental results for each researches we can say that, the welding process can be represented numerically through software programs.

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الملخص :

لحام الاحتكاك الدوار هو تقنية ربط بالحالة الصلبة لقطعتين من المواد معا باستخدام الطاقة الحرارية المتولدة نتيجة الاحتكاك بين هاتين القطعتين من خلال قوة محورية خارجية. تتمثل الأهداف الرئيسية لهذه الدراسة في مراجعة الابحاث السابقة التي درست عملية لحام الاحتكاك الدوار ، فهم النموذج الحراري لعملية الحام لهذه الابحاث ، والاطلاع على النماذج الرياضية ونماذج المحاكاة لكل بحث والافتراضات التي تم أخذها في الاعتبار والمقارنة مع النتائج التجريبية لأبحاثهم إن وجدت. النتائج التي حصلنا عليها من الابحاث السابقة كانت كالتالي: ارتفاع درجة حرارة القطعتين اثناء عملية اللحام يؤدي الى تغيير في خواصهما لذا الحرارة المتولدة خلال العملية ليست ثابتة. وجد أن الحرارة المتولدة أثناء عملية اللحام يمكن تقسيمها إلى جزأين، الحرارة الناتجة عن الاحتكاك الدوراني والحرارة المتولدة أثناء التشوه البلاستيكي الحاصل للقطع. مع ارتفاع درجة حرارة الحام فأن اجهد الخضوع يقل الى ان يصبح اقل من اجهاد التدفق عندها يبدأ التشوه في القطعتين. يمكن حساب الحرارة المنتقلة خلال نماذج القضبان من خلال قانون فوريبه للتوصيل الحراري. بالمقارنة بين نتائج المحاكاة مع النتائج التجريبية لكل بحث، يمكننا القول ان عملية اللحام يمكن تمثيلها عدديا من خلال برامج الحاسوب.

الكلمات الداله :

لحام الاحتكاك الدوار، تحليل العناصر المحددة، ملف درجة الحرارة، الحرارة المتولدة.