STUDY, DESIGN AND DEVELOPMENT OF A VACUUM FURNACE TO PERFORM PRESSURING DIFFUSION WELDING OF LIGHTWEIGHT ALLOYS

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Abstract

The joining process carried out in the solid state, named Pressuring Diffusion Welding (PDW), is a modified and not well studied version of Diffusion Welding (DW). In PDW, the load applied to the samples to be joined varies in a sine wave pattern during the whole process instead of being kept constant as in DW. The PDW process produces high strength joints with a significant reduction of the processing time at the joining temperature, due to the fact that the load wave pattern enhances rupture of the oxide scales during the initial stages of the joining process. The oxides scales that are spontaneously formed in most lightweight materials such as Al and Ti alloys difficult joining since they limit atomic diffusion between the samples to be joined. Thus, prompt rupture and/or destabilization of the scales will hasten the joining procedure.

Therefore, the objective of this project is to upgrade an existing vacuum furnace, currently used to produce joints by DW, in order to enable PDW joining; the joining apparatus should be capable of developing cycling loads ranging from 70 N to 11.2 kN, with an operative frequency comprised between 0.5 and 5 Hz.

The mechatronic project of this new equipment has already started and this paper will present and summarize the main steps of the study, design and development of this equipment which allows joining of materials by the PDW technique. The selection and the dimensioning of the mechanical systems, the selection of the sensors and actuators and of an adequate data acquisition system to acquire, monitor and analyse the signals obtained to perform the automatic control of the furnace will also be discussed in the paper.

***Keywords**: mechanical design; mechatronics; diffusion welding; pressuring diffusion welding; transition joints*

Resumo

O processo de união conduzido no estado sólido, designado por *Pressuring Diffusion Welding* (PDW), é uma variante ainda pouco estudada da Soldadura por Difusão (SD). Nas juntas obtidas por PDW, a força aplicada aos materiais a ligar varia sinusoidalmente no decorrer do processo, em vez de ser mantida constante como na SD. O PDW produz juntas de elevada resistência mecânica e possibilita reduzir significativamente o tempo de estágio à temperatura de ligação, em virtude de promover a rotura da película superficial de óxidos, durante os instantes iniciais do processo.

Pretende-se assim efectuar um “upgrade” a um forno de vazio já existente, que é usado correntemente para SD, para efectuar PDW, devendo ser capaz de aplicar cargas cíclicas de 70 N a 11.2 kN a uma frequência de operação de 0.5 a 5 Hz.

O projecto mecatrónico deste novo equipamento já se iniciou e este artigo pretenderá apresentar e resumir as principais etapas de estudo, concepção e desenvolvimento do equipamento para processamento de juntas transientes por PDW, as quais envolvem a selecção e o dimensionamento dos dispositivos mecânicos, a selecção de sensores e actuadores e de um sistema de aquisição de dados para adquirir, monitorizar e analisar os sinais dos sensores, necessários ao controlo automático do forno.

Palavras-chave: *projecto mecânico; mecatrónica; soldadura por difusão; soldadura “pressuring diffusion welding”; juntas de transição*

1. Introduction

PDW is a novel joining technique that allows reduction of the processing time in comparison to conventional DW. The advantage of PDW results from applying the load to the materials to be joined in a sine wave pattern, instead of holding it at a constant value in the course of the joining procedure. The load wave pattern enhances rupture of the oxide scales that limit both atomic diffusion and available contact area between the parts to be joined. This enhances joining, since effective bonding only occurs after removal of the oxides. Therefore, early breaking of the scales will allow speeding up the joining process, in particular during the first stages of joining (Yuan et al., 2008).

PDW is mostly interesting for production of joints between materials with a strong oxide forming tendency, such as lightweight Al, Ti, Mg and TiAl alloys.

The main objective of the research herein proposed is to develop a conceptual design for the upgrade of an existing vacuum furnace, which is currently used for DW, to enable PDW joining. The new equipment must be capable to apply cycling loads from 70 N to 11.2 kN, with an operating frequency ranging from 0.5 to 5 Hz.

To accomplish this objective it is necessary to carried out a mechatronic project, which will involve the selection and/or design of mechanical components and/or devices (in terms of hydraulic components and actuators to apply the cycle loading), as well as the selection of sensors and a data acquisition system to command, acquire, monitor and analyze the signals from the sensors to perform the automated control of the modified vacuum furnace. All steps necessary for pursuing this design will be detailed discussed and described in this paper as part of a research project undertaken at the Centre for Mechanical and Materials Technologies (CT2M) – Department of Mechanical Engineering, University of Minho.

2. Joining Materials for the Production of Lightweight Functionally Graded Sheets

Production of lighter and lightweight vehicles is compulsory for both aircraft and spacecraft manufacturers. Decreasing the weight of structural parts is a straightforward way of achieving these goals, since it can induce a significant overall weight reduction of the vehicle. Therefore, research efforts focused to improve the efficiency of manufacturing processes and materials used in the conception of structural parts are mandatory (Williams & Starke, 2003).

Designing lighter but sufficiently strong structures requires optimization of material distribution within the structural parts (Zadpoor et al., 2008). One way of overcoming this issue is the use of sheet material with a functional gradient of properties, which is fabricated by joining multiple sheets made of different shapes, grades/materials and thickness into a single plane, prior to machining or forming. Combining lightweight with high strength or high temperature capability materials in Functionally Graded Sheet (FGS) is an interesting approach for this purpose.

Fabrication of FGS requires the joining of dissimilar materials and thus, the production of transition joints (TJ). The properties of the FGS at the TJ may be quite different from those of the base materials, because the joining process induces at the transition/welding zone the formation of phases with different composition, distribution and/or morphology from those present in the parent materials (Ghosh & Chatterjee, 2003), (Krishna et al., 2005), (Cavaliere et al., 2009). Consequently, the properties of TJ may have a negative impact upon the performance of FGS. Therefore, it is essential to develop suitable joining technology and to optimize the set of joining processing parameters to obtain TJ in FGS with adequate properties.

Joining processes like conventional Fusion Welding (FW) or Friction Stir Welding (FSW), allow high production cadencies, but high residual welding stresses and formation of brittle phases in the welding zone may enhance nucleation and growth of cracks, in particular when low ductility materials are joined. Additionally, changes in material property across the resulting thick TJ may have a detrimental effect on the mechanical behaviour of the joints (Cavaliere et al., 2009), (Commin et al., 2009), (Kumar & Sundarrajan, 2009). Altogether, this makes rather difficult to obtain high performance joints.

Diffusion Welding (DW) promotes joining by the combined effects of temperature and localized microscopic plastic deformation at the contacting surfaces; no liquid phase is formed in the course of the joining process. Consequently, solid state cracking is eliminated, degradation of the parent materials properties and brittle phase formation across the resulting narrow welded zone are minimized (Nicholas & Crispin, 1982), (Santela, 1992), (Mahoney & Bampton, 1993). A major drawback of DW is the low production cadence.

Pressuring Diffusion Welding (PDW) is novel variant of conventional DW. In PDW, the load is applied in a sine wave pattern to the joining assemblage instead of being held at a constant value. PDW is reported to produce high strength joints with the advantage of inducing a significant decrease of the holding stage at the joining temperature, because breaking off of the oxide scales during the initial stages of joining is enhanced (Yuan et al., 2008). Thus, PDW is of major interest for the production of TJ between alloys with a strong tendency to form oxide scales, such as alloys based on either Al, Mg, Ti or gamma-TiAl, which are particularly appealing for aeronautical and aerospace applications.

3. Production of Transition Joints by Diffusion Welding and Pressuring Diffusion Welding

Joining by both DW and PDW is promoted by the combined effects of temperature and plastic deformation. Joining is performed in the solid state, typically between 50 to 80% of absolute melting temperature of the base materials. The dwelling time at the joining temperature is dependent of the system of materials to be joined and may range from a few minutes to several hours. The load applied to the joining assemblage promotes localized microscopic plastic deformation of the asperities at the contacting surfaces between the parent materials, without causing macroscopic plastic deformation of the bulk (Mahoney & Bampton, 1993), (Orhan et al., 1999).

It is accepted that joining is established by a mechanism that comprises the following three stages (Mahoney & Bampton, 1993):

- Stage I – Plastic deformation of asperities;
- Stage II – Mass transport controlled by atomic diffusion;
- Stage III – Migration of the interface.

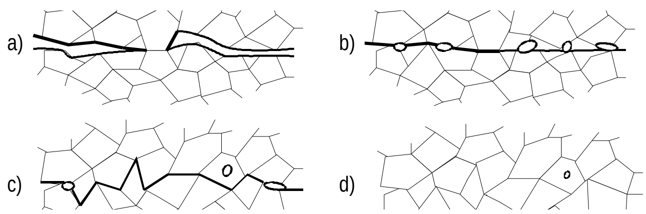
In stage I, the applied load promotes plastic deformation of the asperities at the contacting surfaces between both parent materials. As deformation proceeds, contacting area and pore closure increase. Ideally at the end of the stage, a planar contact surface with low amount of porosity is formed.

Due to the increased contact area, atomic diffusion between the parent materials becomes the preponderant phenomenon in stage II. The combined effects of atomic diffusion and plastic deformation lead to near total collapse of pores, and promote chemical homogenization across the joint.

As joining enters stage III, the interfacial grain boundary becomes increasingly mores irregular, with local penetrations of a few microns into the bulk of each base material. As this stage proceeds the boundary becomes hardly noticeable and hard to distinguish from those of the base materials because chemical composition is being further homogenised. In fact the interfacial grain boundary is progressively being removed. The driving force for the interfacial grain boundary migration and annihilation is the decreases of surface energy associated with its elimination. A schematic representation of the mechanism that governs the establishment of joining is presented in Figure 1. It should be noted that the main advantage of PWD in comparison to DW is mainly noted as stage I develops, since PDW early breaking enhancement of the oxides scales will reduce time required to expose clean contacting surfaces between the base materials.

DW and PDW joining produce high performance and thin TJ, with a minimum formation of brittle phases and mechanical properties that closely match those of the base materials (Nicholas & Crispin, 1982), (Santela, 1992), (Mahoney & Bampton, 1993). However, both processes lack the readiness of either Fusion Welding or Friction Stir Welding that allow high production cadencies. Nevertheless, DW and PDW are of major interest for aeronautical and aerospace industries, which favour performance over production rate. For instance, DW of Ti alloys was used to produce the wing box of the B1-B bomber aircraft (Williams & Starke Jr, 2003).

Figure 1: Schematic representation of the bonding mechanism under DW joining. a) initial contact area limited to some asperities; b) plastic deformation of asperities increases contact area; c) collapse of pores and interface migration; d) at the end of the process, interfacial grain boundary is indistinguishable of those of the base materials (Adapted from (Mahoney & Bampton, 1993))



In order to control and optimize the processing of TJ by PDW it is imperative to be able of adequately control and monitor the joining processing variables. The main variables of PDW joining are the following:

- Temperature;
- Dwelling time at the joining temperature;
- Vacuum level inside the furnace chamber;
- Load parameters:
    - Intensity (minimum and maximum values);
    - Frequency.

4. Mechatronic Project

The project aims to optimize the PDW processing of TJ between Al and Mg alloys, as well as between Ti and gamma TiAl alloys, in order to produce lightweight FGS.

Successful undertaking of this project requires the following challenges to be surpassed:

1- To instrument a vacuum furnace currently used to process DW joints, in order to be able to monitor and control the load applied during PDW joining, and

2- To optimize the set of PDW joining processing variables in order to produce TJ with adequate properties for the fabrication of FGS.

4.1 Equipment to Process DW Joints

Figure 2 shows the equipment currently used to process TJ by DW. In the figure, the main components of the furnace are identified. The equipment consists of a controlled atmosphere chamber for high temperature joining, where a matrix, which contains the materials to be joined, is loaded by means of a punch. The matrix (see Figure 3) is instrumented with thermocouples so that temperature at the joint is continuously measured in the course of joining. Heating is provided by an induction coil, located around the furnace chamber.

Figure 4 shows a micrograph of the interface of a TJ between AISI 304 and c.p. titanium, processed by DW at 625 ºC with a dwelling time of 60 min. and an applied load of 29 MPa, using the vacuum furnace shown in Figure 2.

4.2 Specifications

Table 1 shows the process variables considered for the control system of the upgrade of the furnace from DW to PDW.

For the design of the new furnace equipment, and for these specifications, topic 4.4 will present the command and control block diagram currently being used for this development.

4.3 Project Functional Diagram

Figure 5 depicts the functional block diagram of the project, in which all the design phases are considered, as well as the main inputs and outputs.

Figure 2: Vacuum furnace used for DW joining

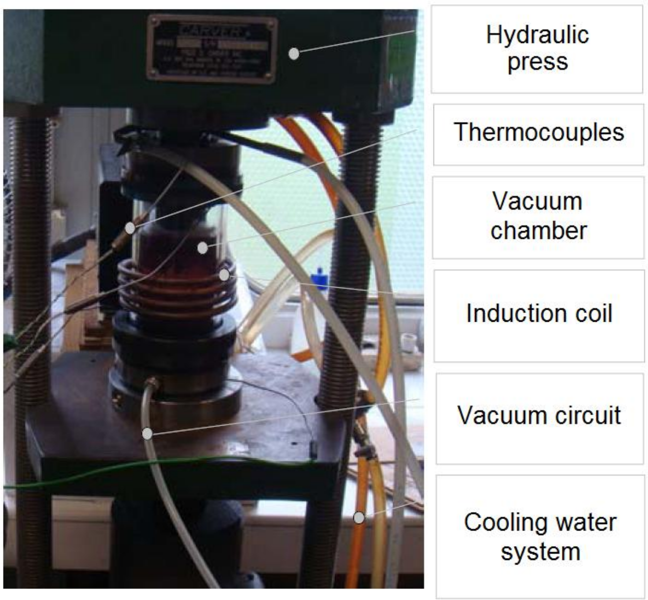


Figure 3: Matrix assemblage sequence: a) lower part of the matrix; b) matrix with samples to be joined; c) matrix ready to SD joining

a) b) c)

Figure 4: Scanning electron microscopy image of an AISI 304 (left side) / c.p. titanium (right side) TJ obtained by DW

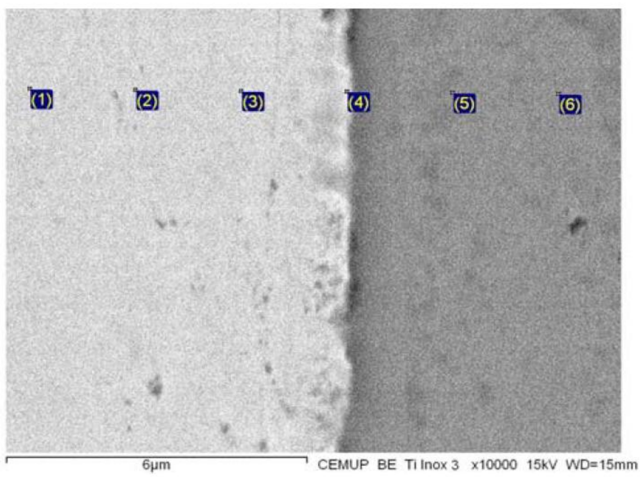
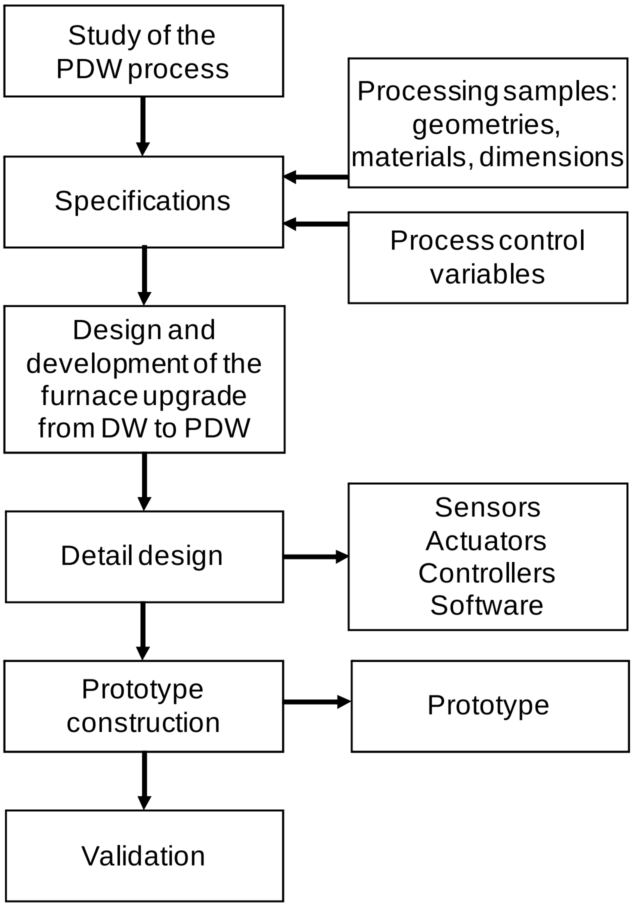


Table 1. Specifications of the processing variables for the control system

Processing variables	Values
Temperature	200-900 ºC
Cyclic load	0.07-11.2 kN
Load frequency	0.5-5 Hz
Dwelling time at the joining temperature	60-3600 s
Vacuum level inside the furnace chamber	$<10^{-4}$ mbar

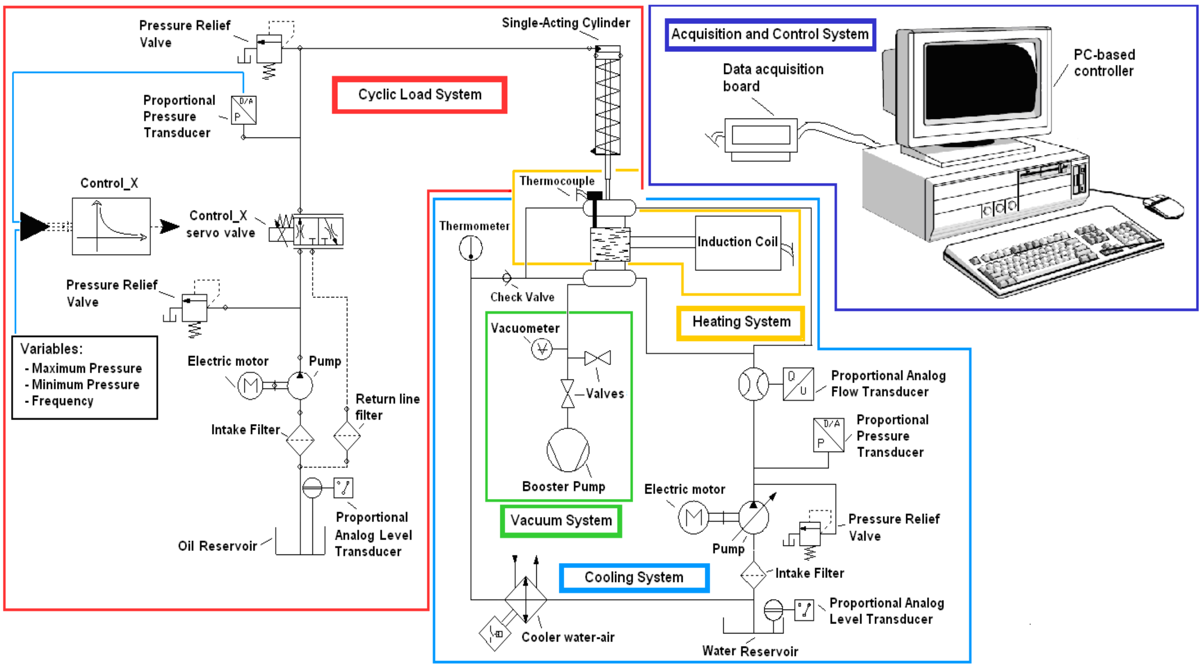
Figure 5: Functional block diagram of the project



4.4 The Command and Control System

A schematic representation of the mechatronic system to carry out the overall command and control of the furnace for PDW joining is highlighted in Figure 6. This project includes the development of the measuring system, the implementation of the actuation setup, and, of course, the design of a specific controller. For the sake of completeness, it must be referred that the circuits presented in Figure 6 were designed and simulated using the Automation Studio™ (from Famic Technologies Inc.).

Figure 6: Detailed schematic representation of the overall developed control



The vacuum chamber is instrumented with temperature and force sensors to obtain the most relevant variables of the PDW process (such as, temperature and applied load intensity and frequency), a flow rate sensor to determine the cooling rate of the furnace chamber (cooling water system) and a vacuometer sensor to measure the vacuum level carry out by a Booster pump.

The signals from the sensors, which correspond to input variables of the system, will be addressed to a PC-based controller with a data acquisition board.

A software developed specifically for this purpose (based on the LabView platform, from National Instruments) will be used to carry out the acquisition, display and analysis of the obtained signals, as well as the command and control of the whole system in terms of temperature, intensity and frequency of the applied load and cooling rate of the chamber.

The control of the PDW process will be carried out as follows: the controller compares the sensor readings with the reference values of the PDW process stored in a database (temperature, intensity and frequency of the applied load), which depends on the type and dimensions of the material samples to be joined.

Regarding the temperature control, if the measured values are different from those listed as the reference values, the controller (through the power circuit, the induction coil or the water pump) will increase or decrease the temperature of the vacuum chamber.

For the control of the cyclic loading, if the measured values are different from the listed reference values, the controller will drive the hydraulic actuator through a servo valve to increase or decrease the intensity and/or the frequency of the applied load. The adoption of the hydraulic technology is due to the fact that it enables the application of cyclic loadings with high accuracy and repeatability.

Therefore the whole system will be continuously monitored and controlled, since at least one relevant process variable is differing from the reference value.

5. Conclusions and Future Work

The mechatronic design of a vacuum furnace to perform PWD was presented and discussed.

The developed control system of the vacuum furnace is suitable to the required specifications of the project, regarding the control and monitoring of the temperature and cyclic loading, which are the most crucial variables of the PDW joining process.

As for future work, the physical implementation of the developed control system will be carried out first, in order to upgrade the existing DW furnace to perform PDW. The validation phase will be undertaken next, with the optimization of the PDW process variables to obtain TJ with properties suitable for producing lightweight sheets with graded functional properties.

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