OPTIMIZATION OF ULTRASONIC WELDING PARAMETERS AND TEMPERATURE DISTRIBUTION IN METAL MATRIX COMPOSITE BASED ON ALUMINIUM

Marius POP-CALIMANU\(^a\), Dinu GUBENCU\(^a\), Ioana POP-CALIMANU\(^b\), Traian FLESER\(^a\)

\(^a\)"Politehnica" University of Timisoara, Faculty of Mechanics, Bv. Mihai Viteazu no.1, calimanumarius@yahoo.com, dinuval@gmail.com, trfleser@yahoo.com

\(^b\)"Politehnica" University of Timisoara, Faculty of Electronics and Telecommunications, Bv. Vasile Parvan no.2, ioanamonica.popi@gmail.com

Abstract

Ultrasonic Welding is a solid state welding process, where a high-frequency vibration is combined with welding pressure to bond two similar or dissimilar material together in a very short time. The vibrations are applied parallel to the interface between the parts, without producing a significant amount of heat during the process, and without causing changes in the properties of work pieces. In this paper were optimized the parameters of ultrasonic welding like the welding pressure, welding time and amplitude of vibrations to obtain a good bonding of AA2124/SiC/25\%p-T4 metal matrix composite using a 2\(^k\) full factorial design. Of course, we are interested to know which variable of the process affect most the response. The experiment is performed using AA2124/SiC/25\%p-T4 metal matrix composite under thin foil form with 1 mm thickness. It was observed that the factors which influence the most the welding quality and the temperature during the ultrasonic welding process are welding time and welding pressure. The temperature generated during the welding process is measured. Also, the temperature distribution is studied in the best bonding and how this, influence the microstructure of the AA2124/SiC/25\%p-T4 metal matrix composite. It was observed that the temperature developed is not more than 40\% of the melting point of the base metal. After welding, metallographic examinations and hardness measurements are performed in the characteristic areas of the weld. Large hardness differences were observed between the welding zone and the base material, and the structures of the composite material is not modified after welding, at least not visibly.

Keywords: ultrasonic welding, metal matrix composite, temperature distribution;

1. INTRODUCTION

Ultrasonic welding (US) is a solid state welding process, where can be welded various types of material, even metal matrix composite [1]. These materials are welded through the application of high-frequency energy vibrations, parallel on the surfaces which need to be welded under the pressure forces for creating a good bonding, in a very short time, without producing a significant amount of heat during the welding process, and without causing changes in properties of work pieces [2].

Ultrasonic welding has many advantages over the other manufacturing process with role of permanent bonding such as: - the processing in a solid state facilitates the storage in non-equilibrium microstructures produced during previous processing; - the structural heterogeneousness of the bond due to lack of liquid-solid transformation is reduced; - work atmosphere is normal, with no danger of formation of oxides or other chemical compounds[3]; Of course, there is one major disadvantage at the ultrasonic welding process, that the process can be applied only to small parts and wires. Therefore, in this paper we tried to bond and even to optimize the parameters process of ultrasonic welding of AA2124/SiC/25\%p-T4 metal matrix composite, using the 2\(^k\) full factorial experiments method, to evaluate the weldability of the material by studying the mechanical properties of the bond and studying the macro and microstructure of the material, in the characteristic areas of the bond. In this welding process, there are many variables that can affect the ultrasonic welding of AA2124/SiC/25\%p-T4 metal matrix composite, that's why, we will focus only on the
welding pressure, on the welding time and on vibration amplitude of the sonotrode, which are critical parameters in the defining of bond quality, also confirmed by literature [4]. It is known that the welding temperature plays a very important role in the bonding process and has a significant influence on structural change [5]. For this reason, in this paper we will also measure and we will visualize the temperature distribution during the bonding process using infrared thermography and we will study the effect of welding time, welding pressure and vibration amplitude of sonotrode upon the temperature during the ultrasonic welding of AA2124/SiC/25%p-T4 metal matrix composite.

2. EXPERIMENTAL SECTION

2.1 Material used and experimental procedures

The thin foils used in this study are an AA2124 aluminum alloy, reinforced with silicon carbide, under particles form, in a proportion of 25% (AA2124/SiC/25%p-T4). The silicon carbide particles have a size of 2-3 microns. This kind of material was provided in form of forging plates with size 275 mm x 220 mm x 15 mm, which was produced through powder metallurgy and heat treated at T4 temperature conditions. The chemical composition of the AA2124/SiC/25%p-T4 metal matrix composite was in mass fractions: Al-93.8 Cu-3.86 Mg-1.52 Mn-0.62 Si-0.17 % [6]. For this material to be bonded by ultrasonic welding process, we had to cut the forging plate into small pieces (30 mm x 6 mm x 1 mm) by wire electric discharge machining.

The bonding was performed using a conventional ultrasonic metal welding machine (2000 W, 20KHz), for different ranges of the bond parameters which is shown in Fig. 1. The sonotrode used for this experiment is made of steel.

Fig. 1 Ultrasonic welding equipment

The anvil is also made of steel provided with serrations at the top surface. The area of sonotrode which come into contact with the work piece is also provided with serrations, similar to the top surface of the anvil, for preventing the sliding of the work pieces which follow to be bonded. Before bonding process the specimens were cleaned both mechanically and chemically, to remove the oxide layer on the surface, to not affect the bonding process. First, we studied the macrostructure of bonded specimens.

Fig. 2 The bonding specimens AA2124/SiC/25%p

Then was analyzed the microstructure of bonded specimens using a digital microscope. Numerous measurements of Vickers microhardness (HV 0.1) were made, using a 100 g load and a holding time of 15 s, for determine the microhardness variation along the bond. Measurement and visualization of temperature [7] distribution during the welding process was performed in real time using an infrared camera.

2.2 Identification of influence factors

In this paper we focus on those factors which have the greatest influence on the ultrasonic welding process, which are welding time expressed in seconds, welding pressure expressed in bar and vibration amplitude of sonotrode, expressed in percentage from maximum value, $A_{\text{max}} = 100 \mu m$, and the effect of these three factors on the generated temperature during the process. Each of these factors has two levels of variation, as shown in Tab. 1. The pursued objective function is the temperature measurement during the ultrasonic
welding process. Having three influence factors with two levels of variation high level (+) and low level (-), we will have to do eight runs [8]. In Fig. 3 is shown the matrix program of the experiment. Also, are taken into account the interactions between those three influence factors, which are the interaction between welding time and the welding pressure, the interaction between welding time and the amplitude of the sonotrode, and the interaction between welding pressure and the amplitude of the sonotrode. The obtained results were done with specialized software for statistical designing and analysis – MINITAB [9].

3. RESULTS AND DISCUSSIONS

3.1 Optimization of process parameters

For optimization of process parameters used to bond AA2124/SiC/25%p-T4 metal matrix composite specimens with 1 mm thickness, the 2\textsuperscript{k} full factorial experiments was systematically adopted. In Tab. 2 and Fig. 4 are presented the obtained results during the bonding process and the specimens which were done. From the Pareto chart Fig. 4 it can be seen which of those three factors proves to be the most significant effect upon objective factor which is temperature, implicit the bond quality.

Tab. 1 The settings of factors and levels

<table>
<thead>
<tr>
<th>No.</th>
<th>Factor Description</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Weld time (sec) A</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Weld pressure (bar) B</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>Amplitude (%) C</td>
<td>70</td>
<td>85</td>
</tr>
</tbody>
</table>

Fig. 3 Text matrix

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In the Pareto chart it can be observed that welding time (A), welding pressure (B) and the interactions between those two, are the influence factors that have the greatest effect on the temperature, but not on the quality of the bond. To refer to the bond quality we must take into account the vibration amplitude of sonotrode, because it has a very important role in ultrasonic welding process. This can be seen in Tab. 2, where increasing the one or the both major influence factors, will increase the temperature generate during the ultrasonic welding process, and the big problem is when we grow also in the same time the vibration amplitude factor.

Tab. 2 Experimental results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
<td>2.5</td>
<td>70</td>
<td>266.771</td>
</tr>
<tr>
<td>2</td>
<td>2.4</td>
<td>2.5</td>
<td>85</td>
<td>264.116</td>
</tr>
<tr>
<td>3</td>
<td>2.4</td>
<td>3.5</td>
<td>85</td>
<td>275.599</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2.5</td>
<td>85</td>
<td>289.026</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3.5</td>
<td>70</td>
<td>340.699</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>3.5</td>
<td>85</td>
<td>315.161</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>2.5</td>
<td>70</td>
<td>338.768</td>
</tr>
<tr>
<td>8</td>
<td>2.4</td>
<td>3.5</td>
<td>70</td>
<td>318.834</td>
</tr>
</tbody>
</table>

In the Pareto chart it can be observed that welding time (A), welding pressure (B) and the interactions between those two, are the influence factors that have the greatest effect on the temperature, but not on the quality of the bond. To refer to the bond quality we must take into account the vibration amplitude of sonotrode, because it has a very important role in ultrasonic welding process. This can be seen in Tab. 2, where increasing the one or the both major influence factors, will increase the temperature generate during the ultrasonic welding process, and the big problem is when we grow also in the same time the vibration amplitude factor.
that has harmful effect on bond quality. So in this paper the combinations of factors which have the most significant effect upon bond quality of AA2124/SiC/25%p-T4 metal matrix composite are the combination of parameters from Specimen no.1, Specimen no. 5, Specimen no. 7, and Specimen no. 8, and the remaining specimens were not bonded (see Tab. 2). An explanation of the unbounded specimens would be that due to increased the vibration amplitude of sonotrode, the friction at the bonding interface is less, and the work pieces remain embedded in the serrations of the sonotrode and respectively in the serrations of the anvil, because there the friction is higher. Next we will investigate only that specimens which are visual bonded.

2.2 Macro-and micro-structures, and mechanical properties

For investigations of macro and microstructures the specimens were transversally cut, parallel to the linear motion axes. In the top view of bonded specimens (Fig. 2) we could observe the serrations marks made by sonotrode of the ultrasonic welding machine, and in Fig. 5 we don’t notice these marks, meaning that a good bonding of AA2124/SiC/25%p-T4 metal matrix composite can be achieved with a minimal or no deformation of sonotrode on the surface of the work pieces which must be bonded. In Fig. 6a, b, c, d are presented the micro structural investigations in the bonded areas of AA2124/SiC/25%p-T4 metal matrix composite, at different parameters, at those sets of parameters obtained after optimization of the process, and in the Fig. 6e is presented the micro structural investigation of base material. At these bonds can be seen good interface bonding and also unbounded surface. Micro structural analysis is distinguished from

![Fig. 4 Macrostructure of bonded specimens](image)

![Fig. 6 Microstructures near bond interfaces and in the base material of AA2124/SiC/25%p-T4 specimen no. 7, where practical, the bonding line interface doesn’t exist. At this bond we cannot identify any of typical defects found in fusion welding of Al metal matrix composite, such as particle segregation and gas](image)
pores, and in the bonding zone it was observed a uniform distribution of silicon carbide particles and we can’t see any different structural change compared with the base material. This applies to all bonds. In Fig. 7 is shown the distribution of Vickers microhardness (HV0.1) for all four bonds. The microhardness was measured at a distance of 1 mm from each other, along the bonding interface line. The microhardness measured in the base material was between 130-145 HV0.1, and in the bonding zone was between 180-230 HV0.1 for all four bonds. The microhardness difference between base material and bonding zone of AA2124/SiC/25%p-T4 is due to increasing of temperature in a very short time, and the microhardness differences measured in the bonding zone is due to silicon carbide particles which block the uniform distribution of temperature in material.

2.3 Measurement and temperature distribution

The maximum temperatures in the bonding zone are shown in Fig. 8 for different welding parameters. From the results we can conclude that the highest temperature recorded is at the end of the welding cycle. It can be seen that during the ultrasonic welding process, the temperature increase very rapidly at the beginning of the weld, and if we increase the welding time and welding pressure, also will increase the temperature. Because we have a limited space, we cannot show the temperature distribution of all bond specimens, and we decide to present the bonding which is the best from quality point of view, and this is the specimen no. 7. So in the Fig. 9 a, b, c and d is shown the infrared images of the temperature distribution of specimen no. 7 during the ultrasonic welding at different time. During ultrasonic welding process it can be seen that heat is generated at the bond interfaces and in its neighborhood too, and then reach at the surface. This is because we have a small plastic deformation left by sonotrode surface and a high friction, at the bonding interface. So the highest temperature occurs at the bonding interface, where the measured value is 338.768 °C, value which represents about 40% from the melting temperature of the base material.
CONCLUSIONS

1. It has been identified all those factors which have a significant effect upon the bonding of AA2124/SiC/25%-T4 metal matrix composite, with 1 mm thickness.
2. It has been identified the optimal parameters to obtain a good quality of the bond, at least from microstructure investigations point of view.
3. It was studied what effect have welding time, welding pressure and vibration amplitude of sonotrode upon temperature, and what effect has the temperature upon the bonding process.
4. It was measured and investigated the temperature distribution during the ultrasonic welding process upon AA2124/SiC/25%-p-T4 metal matrix composite.

ACKNOWLEDGEMENTS

“This work was partially supported by the strategic grant POSDRU 107/1.5/S/77265, inside POSDRU Romania 2007-2013 co-financed by the European Social Fund- Investing in People.”

LITERATURE


