Laser welding of low friction nanostructured sintered composites: technical and environmental aspects

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Abstract: Low friction materials in nanostructured sintered composites are used for different pairs of moving parts of MEMS configuration. The paper aims to present some elements regarding the behaviour of such type of materials in pulsed laser welding process. The influences that are developed during the interaction between the laser beam and the nanostructured composite have been analysed. Major instabilities have been observed and that involved a very accurate choosing of the laser power. The particles have been measured and visualised from the emitted fume by using special extractors that analysed the emitted gases as well. The particles were put in suspension and visualised by using nanosight microscope and they were measured by using a nanosizer. The analysis showed that they were in nanometric domain that meaning higher impact on the human health comparing to the welding of the classic materials, according to the OSHA.

Keywords: laser welding; low friction; sintered composites; fume emission.
1 Introduction

According to their destination, MEMS require different types of special materials with complex of specific properties. If talking about sensors, materials with properties that can be exploited as sensing active elements should be involved in the building of the sensors. If talking about actuators, materials those possess some advantages like almost zero thermal expansion coefficient, low density, low electrical resistance, low friction coefficient, low or high stiffness and satisfactory ductility are required to achieve the appropriate function of the actuators. Generally, by using a conventional material, not the entire complex of the necessary properties can be obtained. A solution is to design and optimise composite materials, materials that are built by using more than two
distinct materials with different properties, in order to use the advantage of every one of them.

Sometimes such composite materials should be welded to realise a complex shape or a link between two or more elements. The welding process is generally going to the microwelding conditions and it produces different modifications of the structure and of the properties of the base composite materials. At the same time, depending on the structure of the welded material, the emitted fume contains different types of gases and very small particle. The general dimension of these particles depends on the dimensional characteristics of the material structure and on the process, meaning here the quantity of heat that is injected into the base material. The expertise came from previous researches. Savu et al. (2007a) obtained in previous experiments and used for composites iron nano- and micro-particles by vaporising specific raw material in plasma discharge. They stated the ways to control the particles dimension.

The paper aims to present the first step of an experimental research that was performed in order to analyse the general behaviour of different composite materials during welding process. The analysing was oriented to the stability of the process and to the specific emission of fume.

2 Elaboration of the composite materials

As targets, there were accepted three types of composite materials that had the nanoscaled. Table 1 presents these materials.

<table>
<thead>
<tr>
<th>No.</th>
<th>Composite type/main properties</th>
<th>Matrix Chemical (%)</th>
<th>Reinforcement Chemical (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CuAl-SiC&lt;br&gt;Low friction composite, soft matrix, hard reinforcement</td>
<td>CuAl 85</td>
<td>SiC 15</td>
</tr>
<tr>
<td>2</td>
<td>CuSn10-C&lt;br&gt;Low friction composite, soft matrix, hard reinforcement</td>
<td>CuSn10 99</td>
<td>C 1</td>
</tr>
<tr>
<td>3</td>
<td>W-Cu-Ni&lt;br&gt;High thermal conductivity, low thermal expansion and high wear resistance combined with good electrical conductivity</td>
<td>W 95</td>
<td>Cu 1.5</td>
</tr>
</tbody>
</table>

For the elaboration of the materials, our own and literature expertise has been used. Wang et al. (2008) studied the influence of the compaction method on the properties of the sintered materials. They stated that the three axes compaction increases the density of the compact and the mechanical properties are improved, as well. Shtern and Mikhailov (2002) modelled the phenomenon of the compaction before sintering when use stiff dies. A variation of the density was found and the variation was numerically simulated. Rutz et al. (1996) analysed the methods to obtain a high density compact by using single pressing process. They optimised the conditions and the geometry of the dies. Orban (2005)
introduced a method to obtain controlled properties sintered steels. Vaucher (2005) activated the sintering process by heating using microwaves. He optimised the heating evolution. Grossin et al. (2005) used microwave heating sintering to create composites with different properties materials. The composite materials were obtained by powder metallurgy techniques. Micrometric powder for the matrix and nanometric powder for the reinforcement have been accepted for that. The elaboration process is presented in Figure 1. According to Figure 1, the powders used for the base materials were dry milled in planetary mill in order to achieve the appropriate dimension. The powders used for the matrix of the composite were milled for 5 h and the powders used for the reinforcement were milled for 40 h. In such manner, the main range for the dimension of the matrix powder was 400–600 μm and the main range for the dimension of the reinforcement powder was 80–200 nm. The powders were mixed and milled together for ten minutes to achieve a proper homogeneity. The resulted mixing was introduced in a die and pressed with 600 MPa stress. Before pressing, the entire die was vibrated using a ultrasound device. The vibration process was applied as a pre-compaction process. During the vibration the relative positions of the particles are reorganised and the density of the mixture is increasing in time. The compact was in an initial established shape and dimension. It was introduced in an electric furnace to perform the sintering process. The parameters of the sintering process were specific to every type of materials that was used.

The final probes: hollow cylinders 30 mm diameters and 50 mm length. Taking account of the application that the materials are dedicated to, the shape was chosen in order to model the real pieces. After the sintering process, the grains size of the reinforcement increased with about 50% due to the heating that is specific to the sintering process.

### 3 Welding of the composite materials

The sintered pieces were subjected to laser welding process. As in the elaboration of materials process, own and literature experience has been used. Birdeanu et al. (2007) used the factorial experiment in order to create a base for the modelling of different phenomena that are developing during laser welding of the soft matrix composites. They stated the influences of the both pulsing frequency and pulse time on the porosity of the weld. Savu et al. (2007b) compared different processes to obtain low electrical resistance for the welded joint. Laser microwelding showed the most appropriate behaviour. The electrical resistance increased only a few mΩ because of the weld. The laser used in the experiment was a pulsed Nd:YAG laser that is able of a 5 kW on the pulse and its maximum average output power is up to about 120 W. The travel speed was fixed to 3.7 mm/s and the spot diameter to 0.6 mm. The pulse shape was rectangular and the welding was performed under gas shielding (Ar 99%). The fusion passes were done with and without preheating. When preheating was performed, the preheating temperature was in the range 100–200°C. The parameters that were modified during experiments were the pulse power, the pulse width and the pulse repetition rate. For that last parameter, manual spot by spot pulse was a used regime, too.

According to previous expertise Savu et al. (2007a) in laser welding the range that are presented in the Table 2 were covered by the experimental programme.
Figure 1 Elaboration process of the composite materials (see online version for colours)
Table 2 Parameters domain

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pulse power</td>
<td>200–2,400 W</td>
</tr>
<tr>
<td>2</td>
<td>Pulse time</td>
<td>0.5–20 ms</td>
</tr>
<tr>
<td>3</td>
<td>Pulse repetition rate</td>
<td>1–80 Hz and spot by spot</td>
</tr>
</tbody>
</table>

Criteria of the process stability that were in target are: spattering; continuity and invariability of the melting process; speed of solidification; behaviour of the elements with high difference between the melting point; laser absorption; and effect of the preheating.

Criteria of the weld quality that were in target are: penetration; continuity; aspect of the bead; non-existence of the spatter on the base metal; and porosity.

The pieces are presented in Figures 2(a)–2(c) and the results in Figures 3(a)–3(c).

Figure 2 Welded pieces, (a) CuAl-SiC (b) CuSn10-C (c) W-Cu-Ni (see online version for colours)
Figure 3  The characteristic domains of the laser welding (see online version for colours)
In Figure 3, it can be observed that:

- For all three materials, a low pulse power involves spattering and explosions of the molten material. The process is noisy and discontinuities of the process could be often detected.

- For all three materials, the preheating of the base material permitted a decreasing of the pulse power and of the pulse duration in the condition of the same quality and stability. The minimum power that determined stability was 200 W for the CuAl-SiC and CuSn10-C materials and above 950 W for the tungsten alloy.

- For all three materials, conduction heating (spot by spot pulsing) gave the best results from the stability point of view. From the weld quality point of view, the solidification was too fast for low pulse times but good aspect was obtained for higher than 6 ms pulse time. The preheating up to 200°C decreased that limit to 3 ms.
CuSn10-C presented the lowest weldability, for all the parameters and without preheating the stability was low: high spattering, violent explosions and excessive burning of the materials. These were involved by the difference between the melting points of the components.

In the case of the CuAl-SiC, by modifying the parameters of the heat source, different types of melting of the base metal were obtained. Even if all the regimes were specific to welding, some melting processes developed as in the cutting processes modes. Every situation was characterised by high instability and that came from the porous structure of the base metal, structure that is specific to the sintered materials. The effect of the porosity was amplified by the difference between the two materials from the composite: a metallic and a ceramic material. Such different materials involve different heat inputs for melting.

The welding of the W-Cu-Ni was almost impossible. It was necessary to have long pulses (12–18 ms), but even using these precautions, the stability was low. By increasing the pulse power, a constant and stable melting started at about 1,000 W, but very fast, at about 1,600 W the process became a cutting process.

4 Fume emission

The interest to know the dimensions of the particles that form, together with specific gases, the emitted fume during the welding process, comes from some previous research results that revealed a higher impact of the nanoparticles on the human body comparing to the microparticles. Savu and Birdeanu (2007) analysed the emission of the fume during welding of different nanostructured metallic matrix composites. At the same time, a comparison between the gas emission levels (http://www.lincolnelectric.com/knowledge/articles/content/fume1.asp.), when nanostructured materials are laser welded, and the limits considered dangerous by the Occupational Safety and Health Administration (OSHA) (http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=20326.) was in the target, in order to establish the main characteristics of the welding process of the nanocomposites.

The experiments consisted in the monitoring of the emitted fume during laser welding of the three subjected materials. The criteria of monitoring were:

- determination of the levels of the main emitted gases (CO, CO₂, NO, NO₂)
- determination of the dimensions of the fume’s solid particles, in order to establish if the reinforcing particle is emitted during the welding process in the fume at the same dimension as in the base metal it is.

Figure 4 shows the equipment used for the monitoring of the emitted gas and the laser-fume extractor system.

All the measurements have been done during the welding passes that were done to establish the stability of the welding process. Because of that, emissions that are specific to stable and unstable regimes were monitored.
Figure 4  The monitoring system for the fume emission (see online version for colours)

Figure 5 shows the level of the monitored gases for the three subjected materials. The current OSHA permissible exposure limit (PEL), for the monitored gases are as follows [as an eight-hour time-weighted average (TWA) concentration] (Shtern and Mikhailov, 2002; Rutz et al., 1996):

- carbon monoxide: 50 parts per million (ppm) parts of air [55 milligrams per cubic metre (mg/m³)]
- carbon dioxide: 5,000 ppm parts of air (9,000 mg/m³)
- nitrous monoxide: OSHA does not currently regulate nitrous oxide, but The National Institute for Occupational Safety and Health (NIOSH) has established a recommended exposure limit (REL) for nitrous oxide of 25 ppm parts of air (45 mg/m³)
- nitrogen dioxide: 5 ppm parts of air (9 mg/m³).

Regarding the dimensions of the solid particles from the fume, they were prelevated by using the same equipment as in monitoring of the gases. The difference was that the circuit of the extracted fume was modified in order to make the fume to pass through special filters that stopped the particles. The filters were washed by using flat water and the particles had been detached from the filters. Suspensions were created in that manner. The equipment used for the analysis of those suspensions was a high performance viewer and measuring system for nanoparticles (Figure 6).
Figure 5  Intensity of emission for the monitored gases, (a) CuAl-SiC (b) CuSn10-C (c) W-Cu-Ni (see online version for colours)
In Figure 7 is presented an image of the C nanoparticles that were prelevated from the fume emitted when CuAl-SiC was welded.

Figures 8(a) and 8(b) presents the dimensional distribution and the main dimension for the situation presented in Figure 7.

The measurements revealed that the nanoparticles from the fume are in the range of 80–250 nm. The range is given by the initial dimension of the reinforcing particles and by the heat input. Starting with a 50 nm main dimension the particles of C increased up to five times. Even if an increasing took place, the particles from the fume remain more dangerous comparing to the particles of 800–900 nm that are specific to the welding of the classic materials.
5 Conclusions

Specific to the stability of the welding process, in the cases of the three subjected materials are:

- low heat inputs (up to 600 W) involves spattering and explosions of the molten material, even if high pulse time is used
- the preheating decreases spattering and permits the decreasing of the pulse power and of the pulse duration in the condition of the same quality and stability
- best results have been obtained when conduction heating (spot by spot pulsing) was used.
The welding of the CuSn10-C was characterised by high instabilities (spattering, violent explosions and burnings). Unaesthetic welds were obtained.

The welding of the CuAl-SiC, was the most stabile, even if porosity, spattering and variable melting were observed. The welds were relatively aesthetics.

In the case of the W-CU-Ni, the stability was the lowest one for all the tested regimes. The welds were anaesthetic.

The intensity of emission of the four gases for all three subjected composites is lower than the limits gave by the OSHA regulations.

An interesting result consists in the decreasing of the CO and of the NO when the heat input increased. That means that the measures for the productivity increasing will not lead to a important increasing of the intensity of emission.

Regarding the solid particles that are in the emitted fume, their dimensions are increasing from the initial value (before the sintering process) and up to about 250 nm, for the heat inputs that were used. The nanoparticles are organised in chains or in clusters, rarely being revealed as individuals.

As general technological recommendations that are applicable to all the three materials, it can be mentioned:

- 100–200°C preheating if the thickness of the materials is higher than 3 mm
- the value of the pulse time should be set higher than four but no higher than 14 ms; only W-Cu-Ni material accepts up to 18 ms pulse time.

References

‘Controlling welding fume, a total systems approach’ (2004), Available at http://www.lincolnelectric.com/knowledge/articles/content/fume1.asp.


