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Advanced materials joining using a hybrid ultrasonic-electric resistance technique

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The energy used during the joining process is a critical parameter in the case of joining new metallic materials as shape memory alloys. The use of ultrasonic welding process as a "cold" welding technology represents a valuable possibility to join these materials. However the resulting joint can be improved with hybrid techniques that locally use an additional form of welding energy, like electric resistance. The paper approaches the problem of hybrid welding of new materials like shape memory alloys (Cu, Fe and Ti-based) and biocompatible materials (TiAl6V4) in similar and dissimilar joints, potentially used in the fabrication of microsensors and for biomedical applications. Aspects related to the process parameters and the joints properties are presented with focus on the new hybrid welding technique.

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1. Introduction

Functional and multifunctional materials are considered nowadays for the development of new applications in a wide range of fields, such as mico-opto-electro-mechanical systems, bioengineering, etc. For this purpose, shape memory alloys and biocompatible materials are of high importance since they can offer several functions like: one way and two way shape memory effect, superelasticty, damping, magnetostriction and biocompatibility.

The properties of functional materials can be affected by a number of factors, among which the high temperature developed during conventional welding is a major one. For example, shape memory alloys are especially affected since most of their properties are associated with the diffusionless martensitic transformation which develops between a hard, high temperature austenite phase and a softer low temperature one – martensite. Such a phase transition can be thermally or magnetically controlled.

The issue of welding thermally-sensitive functional materials is a complex one because several functional phenomena sensible to the influence of structural factors can be superposed on specific welding phenomena. The energy used during welding can thus have a critical influence on the joint functionality. Most of the welding techniques are associated with heating at melting temperatures and thermal changes that affect the structure beyond the joint. Several techniques have been considered so far for welding shape memory alloys. Laser welding experimented for Ti joining [1,2] and applied to Ni-Ti alloys showed a 3.5 mm heat affected zone [3], where the pseudoelasticity was reduced [4]. Friction and electric resistance welding can also be a solution [5, 6], since functional properties can be preserved [7], while TIG welding [8] as well as brazing [9] have been tested in order assemble Ni-Ti alloys and resulted in diminished functional properties.

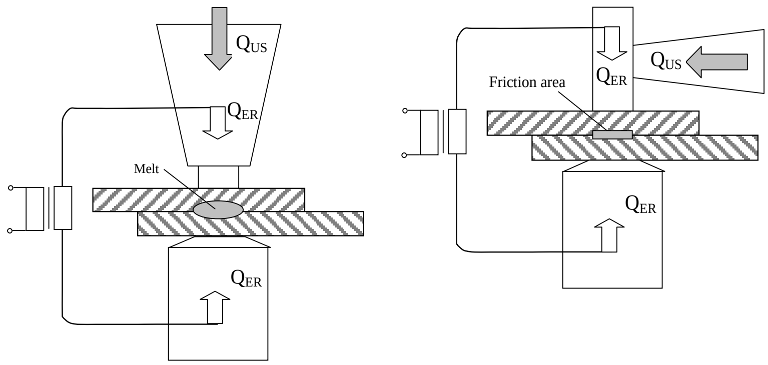
"Cold welding" techniques using ultrasonic energy are a current challenge especially for joining advanced materials such as shape memory alloys. The quality of the welded joint is not always very high, especially if the materials are thin [10], thus the procedure is under continuous investigations in order to define the welding compatibility as a function of structural and functional changes.

Hybrid techniques [11-13] use an additional form of energy, beside the main one, in order to activate the welding process, therefore leading to additional phenomenological aspects that could generate improved joints.

The paper deals with the complex aspects related to the use of a hybrid welding technique in order to improve the quality of the ultrasonically welded advanced materials, with focus on shape memory and biocompatible alloys, for which the functional properties can be significantly affected by compositional and structural changes.

2. Hybrid ultrasonic–electric resistance welding technique

The active combination of the ultrasonic welding (US) with the electric-resistance (ER) welding using resistive effect takes into account as main factors the yield stress a room temperature, and at the temperature on the joining interface, respectively; the welding energy, the hardness and the thickness of the welded material in contact with the sonotrode. An increase in the temperature leading to a reduction of the yield stress and of the hardness is a favoring factor for ultrasonic joining. Thus, by coupling two techniques, such as those based on electric resistance and ultrasonic energy, an improved hybrid technique can be developed in order to achieve an improved joining. The basic principles for two possible versions of the hybrid technique are described in Fig. 1.



a. Hybrid welding technique based on electric resistance (ER) with ultrasonic enhancement (US)

b. Hybrid welding technique based on ultrasonic (US) with electric resistance (ER) enhancement

Fig.1. Schematic principle of the two versions for hybrid welding using electric *resistance (Q_{ER}) and ultrasonic (Q_{US}) energy*

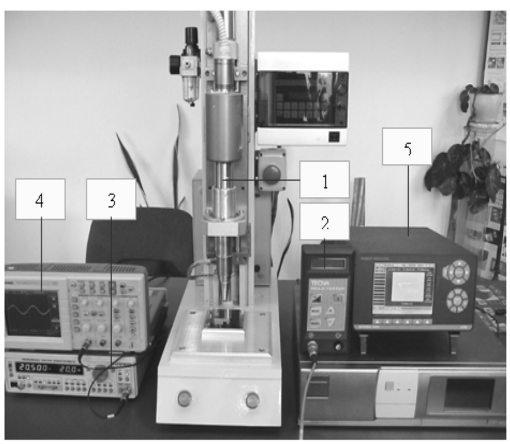


Fig 2. Specialized equipment for hybrid welding using electric resistance and ultrasonic energy.

Depending on the relative contribution of each type of welding energy, two main versions can be defined, based on the temperature developed during the joining process:

- for *higher welding temperatures*, the hybrid electric pressure and ultrasonic (H_{ER-US}) technique is characterized mainly by Joule effect, while the ultrasonic energy generates an extension of the welding spot diameter;

- for *lower welding temperatures*, the hybrid ultrasonic and electric pressure (H_{US+ER}) technique is characterized by ultrasonic energy, while the Joule effect favors a local increase of temperature. The melting temperature of the components is not reached during the welding process.

Depending on the amount of Q_{ER} and Q_{US} energy used for hybrid welding one could expect variations of the joint heat or thermomechanically affected zones, thus a wider range for selecting the welding parameters needed to preserve the functional properties of advanced materials, such as shape memory alloys.

3. Experimental details

The specialized hybrid welding equipment is based on an ultrasonic welding system for metallic materials interfaced with an electric resistance welding one and a programming module. The equipment used in the experiments, presented in Fig.2, has the following main parts: a specialized welding head (1), a current analyzer (2) for ER resistance welding, a signal generator (3), and oscilloscope (4) and an analyzer (5).

The parameters used for experiments were: 20kHz frequency, 2500 W ultrasonic power with a 3000 W piezoceramic converter and 35kVA electric power at 50% DA for the transformer.

A sonotrode with two active surfaces and computerized controller in order to provide the optimal experimental parameters detailed in Table 1 for Cu and Fe-based alloys has been used.

Table 1 Characteristic of the optimized sonotrode for copper and iron based shape memory alloys.

Material	Sound speed [m/s]	Sonotrode length [mm]	Resonance frequency [kHz]	Amplification factor	Maximum load MPa	Location of half-wave node [mm]	Dissipated power [W]
Cu –based aloys	4063	97	2,51	2,75	0,94	30,5	$1{,}9\ 10^{-4}$
Fe-based alloys	5334	146,9	2,0	2,51	3,16	65	$2{,}0\ 10^{-3}$

Several shape memory and biocompatible alloy, with the composition given in Table 2 have been used for experiments. The materials were used as bulk and melt-spun ribbons, respectively.

Table 2 Details about the materials used for experiments.

Composition	Cu	Zn	Al	Ni	Fe	Mn	Si	Ti	V	Type	Thickness
Cu-Zn-Al [mass %]	71.34	23.42	5.24	-	-	-	-	-	-	bulk	0.3 mm
Cu-Al-Ni [mass %]	83.04	-	13.11	3.85	-	-	-	-	-	bulk	2 mm
Fe-Mn-Si [mass %]	-	-	-	-	62	32	6	-	-	bulk	0.5 mm
Ti-Ni-Cu [at%]	25	-	-	25	-	-	-	50	-	ribbon	40 µm
Ti-Al-V [mass %]	-	-	6.25	-	0.18	-	-	89.77	3.8	bulk	1.5 mm

The experimental program has considered hard and soft welding regimes, for which the welding compatibility and results have been considered with respect to the parameters used and the materials particularities. The resulting joints have been analyzed by macroscopic and microscopic investigations in order to explore the integrity of the welding areas and the extent of the heat and thermomecanically affected zone.

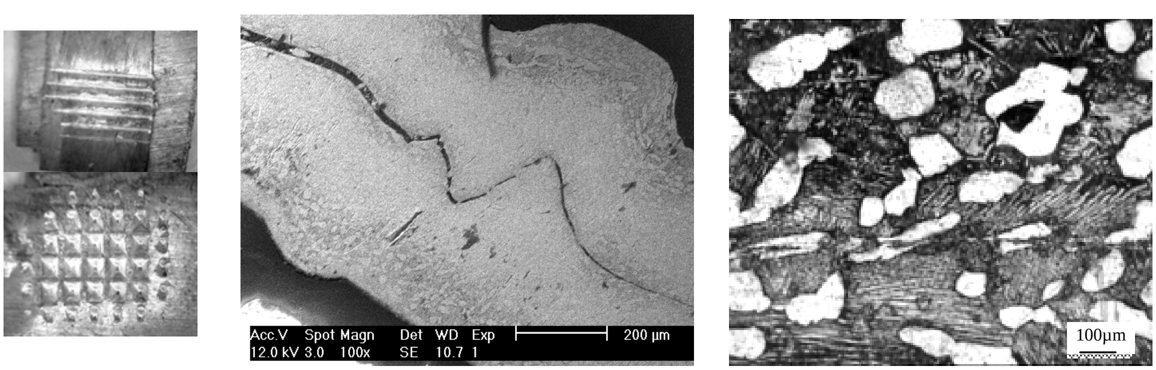
4. Results and discussion

The welding of Cu-Zn-Al and Cu-Al-Ni bulk alloys has been made using an ultrasonic (US) technique and a hybrid US-controlled welding process with ER enhancement ($H_{US\text{-}ER}$), respectively, with the parameters shown in Table 3.

Table 3. Parameters used for hybrid welding ($H_{US\text{-}ER}$) of Cu-Zn-Al and Cu-Al-Ni bulk alloys.

Welding time US/ ER	US Welding energy / ER Welding current[%]	Fw / Pn [N / bar]	Active surface [mm^2]
10 / 20	75 / 30	188 / 1,5	20

Massive deformations at surface (fig. 3a) are transmitted to the interface of copper-based shape memory (fig.3b) as results of the interactions controlled only by ultrasonic energy, while the contribution of the Joule effect favors a well defined welding interface (fig.3c), where typical martensite and precipitates resulting from diffusion are present.



a. surface imprint of sonotrode (top) and anvil (bottom)

b. interfacial deformation as result of US welding

c. hybrid welded interface

Fig. 3. Welded CuZnAl / CuZnAl joints.

Beside deformations and precipitations, no melting has been observed at the interface and the tensile unbuttoning tests showed a better behavior of the hybrid welded samples, compared to the US ones.

The microstructure of Fe-Mn-Si alloys is shown in Fig. 3, and the results for the experiments made on welding using ER and H_{US+ER} techniques, respectively, are shown in Figs. 4 and 5.

The ER welded samples show a thermomechanically affected zone (fig. 4 b), with a well defined imprint as a result of the pressure applied on the welding electrodes. The microstructural analysis of the heat affected zone shows a well defined area, where the structure is modified compared to the bulk one.

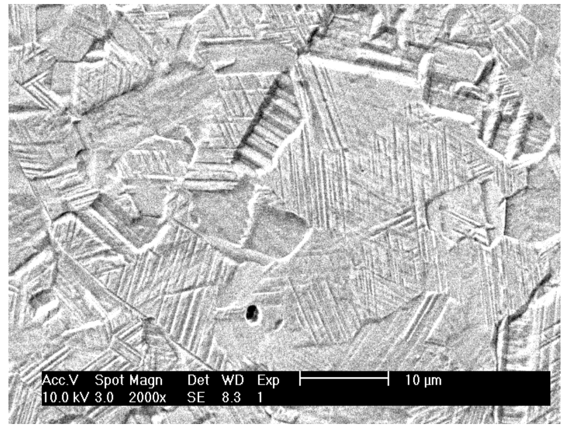
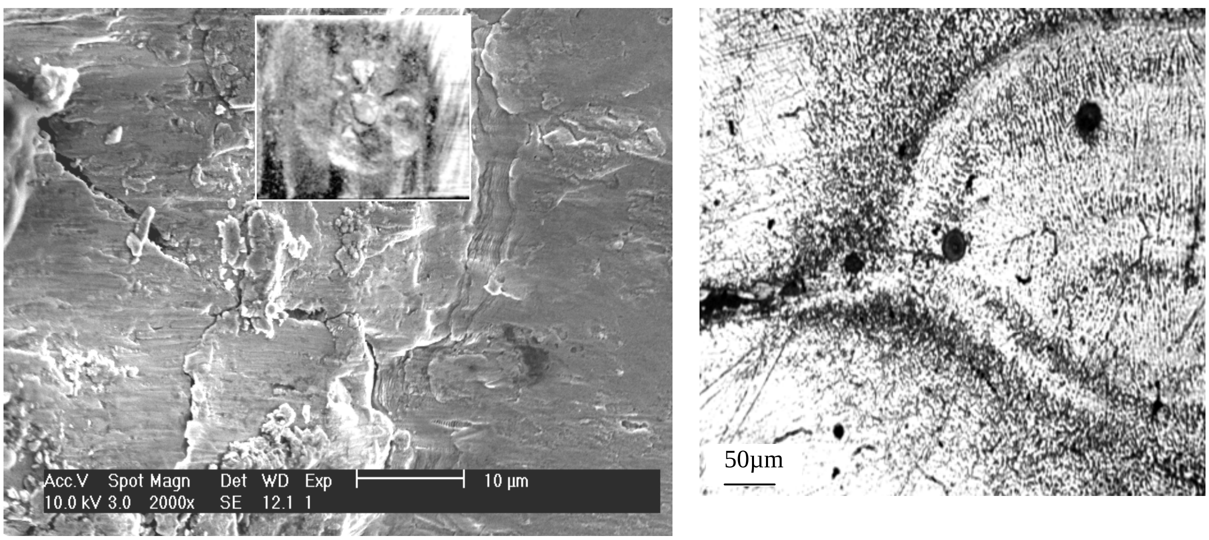


Fig.4. SEM showing typical martensitic structure in the Fe-Mn-Si sample.



a. ER surface imprint with macroscopic detail insert

b. Heat affected zone

Fig. 5. Details of the ER welded Fe-Mn-Si samples

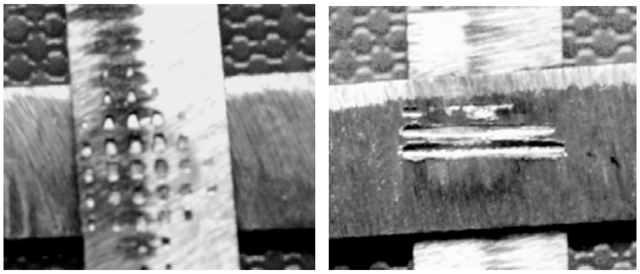
The hybrid welding experiments (H_{US-ER}) have been performed using the parameters detailed in Table 4.

Table 4. Parameters used for hybrid welding (H_{US-ER}) of Fe-Mn-Si shape memory alloys.

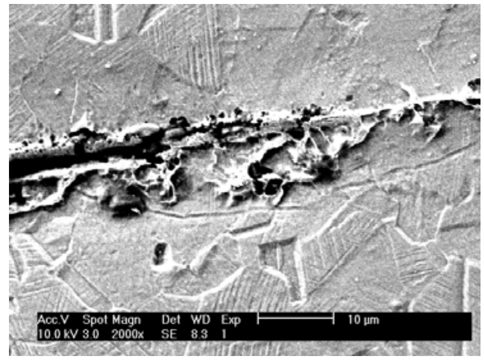
ER time / US time [ms]	ER current / US energy [%]	Fw / Pn [N / bar]	Active surface [mm^2]
10 / 20	48,5 / 75	300 / 1,95	20

The resulting joints show surface imprints from the sonotrode and the anvil of the US process, as well as clear marks of heating as result of ER.

The welded joints have been tested by specific tensile unbuttoning technique showing an increased resistance of the joint for the hybrid welded ones compared to the case where the ER preheating was not used.



a. sonotrode and anvil imprints and ER burns



b. microstructural details

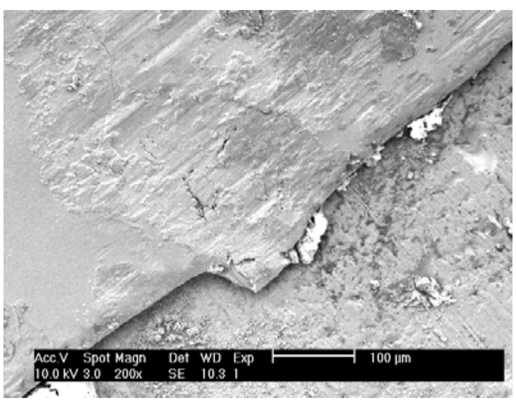
Fig. 6 Macro and microstructural details about hybrid welded (H_{US-ER}) Fe-Mn-Si samples

Hybrid welding of Ti-Ni-Cu shape memory alloy rapidly solidified ribbons to $TiAl_6V_4$ bulk alloy and to other Ti-Ni-Cu ribbons is a difficult task also and leads – as ultrasonic welding only – to significant deteriorations of the welded materials.

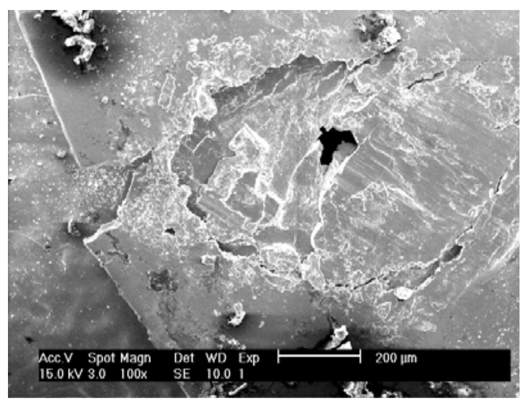
Deteriorations depending on the parameters used and the type of welding materials have been observed on the ribbons, due to their low thickness, as shown in fig. 7.

Table 5 Parameters used for hybrid welding of shape memory alloy ribbons to bulk $TiAl_6V_4$ alloys.

ER time / US time [ms]	US energy / ER curent [%]	Fw/ Pn [N / bar]	Active surface [mm^2]
12 / 25	65 / 30	100/ 0,65	20



a. $Ti_{50}Ni_{25}Cu_{25}$ ribbon welded on bulk $TiAl_6V_4$



b. $Ti_{50}Ni_{25}Cu_{25}$ ribbons welded together

Fig. 7 Ribbons deterioration as result of hybrid (H_{US-ER}) welding

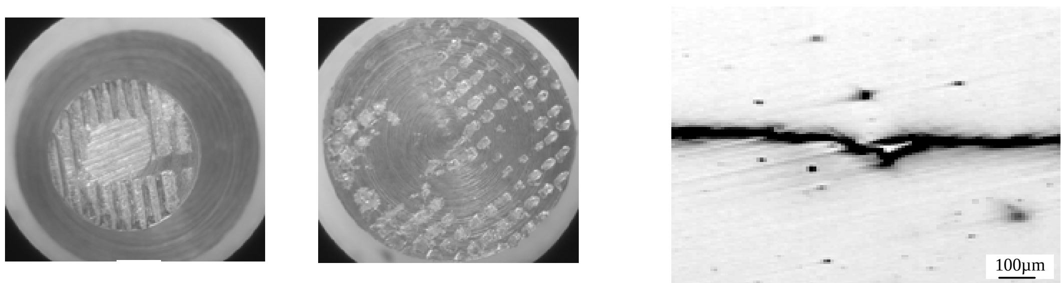
Imprints in the ribbons have been detected even for soft welding regimes and are localized in the ribbon (fig. 7a.) Massive deteriorations have been observed when the ribbons were welded together, because of the joint action of the sonotrode and anvil over a very low cumulated thickness (fig. 7b). Based on the experimental results it is considered that the hybrid technique is not recommended for welding shape memory alloy ribbons.

The hybrid technique has also been used to assemble bulk biocompatible alloys $TiAl_6V_4$, using two welding versions, with parameters detailed in Table 6, one US-based with ER (H_{US-ER}) enhancement and a ER –based with US enhancement (H_{ER-US}).

Table 10. Welding parameters used for two versions of hybrid welding.

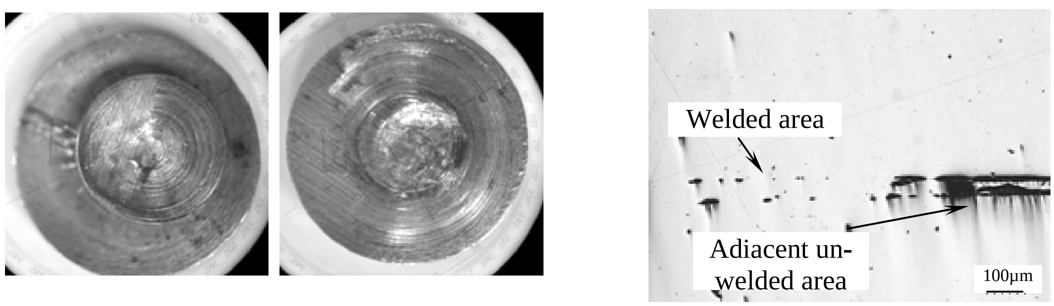
Hybrid version	ER time / US time [ms]	US energy / ER curent [%]	Fs / Pn [N / bar]	Active surface [mm^2]
H_{US-ER}	10 / 25	75 / 30	250 / 1,65	20
H_{ER-US}	20 / 5	75 / 30	300 / 1,95	7

The US-based hybrid welding does not generate the melting of the welded alloys, thus only friction between the abraded surfaces is the one that leads to welding. The surfaces of the bulk material show typical superficial imprints generated by anvil and sonotrode profiles (fig. 8a), while the resulting joint shows a weak bonding (fig. 8b), with separation at the interface.



a1. anvil and sonotrode imprints on the surfaces a2. separation of a weak joint

a. Ultrasonic-based welding



b1. electrode imprints on the surfaces b2. extended welded interface

b. Electric resistance wedling

Fig. 8 Comparative results for welding $TiAl_6V_4$

A much better welding joint is obtained for the ER-based hybrid technique. The surfaces of the joint materials show the marks from the electrode, but the joint is well defined as a result of melting the alloys, whereas the US effect was materialized in an enlargement of the melted area.

4. Conclusions

Functional materials behavior, such as shape memory alloys, can be frequently affected by thermal factors like the ones that develop during welding using conventional methods. Therefore, the need to develop methods that do not lead to the development of high temperatures in the welded materials is a priority.

Ultrasonic welding can be a potentially important method to assemble advanced functional materials with similar or dissimilar materials, since it does not lead to heating at elevated temperatures. On the other hand this process has limitations that can be surpassed by using additional energy, such as the one generated by electric resistance, thus leading to a hybrid solution. Depending on the relative amount of energy (ultrasonic and electric resistance respectively), one could develop a welding strategy to preserve the needed properties.

Bulk shape memory alloys show improved microstructural results when hybrid techniques are used, but the melt-spun ribbons are severely penetrated by the sonotrode and/or anvil in both ribbon-to-ribbon or ribbon-to-bulk alloy joints.

The extent of the heat affected zone in US controlled hybrid process ($H_{US\text{-}ER}$) is influenced by the electric resistance energy used, while the ultrasonic energy contribution is related to the extent of the melted bath in ER controlled hybrid ($H_{ER\text{ -}US}$) process.

Hybrid welding shows a high potential to be used in order to find the optimal parameters for welding advanced functional materials that are sensitive to heating, close to or above melting temperatures. The possibility to vary the ratio between the ultrasonic and electric resistance energies coupled with macro and microscopic observations is the main technological parameter that can be use to optimize the welding structural and functional outputs of the joint.

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