Shape Memory Effect in Diffusion Bonded Cu Base Shape Memory Alloys/Steel Interfaces

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ABSTRACT

In many applications, Cu base Shape Memory Alloys (SMA's) are a more economical alternative to other systems showing Shape Memory Effect (SME). However, bearing in mind the potential use of these SMA it is becoming increasingly important to develop suitable techniques to join them satisfactorily to themselves and to another material. In that sense, a liquid phase diffusion bonding process with silver/copper interlayers is proposed for bonding Cu base SMA's to the ASTM-1045 steel with semi-hard denomination. Specimens have been metallographically characterized by SEM. The bend strength of the bonded part is attained over 80% of that of the base materials. For checking the SME, the ratio of the total heat measured in forward to reverse thermoelastic martensitic transformation, measured by Differential Scanning Calorimetry (DSC), has been used.

1. INTRODUCTION

From every point of view, a joining technology of SMA's is indispensable to widen their range of engineering applications. In principle, Cu base SMA's can be welded, brazed, soldered or bonded. However, thermal effects on the weld and the heat affected or diffusion affected zones must be evaluated. Commonly, the weld is shape memory inactive due to, among other reasons, the change in chemical composition or the significantly different cooling processes. The SME may also decrease in the heat or diffusion affected areas because of decomposition or aging effects.

At present, scarce works have been done in relation to SMA's joining. Mostly, these works are related to Ni-Ti alloys, which suffer loss of SME very often due to the welding method (1) (2). However, a liquid phase diffusion bonding process has been recently proposed to joint Cu base SMA's which provided encouraging results (3) (4). This method resulted in sound joints and the SME of the bonded specimens was found after the bonding. On the basis of those previous works, a liquid phase diffusion bonding process is proposed to bonding Cu base SMA's to a steel in this study.

2. MATERIALS AND EXPERIMENTAL PROCEDURES.

2.1. Base materials.

Base materials used in this investigation were a Cu-Zn-Al (denominated M9) and a Cu-Al-Mn (denominated MN3) alloys whose chemical composition and transformation temperatures are given in Table I.

Table I Cu base SMA's composition

BASE MATERIAL	Cu % wt	Zn % wt	Al % wt	Mn % wt	Mf	Ms	As	Af
M9	68,96	27,30	3,74	-	-25	10	-13	20
MN3	81,92	-	11,46	6,62	-97	-48	-53	-22

The ASTM 1045 steel composition is shown in Table II. Ag and Cu foils were used as bonding interlayers. The specimens to be bonded were in the form of cylinders 10 mm diameter and 25 mm long. The surfaces were ground with 600 grade silicon carbide paper and to obtain an average roughness of $0,1 \mu\text{m}$. The ground surfaces were ultrasonically cleaned.

Table II ASTM 1045 steel composition.

%wt C	% wt Mn	% wt Si	% wt P	% wt S
0,45	0,55	0,22	0,04	0,04

2.2. Diffusion bonding conditions.

Diffusion bonding of Cu base SMA's to the ASTM-1045 steel was carried out in two stages. Firstly, the steel was solid state diffusion bonded to a copper interlayer. Then, the specimens obtained were liquid phase diffusion bonded to the SMA's using a Ag interlayer in another separately process.

The steel/Cu SMA's diffusion bonds were made in a vacuum environment of 10^{-3} Pa using constant temperature and bonding pressure (900 °C and 3,1 MPa) during 100 min. (Fig 1). On the other hand, specimens made at those conditions were diffusion bonded to SMA's at 775 °C without bonding pressure during 15 min in a vacuum of 10^{-1} Pa (Fig.2).

Fig.1 Diffusion bonding cycle used to obtain ASTM 1045/Cu joints.

The equipment used to produce the bonds was described in a previous paper (5).

Fig.2 Diffusion bonding cycle to obtain
ASTM 1045/Cu/Ag/SMA $\dot{s}$ joints.

2.3. Bend test procedure.

Bend test specimens were in the form of 50 mm long and 6 mm diameter with the bond line located just in the middle. Tests were carried out at room temperature in accordance with the standard UNI 5599 (6). Bend strength was determined for both ASTM 1045/Cu/ASTM 1045 and ASTM/Cu/Ag/SMA $\dot{s}$ joints.

2.4. DSC test.

Transformation temperatures were measured using a DSC. The samples for DSC were prepared by cutting specimens of 30-35 mg. They were ground with 600 grade silicon carbide and heat treated at 850 °C for 10 minutes and quenched in water at room temperature. The heating and cooling rates were 10 °C/s and the range of temperature measurement was - 100 to + 100 °C.

3. RESULTS AND DISCUSSION.

3.1 Microstructure of diffusion-bonded joints.

Figure 3 shows a cross-sectional view of a macrostructure of the bonded specimens in which two bonding interfaces can be distinguished: ASTM 1045 steel/Cu and Cu/SMA $\dot{s}$. Unreacted Cu can be also observed.

Iron oxides (FeO and Fe_3O_4) and Fe in Cu solid solution were detected in the Cu matrix close to the ASTM 1045/Cu interface; Cu in Fe solid solution was detected in Fe- α matrix. Besides, an enrichment in α phase belonging to the SMA $\dot{s}$ system was produced due to Cu diffusion from the Cu interlayer.

Obviously, this microstructure changes dramatically when the samples were subjected to the previous heat treatment to the DSC measurements. After that, martensitic transformation is induced both in steel and SMA $\dot{s}$ (Fig.4 and Fig.5).

Fig. 3 Cross-sectional view of the bonded specimens

However, a non transformed zone close to the Cu interlayer was observed. This zone correspond to that occupied by the α phase belonging to the SMA's system and will be shape memory inactive.

Fig.4 Martensitic microstructure in the steel

Fig.5 Martensitic microstructure in the SMA

3.2 Result of the bend test

Bend strength results are collected in Table III. Bend strength of ASTM 1045/Cu/ASTM 1045 was always higher than that belonging to the ASTM/Cu/Ag/SMA joint before and after the heat treatment.

Table. III Bend strength of the bonded joints

Type of joint	Bend strength (MPa)
As bonded ASTM 1045/Cu/ASTM joint.	650
As bonded ASTM/Cu/Ag/M9 joint	425
As bonded ASTM/Cu/Ag/MN3 joint	360
Heat treated ASTM 1045/Cu/ASTM joint.	550
Heat treated ASTM/Cu/Ag/M9 joint	375
Heat treated ASTM/Cu/Ag/MN3 joint	175

This behaviour is because of the liquid phase diffusion bonding process was carried out at lower vacuum an a certain oxidation was detected in the unreacted Cu/Ag interface. The adverse effect of this oxidation was in some cases improved by the porosity located in the bonding interface which appears as a consequence of the diffusivity process that take place.

On the other hand, bend strength of as bonded specimens is always higher than the strength of the heat treated specimens. This fact is related to the grain growth which promotes the mechanical deterioration. The grain growth is much higher in MN3 alloy and therefore its decrease in bend strength is also higher.

3.3 Evaluation of SME in diffusion bonds

The DSC records for bonded specimens appear in the Fig.6 and Fig.7.

The latent heat measured in a forward (Q_M) and a reverse (Q_A) thermoelastic transformation induced by temperature are directly related to the SME due to martensitic transformation. If it is assumed that frictional energy is the same in both direct and reverse transformation and that the elastic enthalpy values are far low in relation to chemical contributions to the free energy change, the ratio martensitic/reverse transformation latent heats could be considered like a index of the SME (7). Q_M , Q_A , the Q_M/Q_A index and the transformation temperatures of the base material and bonded samples are collected in the Table

Fig. 6 ASTM 1045/Cu/Ag/M9 DSC record

Fig. 7 ASTM/Cu/Ag/MN3 DSC record

IV. The index is 1 for the ASTM 1045/M9 and 1,1 for the ASTM 1045/MN3 bonded specimens and 1,4 for both base materials. These values give a SME in bonded samples of 70 and 80 % respectively of that of the base material. It is necessary to note that the values corresponding to bonded specimens belong to a zone located approximately 0,3 mm away from the bonding line which is just in the interface between the α phase of the SMA δ system and the martensitic of these materials. Therefore, the damage on the SME is due to the enrichment of Cu from the interlayer and probably by the permanent deformation induced on the samples as a consequence of the pressure applied during the bonding process. On the other hand, this memory loss result in a widen of the hysteresis transformation temperature cycle. This hysteresis cycle is wider in the ASTM 1045/M9 than in the ASTM 1045/MN3 samples.

Table IV. Data obtained from DSC measurements.

SAMPLE	Q_M (J/mol)	Q_A (J/mol)	Q_M/Q_A	Mf (°C)	Ms (°C)	As (°C)	Af (°C)
M9	$282,4 \pm 0,1$	$204,3 \pm 0,1$	1,4	-25	10	-13	20
MN3	$245,5 \pm 0,1$	$175,3 \pm 0,1$	1,4	-97	-48	-53	-22
ASTM 1045/M9	$360,5 \pm 0,1$	$354,5 \pm 0,1$	1	-15	12	15	54
ASTM 1045/MN3	$338,2 \pm 0,1$	$316,4 \pm 0,1$	1,1	-81	-40	-47	-8

4. CONCLUSIONS

Diffusion bonding of two Cu base SMA's to the ASTM-1045 steel was carried out in two stages. Firstly, the steel was solid state diffusion bonded to a copper interlayer. Then, the specimens obtained were liquid phase diffusion bonded to the SMA's using a Ag interlayer in another process apart. The following conclusions can be deduced:

1. The viability of the process proposed has been proved by metallographic, mechanical and calorimetric tests.
2. The bend strength of the ASTM 1045/Cu joints is always higher than that belonging to the ASTM/Cu/Ag/SMA's joints, due to the oxidation produced in the Cu/Ag interface as a consequence of the vacuum environment and because the presence of porosity. Heat treated specimens show a lower bend strength due to the grain growth.
3. 80% and 70% SME recoveries for ASTM 1045/MN3 and ASTM 1045/M9, respectively, were obtained for a distance of 0,3 mm away from the bonding line.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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