Joining processes for shape memory alloys – A review

R. M. Miranda[1], L. Alberty Vieira[1], F. M. Braz Fernandes[2], L. Quintino[3]
[1] UNIDEMI, Departamento de Engenharia Mecânica e Industrial, Faculdade de Cięncias e Tecnologia,
FCT, Universidade Nova de Lisboa, Portugal
[2] CENIMAT/I3N, Faculdade de Cięncias e Tecnologia, FCT, Universidade Nova de Lisboa, Portugal
[3] IDMEC, Instituto Superior Técnico, TULISBON, Lisboa, Portugal
e-mail: rmiranda@fct.unl.pt

Keywords

Shape memory alloys; welding; friction welding, TIG, ultrasonic, laser, plasma, laser brazing

1. Shape memory alloys

Shape Memory Alloys (SMAs) are advanced functional materials due to their particular properties such as shape memory effect and pseudoelasticity, including superelastic effect. They are also known as smart materials since they can "remember" their original shape after being deformed or heated and thus, can act as sensors and/or actuators.

Although applied since the 1970's, some difficulties related to processing, particularly joining, must still be overcome, so that they can reach their full potential [1-5]. As a consequence of several R&D projects, Shape Memory Alloys are being used with increasing success in a number of industrial fields, namely: automotive, aeronautical, biomedical and other high added value applications. Nowadays, new challenges for SMAs come from aerospace and energy industries, for actuators in tough applications involving high temperature and hostile environments.

SMAs are usually classified according to their chemical composition in three major groups: NiTi, Cu-based and Fe-based.

NiTi is known for its shape memory effect (SME) and superelasticity. Due to its high resistance to corrosion and biocompatibility, it has been used in biomedical applications with great success. The addition of Cu reduces the hysteresis response, the transformation strain, the pseudoelastic hysteresis and the sensitivity of martensite finish temperature Ms to composition so they find applications in high force actuators, with copper contents between 5 and 10%. [6].

The Cu-based SMAs (CuZnAl and CuAlNi) are less expensive than Ni-Ti based alloys and also show less hysteresis and transformation temperatures highly dependent on the composition. They are an alternative when good electrical and thermal conductivity are required, as well as good formability.

Iron-based shape memory alloys have recently attracted much attention mainly due to its high mechanical strength and good formability at low cost. Despite the advantages, these alloys have limited functional properties. Shape memory effect can only be observed after thermomechanical training, involving several cycles of deformation and annealing under tension [7, 8].

2. Functional properties of SMAs

A Martensitic transformation is responsible for the shape memory effect (SME) and Superelastic Effect (SE) of SMAs. When deforming a SMA, shearing of the crystal structure is observed, that is a reversible phase transformation austenite ó martensite. The martensitic transformation may occur only by temperature change, in the absence of stress but no diffusion is observed, thus highly dependence on chemical composition.

Special properties of SMA's include shape memory effect and pseudoelasticity. Shape memory effect is a functional property that can be present as one-way or two-way shape memory effect. The former is observed when a shape memory alloy is below austenite start temperature (As) and the alloy is deformed (bent, stretched, twisted) keeping this shape till heated above transition temperature. Upon heating, original shape is restored. If temperature decreases it keeps the high temperature shape until it is deformed. Figure 1 shows a schema of this effect and Figure 2 the phase transformation diagram.

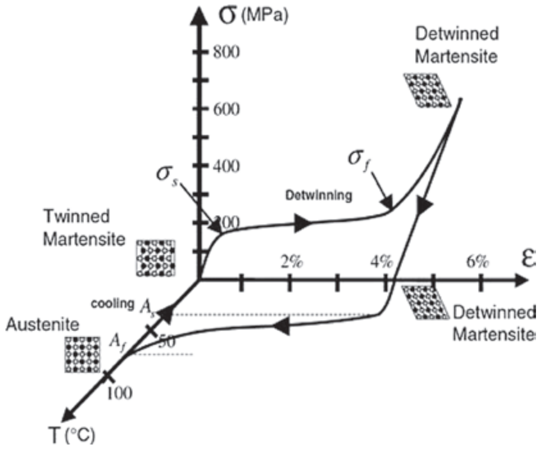

Figure 1. Scheme of the shape memory effect [6]

In the two-way shape memory effect, the material remembers both different shapes: one at low and the other at high temperature. This effect is attained by thermomechanical training, which needs to assure repeatable behavior under cyclic thermal loads for some particular applications. As a consequence, for a given SMA just two states are clearly shown: one at low temperature and the other at high temperature, with associated different shapes. This behavior, the two-way shape memory effect, is not a standard feature of commercial SMAs and is achieved after a training process that consists of applying a large number of repeated thermomechanical cycles, along a specific path. This training process causes changes in the microstructure to a desirable macroscopic behavior, achieved by material's hysteretic response stabilization, due to no additional accumulation of inelastic strain, after a given number of cycles.

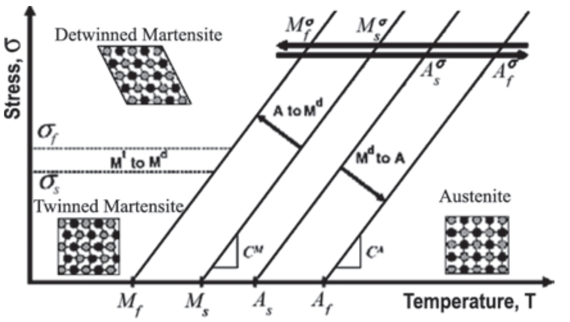

Figure 2. Phase transformation diagram [6]

In fact the two-way shape memory effect is a consequence of creating an internal residual stress state that privileges particular variants during the martensitic transformation. As a consequence of such dependence, any change in the internal stress state will cause detraining (overloading, for example), which is known as 'amnesia'. A training process for a NiTi SMA wire at constant stress under thermal cycling loading is shown in Figure 3.

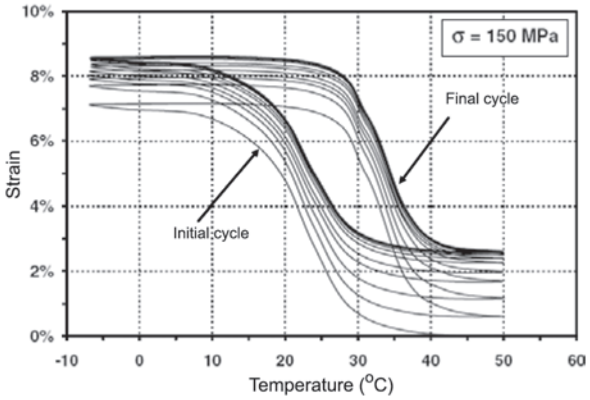

Figure 3. Training a NiTi SMA [6]

Pseudoelasticity aims a functional property, superelasticity or superelastic effect. Shape memory effect is observed on SMAs, either austenitic or martensitic at room temperature. However superelasticity, based on stress-induced transformation, is only attainable starting from the parent phase.

Considering Figure 2, it can be observed that, for a constant temperature in the parent-phase, it is possible to accomplish the martensitic transformation just by applying a mechanical load high enough to overcome the martensitic finish transformation stress, at that temperature. The result of such load is stress-induced detwinned martensite with shape modification. This path is schematically presented in figure 4.

Being the thermoelastic martensitic transformation a reversible process, if the stress level is lowered below $\sigma_{A_f}\big|_T$ by relieving the applied load, the reverse transformation occurs due to thermodynamic destabilization of martensite and the original parent phase shape is recovered. The behavior described above is known as superelasticity, or simply as superelastic effect. This effect can be represented in a stress-strain diagram as shown in Figure 1, in which it's possible to identify a hysteresis behavior. The upper plateau occurs during the stress-induced martensitic transformation and the lower during the reverse transformation, when unloading.

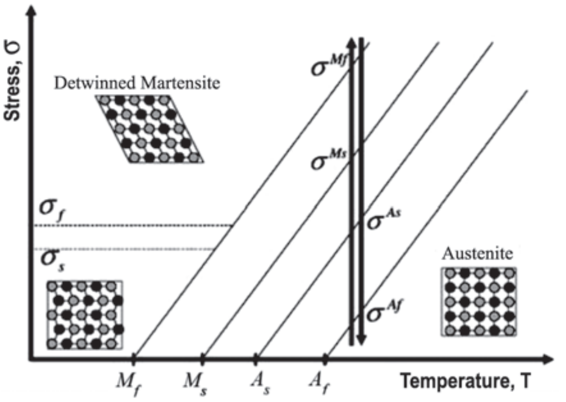

Figure 4. Superelastic effect [6]

3. Applications of SMAs

Shape memory alloys find applications over a wide range of industries though confined to high added value markets in fast growing. The main reason is a lack of engineering techniques outside those markets, due to technical difficulties in scaling up techniques and materials, as well as, due to the difficulty of immediate visible benefits. However, the list of applications of SMAs has increased enormously during the last decade, which resulted in production increase and cost decrease. NiTi is by far the most applied SMA since it exhibits some of the most useful characteristics in terms of its active temperature range, hysteretic performance, recoverable strain and relatively simple thermal processing.

Automotive industry

Although not visible, nowadays automotive industry largely applies SMAs in a variety of components and mechanisms actuated by SMAs, as depicted in Figure 5. It is by far the biggest consumer of SMAs. A curious and simple engineering solution was developed to adjust the clearance of taper roller bearings using SMAs and their extrinsic two-way effect ('fake' two-way effect). Bearings technology demand constant axial play and constant pre-loads, but thermal expansions between the inner and outer rings usually lead to a loss of pre-load or decreasing of axial play, leading to bearing

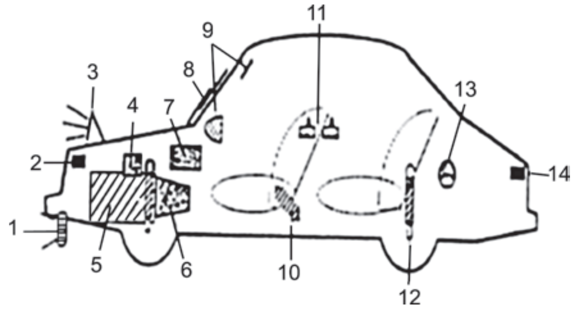

Figure **5.** Automotive application of SMAs
1 – bumper protection; 2 – latch; 3 – headlights lifter;
4 – carburettor regulator; 5 – engine control;
6 – transmission gearbox regulator; 7 – vent regulator;
8 – windscreen pressure control; 9 – mirror adjustment;
10 – tilt tuner; 11 – central latch; 12 – adjustable
suspension; 13 – safety lock; 14 – luggage latch

failure. The solution developed aims at the bearing adjustment by axial movement, clamped between steel springs and NiTi specially trained elements. Another component that works on the same principles uses the shape memory effect to actuate a temperature dependent fluid valve.

Aerospace applications

Aerospace industry is well known for demanding state of the art materials and technologies. Shape memory alloys are already employed with great success in specific demanding applications. They are used to create shrink-to-fit Nitinol metal couplings to join the hydraulic tubing of the F14 fight aircraft, which is made of titanium alloys and present poor weldability (figure 6). Efforts are being made in the aerospace industry to implement SMAs in a large scale, with special interest in adaptive serrated nozzles for aero-engines that reduce noise pollution [10,11]. Boeing, General Electric Aircraft Engines, Goodrich Corporation, NASA and All Nippon Airways (ANA) developed a variable geometry chevron for jet noise reduction using SMAs (figure 7). Smart materials lead to new design concepts, allowing fully integrated and distributed actuation by means of simple mechanisms that do not add weight.

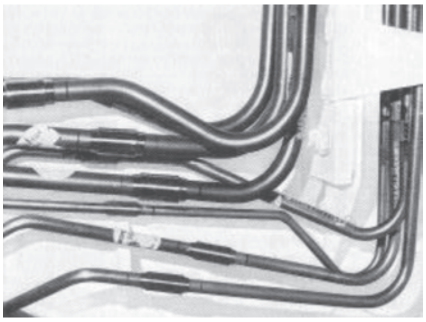

Figure 6. F14 aircraft hydraulic tubing with shrink-to-fit NiTi memory metal couplings - Cryofit®

Figure 7. Commercial aircraft aero-engine showing adaptive serrated nozzle actuated by SMAs (on top)

Other applications are under studied, as the unique-body aircraft wing, without servo mechanisms including moving parts, only actuated by Nitinol wires introduced to create a highly flexible structure that is adjustable by remote current control. Made of a single continuous body, it reduces problems like the separation of the boundary layer. SMAs that resist to high temperatures like NiTi(Hf), NiTi(Nb), NiAl and Fe-based systems are also under extensive research.

Biomedical applications

The interest of the Biomedical community on NiTi relies on its unique combination of shape memory effect, superelasticity and good biocompatibility, to fulfill applications as for invasive surgical applications, amongst others. In this field, there is a need for joining technologies as laser welding to produce components in a micro scale [12].

Some successful applications reported are: endovascular stents to expand blocked conduits in the human body introduced in a small and deformed shape that expands to an appropriate one in place; vena-cava filters used in one of the outer heart chambers to trap blood clots introduced in a compact cylindrical form about 2.2 mm in diameter that in place is released to an umbrella shape; Nitinol strips to apply gentle outward pressure to small incisions to access the heart [13].

Applications of NiTi in orthodontics are still very promising. Combining NiTi with other non-smart materials allows obtaining selective components able to control the force applied on each teeth, resulting in a very effective therapy. The interest of joining different materials, eg SMAs and biocompatible stainless steels exists for biomedical applications.

Civil construction applications

Nowadays Civil Engineers recognize the needs of functionality and load carrying under static conditions to design and build civil structures. The increasing demand of highly adaptive structures reveals the great potential of SMAs to enhance them. Pre-existing and new applications are being developed in field of civil engineering for damping, active vibration control and prestressing or posttensioning of structures with fibers and tendons. Regarding these fields, according to Janke et al [14], Fe-based SMAs are pointed as potential low cost alloys, in order to enhance viability in future applications.

4. Joining SMAs

The poor workability of SMAs by conventional machining processes and their increasing application demands suitable joining techniques in order to obtain complex components [15,16]. In the last two decades the number of experiments reported in literature concerning welding joining techniques of shape memory alloys has increased significantly. Traditional welding processes were mainly tested, but the increasing requirements to perform specific tasks lead to the employment of state of the art technologies, like laser welding, with promising results.

Welding SMAs is a challenge when compared to conventional welding techniques performed on steels or other well known alloys. Unlike those materials, SMA's response, mechanical properties and corrosion resistance are strongly dependent on chemical composition, microstructure and transformation temperatures between the base material and the joint region.

Dissimilar metal welds are in many aspects different from similar ones. Base material thermo-physical properties are usually different, leading to different heat transfer. During the process, composition varies across the weld pool, and it is not clear the interface between solid-liquid phases. Intermetallic compounds are formed and convection processes occur, like Marangoni effects, since base metal densities vary significantly. First studies on dissimilar weld of Ti and Ni conclude that results are strongly limited by the formation of brittle intermetallics that lead to cracking. Some detailed studies about the solidification mechanism were conducted [17,18] reporting the microstructural evolution in the fusion zone of a dissimilar NiTi weld. Embrittlement occurs mainly due to high temperatures reaction of elements such as oxygen, nitrogen and hydrogen. Brittle intermetallics like Ti_2Ni and $TiNi_3$ can also precipitate during solidification, having adverse effects on strength and shape memory characteristics. In order to fulfill specific needs of medical industry, welding experiments on dissimilar joints like NiTi/stainless steel or Hastealloys were performed. In the aerospace industry new parts like gas turbine nozzles are being tested using NiTi and Ti-6Al-4V, previously joined by fasteners [15].

4.1. Friction welding and resistance butt-welding

Friction welding, is a solid state welding process that prevents high temperature exposure with grain growth and oxidization, so good mechanical properties can be achieved. However, when using this method heat treatments are needed after welding, in order to minimize the variation of transformation temperatures between the welds and the base metal.

First tests on resistance butt welding were performed on thin wires of Ti-50 at % Ni, welded without fusion [19] consisted of feeding the welded parts with a welding current of 385-600 A during a short period of time, while applying a constant force between 50 and 200 N. The axial force during process closes possible grain boundary cracks, as well as oxidization is prevented by extrusion of the fusion zone. The shape memory effect of the welded part remained the same, and the tensile strength was about 80% of the base material. However butt-weld joints require some work to trim extrusions and complex geometries are not allowed.

4.2. Tungsten inert gas – TIG

This welding technique usually causes an extended heat affected zone (HAZ), due to heat input delivered during the process. However, Qiao et al [20] investigated the microstructure of the HAZ using scanning electron microscopy (SEM) and X-ray diffraction the microstructure of an Iron-based SMA (Fe-Mn-Si-Cr-Ni), and showed there was no obvious change. The effect of welding on shape recovery was also examined by bending tests concluding that the weld exhibited almost the shape memory effect as the base material.

4.3. Ultrasonic welding

When joining SMAs the main key to success is basically to keep temperature low to minimize changes in the base material. Ultrasonic welding is a simple and promising technique that allows to control with great precision temperature peaks around the welding spots. Budau et al [21] tested ultrasonic welding on bulk and ribbons made out of SMAs (Cu-Zn-Al and Ti-Ni-Cu), with similar and dissimilar materials, concluding that macrostructurally the welds are feasible. Microstructural observations showed a good interface for bulk joints.

4.4. Plasma welding

Experiments with plasma welding of NiTi SMAs on similar and dissimilar joins were reported by Eijk et al [22] in 2003 and concluded that the welding process did not affect the Ni/Ti ratio in the weld, on similar NiTi joints. However, the phase transformation temperatures changed, while the mechanical properties degraded. This study also revealed extreme difficulty to weld dissimilar joints of NiTi to stainless steel, due to brittle phase formation close to the fusion line, as NiTi tends to absorb elements from the steel.

4.5. Laser welding

Laser welding has been extensively studied by several R&D groups due to its particular characteristics, namely very low heat input and high precision. Both CO_2 and Nd:YAG lasers have been searched to join SMAs, specially NiTi, and the effect of weld thermal cycle on shape memory properties, superelastic and mechanical behavior, as well as, on corrosion.[23] Although both lasers can weld NiTi, more significant effects on mechanical resistance and functional properties are observed in CO_2 welded joints, while Nd:YAG laser welded joints preserve good tensile strength and functional properties [24-27].

4.5.1. Effects on functional properties

The mechanical behavior of a Nd:YAG laser welded Ni-rich TiNi SMA (Ti-51.5 at % Ni) was studied [24] by performing tests on metal sheets 0,5 mm thick and observed pronounced stress plateaus upon loading up to strains of about 6%, similar to the base material on laser-welded Ni-rich SMAs. Both austenitic and martensitic conditions were confirmed at the expected temperatures.

The effect of Nd:YAG laser welding on the functional properties of Ni-49,6 at % Ti SMA was evaluated [26] and reported that the original shape memory effect was preserved. However, tensile tests revealed ultimate tensile stresses lower than those observed in the base material and narrower superelastic windows.

Falvo et al [24, 25] evaluated the mechanical and shape memory behavior of laser welded NiTi alloys, and concluded that the shape memory effect of NiTi laser-welded wires is preserved for low strains (about 2,7%), while when increasing the total strain (about 6,2%) the behavior becomes different and the shape memory effect is affected by welding. Performance was reduced, so the joints were not suitable for smart components under large tensile stress, requiring large strain recovery, however, these welds could be used in lighter applications at lower stress levels, requiring lower strain recovery. The welding process, acting as a heat treatment, affected the stress-strain response, reducing the effects of cold working and evidencing the characteristic stress-plateaus. Results showed that the process is a suitable joining technique for NiTi smart actuators, despite the observed reduction in the overall performance.

4.5.2. Effects on mechanical resistance

Generally welding effects on SMAs lower the ultimate tensile stress when working on Ni-49.6 at % Ti SMAs [26]. Tensile tests on welded material revealed lower E modules and smooth transition between the elastic part of the curve and the lower stress-plateau. The explanation presented by the authors is that probably stress is accommodated by slip into the HAZ before reaching σ^s (twinned martensite to detwinned martensite). The same work revealed lower permanent deformation values for welded material, after free recovery. This may be due to defects introduced by the welds and dislocations induced in the HAZ during loading.

Falvo et al [24] also concluded a significant decrease in the mechanical strength of joints, compared to the base material. Ultimate strength decreased about 52,7%, while elongation to fracture was reduced about 41,6%. Results showed a clear embrittlement due to the process; however, the authors concluded that, in the overall, a ductile behavior was present since elongations to fracture was of about 7%. The same work confirmed a clear reduction of martensitic stress-plateau has a consequence of slip in the HAZ.

Fatigue life of heat treated laser-welded NiTi SMAs has also been evaluated [27,28] for wire shape on rotating-bending tests. Results revealed that annealing at 400°C for 1h can improve the fatigue resistance, however if annealed at 500°C during the same time, resistance decreases. That study also associated the size of Ti_3Ni_4 precipitates to fatigue resistance, which decreases when precipitates coarsen, so that heat treatments to produce smaller coherent precipitates may be used improving results.

4.5.3. Ni-Ti dissimilar laser joints

Recent microstructural investigations of Nd:YAG laser welded dissimilar NiTi/AISI 304 stainless steel joints were performed [29]. Dissimilar joints of NiTi SMAs, in particular with steels are combinations that allow wider fields of applications. So, a detailed investigation on weld properties is essential to improve weld quality. A major problem occurs when welding by fusion NiTi to a iron-based alloy, that is the formation of oxides and brittle intermetallic phases as FeTi and Fe_2Ti that lead to cracks, generally on the NiTi side of the joint.

Gugel and Theisen [30] observed epitaxial growth of grains in NiTi/AISI 304 stainless steel joints, as well as fusion and heat-affected zone on the NiTi side (Figure 8). According to XRD, EBSD, and TEM diffraction a predominant B2 structure (austenitic structure) was found in the fusion zone. Also round shaped oxycarbides and TiC carbides were found in the same zone. No heat-affected zone on the steel side was detected (Figure 8), where rich Fe_2Ti microstructure was observed (Figure 9), as the grain size is much smaller compared to the center of the fusion zone.

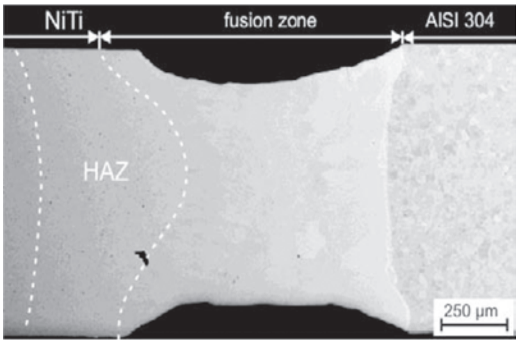

Figure 8. NiTi/AISI 304 joint [30]

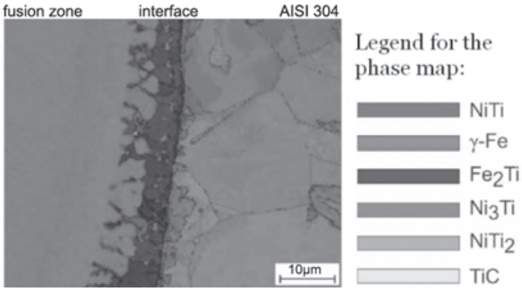

Figure 9. Interface FZ/AISI 304 [30]

Segregation of Ni, Cr and Fe occurred in the interdendritic regions, due to primary solidification of NiTi and successive reduction of Ti by precipitation of carbides, leading to inter-dendritic regions rich in TiC.

X-Ray diffraction revealed a major B2 structure (austenitic) on the Ni-Ti side and fusion zone. Measurements made on the austenitic steel side only confirmed the presence of the steel structure. Electron backscatter diffraction revealed small equiaxed grains of about 20 μm in the HAZ, smaller that those present in the base material, of about 30 μm. In the fusion zone massive grain growth was observed, while the grain structure of the austenitic steel was only slightly influenced. Additionally, by shifting the laser spot position a crack and pore free joint was obtained.

4.6. Laser brazing

Brazing is an especially interesting joining technique when base materials present poor weldability by other methods. In SMA's context, preliminary studies revealed promising results on NiTi to stainless steel dissimilar laser brazed joints. Qiu et al [31] developed experiments on lightly Ti-rich NiTi to austenitic stainless steel dissimilar joints, brazed with an Ag-based alloy. Results revealed a strong relation between heat input and joints mechanical resistance, as well as a superelasticity loss in the NiTi HAZ, which directly depends of heat input. A significant influence of laser brazing parameters on joint behavior was also confirmed when evaluating the properties of laser-brazed NiTis to SS orthodontic wires. The inverse dependence between heat input and preservation of functional properties on NiTi HAZ was again reinforced, as a strong reduction in microhardness measures in the FZ was also observed for higher inputs. An increase in joint tensile strength was observed for higher powers; however shape recovery ratios decreased very significantly. Overall laser brazing is suitable technique for SMAs, however satisfactory joint properties are highly dependent of selecting proper brazing parameters.

5. Conclusions

Shape Memory Alloys (SMA) are advanced functional materials exhibiting a shape memory effect and super elastic behaviour due to the characteristics of the martensitic transformation.

Since the 60´s they have been intensively investigated and several SMAs are known based on binary or ternary systems involving Ni-Ti, Copper or Iron. The ability to be trained in so called two-way shape memory effect is relevant from an industrial perspective requiring repeatability behaviour under cyclic thermal loads.

Welding these alloys, in both similar and dissimilar joints, could enhance applications in a broad range of industrial sectors. Several joining and welding processes have been investigated. Amongst the studied welding processes, Nd/YAG laser welding proved to be effective for ductile superelastic alloys as NiTi. However, a reduction in mechanical strength is observed that hinders more demanding applications. The alloying elements volatilization or combination in brittle phases reduces or even prevents the martensitic transformation responsible for the peculiar behaviour of SMAs.

Dissimilar welding of SMAs to other materials, as high grade stainless steels, was seen to produce brittle phases due to the high affinity of Ti to Fe in steel.

Acknowledgements:

The authors would like to acknowledge the funding of FCT/ MCTES for the project "Joining micro to small scale systems in shape memory alloys using last generation infrared lasers" (PTDC/EME-TME/100990/2008). FMBF acknowledges the plurianual funding of CENIMAT/I3N by FCT/MCTES and from the project SMART COMPOSITES (PDTC/CTM/66380/2006).

References

[1] Otsuka, K., Wayman, C.M., Shape Memory Materials, ed. Cambridge University Press, Cambridge, 1998.

[2] Chang, L.C., Atomic Displacements and Crystallographic Mechanism in Diffusionless Transformation of Gold-Cadmiun Single Crystals containing 47,5 atomic percent Cadmium, Acta Crystallographica ,Vol. 4 (1951), p. 320-324.

[3] Chang, L.C., Read, T.A., Plastic deformation and diffusionless phase changes in metals – The Gold-Cadmium beta phase, AIME Transactions, Vol. 191 (1951), p. 47-52.

[4] Chang, L.C., Read, T.A., Wechsler, M.S., Reversible single-crystal rocking-curve broadening, Acta Crystallographica, Vol. 6 (1953), p. 567.

[5] Buehler, W.J., Gilfrich, J.V, Wiley, R.C., Effect of Low-Temperature Phase Changes on the Mechanical Properties of Alloys near Composition TiNi, Journal of Applied Physics, Vol. 34 (1963), p. 1475-1477.

[6] Lagoudas, D.C., Shape Memory Alloys: Modeling and Engineering Applications, ed. Springer, USA 2008.

[7] Bouraoui, T., Jemal, F., Tensile Properties of a Fe-32Mn-6Si Shape Memory Alloy, Strength of Materials, Vol. 40, No. 2 (2008), p. 203-211.

[8] Stanford, N., Dunne, D.P., Effect of NbC and TiC precipitation on shape memory in an iron-based alloy, Journal of Materials Science, Vol.41 (2006), p. 4883-4891.

[9] Predki, W., Knopik, A., Bauer, B., Engineering applications of NiTi shape memory alloys, Materials Science and Engineering A, Vols. 481-482 (2008), p. 598-601.

[10] Chau, E.T.F., Friend, C.M., Allen, D.M., Hora, J., Webster, J.R., A technical and economic appraisal of shape memory alloys for aerospace applications, Materials Science and Engineering A 438-440 (2006), p. 589-592.

[11] Mabe, J.H., Calkins, F.T., Butler, G., Boeing's Variable Geometry Chevron, Morphing Aerostructure for Jet Noise Reduction, American Institute of Aeronautics and Astronautics, Inc, Proceedings of 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 1-4 May 2006, p 21-42, Newport, Rhode Island.

[12] Morgan, N.B., Broadley, M., Taking the art out of smart! – Forming processes and durability issues for the application of NiTi shape memory alloys in medical devices, Proceedings of the Materials & Processes for Medical Devices Conference- 8-10 Sept 2003, ASM International, California (2004), p. 247-252.

[13] Pelton, A.R., Stockel, D., Duerig, T.W., Medical Uses of Nitinol, Materials Science Forum Vols. 327-328 (2000) pp. 63-70, Proceedings of the International Symposium on Shape Memory Materials held Kanazawa, Japan, May 1999.

[14] Janke, L., Czaderski, C., Motavalli, M., Ruth, J., Applications of shape memory alloys in civil engineering structures – Overview, limits and new ideias, Materials and Structures, Vol. 38 (2005), p. 578-592.

[15] Chau, E.T.F., Friend, C.M., Allen, D.M., Hora, J., Webster, J.R., A technical and economic appraisal of shape memory alloys for aerospace applications, Materials Science and Engineering A 438-440 (2006), p. 589-592.

[16] Popescu, M., Marta C., Mitelea, I., Magda, A., Dorohoi C., General problems when joining shape memory alloys, Annals of the University of Oradea, Fascicle of Management and Technological Engineering, Vol. VIII (XVIII), Romania, 2009.

[17] Vannod, J., Hessler-Wyser A., Rappaz, M., Nd:YAG laser joining between stainless steel and nickel-titanium shape memory alloys, EMC 2008, Vol.2: Materials Science, p. 501-502, Proceedings of 14th European Microscopy Congress, September 2008.

[18] Chatterjee, S., Abinandanan T.A., Chattopadhyay K., Phase formation in Ti/Ni dissimilar welds, Materials Science and Engineering A 490 (2008), p. 7-15.

[19] Nishikawa, M., Tanaka, H., Kohda, M., Nagaura, T., Watanabe, K., Behaviour of welded part of Ti-Ni shape memory alloy, J. PHYS, Colloque C4, Supplement n. 12, Tome 43, December 1982, p. 839-844.

[20] Qiao, Z., Li, L., Wang, D., Li, Z., Microstructure and shape memory recovery characteristics in a TIG-Welded Fe-Mn-Si-Cr-Ni shape memory alloy, International conference on smart materials and nanotechnology in engineering, Proceedings of the SPIE, Vol. 6423, p. 642330, China 2007

[21] Budău, V., Oancă, O., Crăciunescu, C.M., Macro and Microscopic Aspects observed on ultrasonic welding of shape memory alloys, Annals of the University of Oradea, Fascicle of Management and Technological Engineering, Vol. VII (XVII), România 2008.

[22] Eijk, Casper van der, Fostervoll, H., Sallom, Z.K., Akselsen, O.M., Plasma welding of NiTi to NiTi, Stainless Steel and Hastealloy C276, ASM Materials Solutions 2003 Conference, Pittsburgh, Pennsylvania, USA, 13-15 October 2003.

[23] Hsu, Y.T., Wang, Y.R., Wu, S.K., Chen, C., Effect of CO_2 Laser Weld on the Shape-Memory and Corrosion Characteristics of TiNi alloys, Metallurgicall and Materials Transactions A, Vol. 32A, March 2001, p. 569-576.

[24] Falvo, A., Furgiuele, F.M., Maletta, C., Laser welding of a NiTi alloy: Mechanical and shape memory behaviour, Materials Science and Engineering A, 412 (2005), p. 235-240.

[25] Falvo, A., Furgiuele, F.M., Maletta, C., Functional behavior of a NiTi-welded joint: Two-way shape memory effect, Materials Science and Engineering A, 481-482 (2008), p. 647-650.

[26] Tuissi, A., Besseghini, S., Ranucci, T., Squatrito F., Pozzi, M., Effect of a Nd-YAG laser welding on the functional properties of the Ni-49.6 at % Ti, Materials Science and Engineering A273-275 (1999), p. 813-817.

[27] Yan, X.J., Yang, D.Z., Qi, M., Rotating-bending fatigue of a laser-welded superelastic NiTi alloy wire, Materials Characterization 57 (2006), p. 58-63.

[28] Yan, X.J., Yang, D.Z., Liu, X.P., Influence of heat treatment on the fatigue life of a laser-welded NiTi alloy wire, Materials characterization 58 (2007) 262-266.

[29] Gugel, H., Schuermann, A., Theisen, W., Laser welding of NiTi wires, Materials Science and Engineering A, 481-482 (2008), p. 668-671.

[30] Gugel, H., Theisen, W., Microstructural investigations of laser welded dissimilar Nickel-Titanium-steel joints, Germany (2009) 10-28.

[31] Qiu, X.M., Li, M.G., Sun, D.Q., Liu, W.H., Study on brazing of TiNi shape memory alloy with stainless steels, Journal of Materials Processing Technology, Vol. 176 (2006), p. 8-12.