

Two Way Shape Memory Springs with Improved Repeatability on Thermal Cycling

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ABSTRACT: The influence of pre-training heat treatments on the amount and repeatability of the two way shape memory (TWSM) effect developed in Cu-Zn-Al shape memory compression springs is studied. Pre-training heat treatments were achieved by flash heating in a fluidised bed for various times at temperatures between 200°C and 450°C. Training was carried out by constraint ageing at temperatures between 100°C and 150°C. The TWSM was assessed by thermal cycling the springs both unloaded and opposed by weights. TWSM was shown to be critically dependent on the flash heating temperature and time and also on the exact procedure used in the constraint ageing training treatment. Scanning electron metallography and Vickers microhardness measurements were used to correlate TWSM with microstructure.

1. INTRODUCTION

Two way shape memory (TWSM) can be readily achieved in copper based shape memory alloys by various thermomechanical heat treatments. However the amount, durability and long term stability in service of TWSM are the key features which determine the suitability of a TWSM solution for a given set of service conditions [1]. Factors known to affect the long term repeatability of these devices include dislocation arrays introduced on thermal cycling, changes in the degree of configurational order, creep in both the β and martensitic phase, precipitation reactions, martensitic stabilisation, etc. These phenomena lead to the stress-temperature-deformation response of the alloy evolving with time rather than remaining constant [2-4].

One of the fundamental requirements of shape memory alloys is that the martensitic transformation temperatures should not change with thermal cycling or time. Successive thermal cycling through a martensitic transformation is known to produce an evolution of transformation temperature [5-7] which has been related to dislocation arrays formed during thermal cycling [8]. However, the presence of precipitates (γ phase) inside the parent β phase also affects the transformation behaviour [9-11] and the size, coherency and density of precipitates have been found to be important variables [12]. Recent work has shown that by using a complex heat treatment schedule involving step quenching and flash heating a distribution of precipitates of a mean size of approximately 30nm can be produced and the martensitic transformation temperatures of an alloy resulting from such a heat treatment do not change over 200 thermal cycles [13,14]. Hence it might be expected that, following suitable training, the TWSM response of such a material might show enhanced stability [15]. Thus the influence of pre-training heat treatments on the amount and stability of TWSM has been studied and is reported in the present communication. In all cases TWSM training was carried out by the constraint ageing (stabilised stress induced martensite) technique [16-22].

2. EXPERIMENTAL PROCEDURES

2.1. Material

Shape memory compression springs of open length 20.4mm, coil bound length 10.4mm, coil diameter 11.4mm and wire diameter 1.75mm were kindly provided by Memory Metals Limited, Ipswich, U.K. Their nominal composition was copper 73.9%, zinc 20.0%, aluminium 5.7%, zirconium 0.15%. The A_f temperature was approximately 80°C.

2.2. Pre-training heat treatments

All springs were first homogenised by heat treating at 850°C for 20 minutes followed by quenching into water at room temperature. This was followed immediately by flash heating in a fluidised bed at temperatures between 200°C and 450°C for various times. The springs were then quenched into water at room temperature. The important influence of the temperature of the quench medium on TWSM will be reported in a subsequent publication [23].

2.3. Training

Training took place as quickly as possible after the pre-training heat treatment. The compression springs were deformed to the coil bound state at room temperature (corresponding to a change in length of 10mm) and aged, while maintaining this constraint, in an oven at various temperatures between 100°C and 150°C for 30 minutes, previous work having shown this to be the optimum training time [20,24]. The springs were either unloaded at 100°C followed by cooling unconstrained to room temperature or allowed to cool constrained to room temperature and then unloaded.

2.4. Thermal cycling

The performance of the springs was assessed by thermal cycling between -20°C (dry ice and methanol bath) and 100°C (boiling water bath). Thermal cycling, in general, took place a few days after training. The TWSM was measured by inserting the spring into a specially designed measuring device incorporating a linear variable differential transducer. The apparatus was designed for minimum thermal mass and so moderately rapid heating/cooling cycles could be achieved. The TWSM% was obtained from

$$\frac{\text{hot length of spring} - \text{cold length}}{\text{deformation imposed during training}} \times 100\%$$

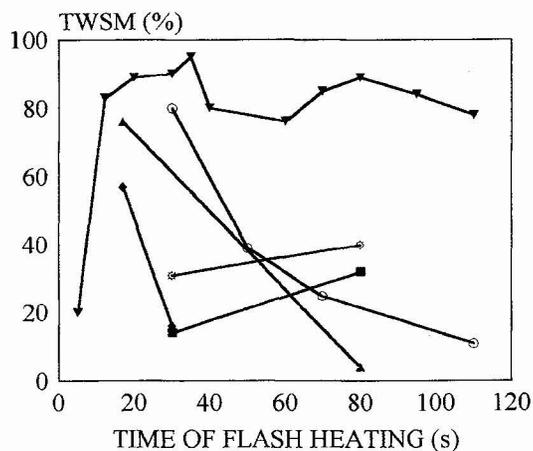
2.5 Microstructural studies

Longitudinal sections were taken through the wire of the springs after testing and metallographically prepared followed by optical and scanning electron microscopy in the etched state, a potassium dichromate etch being used. Vickers microhardness measurements, 200g load, were also carried out on the metallographically prepared sections.

3. RESULTS AND DISCUSSION

3.1. Flash heating

Figure 1 shows the effects of temperature and time of flash heating on the TWSM% for samples which have been trained at 120°C for 30 minutes. The data in the figure relate to the TWSM after 50 thermal cycles. The temperature of flash heating is obviously an extremely important variable in determining the amount of TWSM. From these results the optimum flash heating conditions for maximum TWSM were 35s at 300°C. At temperatures above 300°C the TWSM fell rapidly with increasing flash heating time while for temperatures of 200°C and 250°C the TWSM increased slowly with flash heating time. At 300°C the TWSM first increases with flash heating time and a maximum is reached after approximately 35s. Further increase in flash heating time brings about a slight decrease in TWSM which then increases to reach another maximum at 80s before again decreasing at longer flash heating times. This complex behaviour was confirmed by repeating these pre-training heat treatments on several springs.



■ 200°C ◆ 250°C ▲ 300°C ○ 350°C
 ▼ 400°C ★ 450°C

Figure 1 TWSM% as a function of flash heating temperature and time.

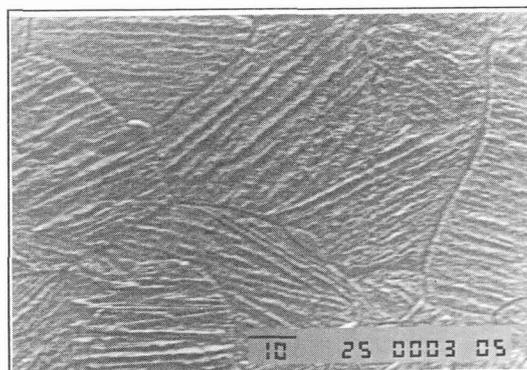


Figure 2 Martensitic structure of sample flash heated at 300°C for 35s and trained at 120°C for 30 minutes.

Figure 2 shows the microstructure of a sample with the largest TWSM achieved. Only one martensite variant is observed in each grain. For samples given pre-training treatments at 200°C and 400°C more than one variant per grain was observed, figure 3, and hence a smaller TWSM would be expected as was observed.

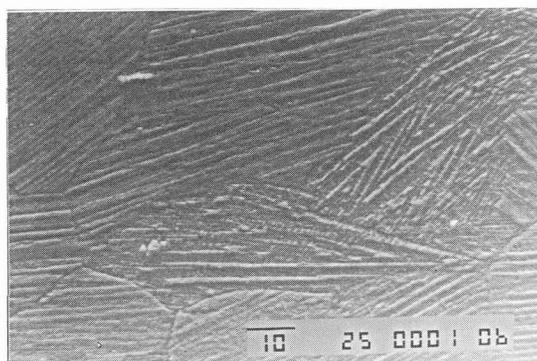


Figure 3 Martensitic structure of sample flash heated at 200°C for 30s and trained at 120°C for 30 minutes.

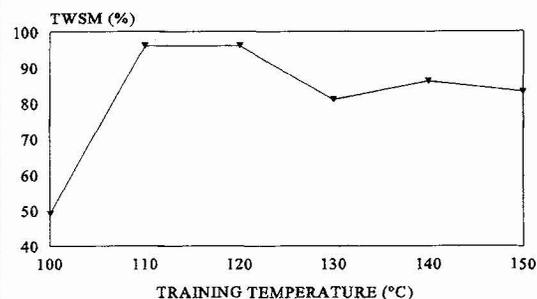


Figure 4 TWSM% as a function of training temperature for springs flash heated at 300°C for 35s.

Figure 4 shows the effect of training temperature on springs flash heated at 300°C for 35s. TWSM first increases with training temperature, reaches a maximum at temperatures of 110-120°C and then slowly falls as the temperature increases to 150°C. This behaviour is similar to that seen in other Cu-Al-Zn shape memory alloys when subjected to constraint ageing without any pre-training heat treatments [16-20]. The maximum TWSM of some 95% of the deformation imposed during training is higher than that obtainable with the optimum constraint ageing training treatment for springs not subjected to any form of pre-training heat treatment of about 60% [25,26]. However, the amount of TWSM developed by constraint ageing springs directly quenched from 850°C into water at room temperature depends critically on the time elapsed between

quenching and training, one hour being sufficient to reduce the TWSM to approximately 15% [25,26]. A direct quench into water at room temperature will result in a quenched in vacancy supersaturation and a large inherited $D0_3$ disorder [27] which lead to rapid stabilisation of the martensite. This manifests itself as a reduction in martensite variant interface mobility and so inhibits the development of a single preferred variant both on compression of the spring and in the training heat treatment and hence decreases trainability.

Figure 5 gives the effect of temperature and time of flash heating on the Vickers microhardness. For flash heating temperatures of 350°C and 400°C the microhardness increases rapidly with flash heating time. However, for a 300°C flash heating temperature the microhardness exhibits a slight drop in microhardness with increase in time. A similar behaviour occurs at 200°C. The rapid increase in microhardness with time of flash heating at 350°C and 400°C coincides with a substantial decrease in TWSM (Figure 1). The maximum TWSM for flash heating temperatures of 300°C and 350°C corresponds to a microhardness value of approximately 190. However a similar microhardness value is achieved after flash heating at 200°C for 30s when the TWSM% is only approximately 10%. Thus microhardness alone is not a critical indicator of the amount of TWSM achievable. The microhardness measured corresponds to that of the martensite which has formed from the β phase which has itself been aged on flash heating during which time a reduction in vacancy supersaturation, changes in degree of order and precipitation reactions occur [13-15,27]. Thus the mechanisms responsible for the improvements in TWSM following flash heat treatments at 300°C may well be due to a combination of factors including a reduction in the quenched in vacancy supersaturation, changes to the degree of order of the β phase as well as precipitation reactions. These changes will affect the development of a single preferred martensite variant upon stressing the original thermal martensite, its stabilisation (stabilised stress induced martensite mechanism [16-22]) and formation of a dominant variant from suitable precipitates.

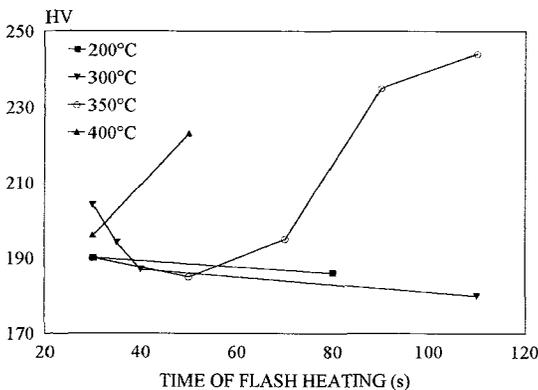


Figure 5 Vickers microhardness as a function of flash heating temperature and time.

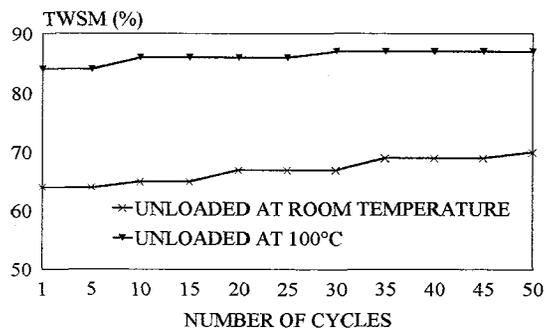


Figure 6 TWSM% as a function of number of thermal cycles for springs unloaded at 100°C and at room temperature.

Figure 6 shows the effect of removing the constraint from the spring at 100°C and at room temperature following flash heating at 300°C for 80s and training at 150°C for 30 minutes. The sample unloaded at 100°C is observed to have a considerably higher TWSM. However, upon thermal cycling the TWSM of the spring unloaded at room temperature increases somewhat. When springs which have been given an identical heat treatment and training procedure are cooled through the martensitic transformation they will both wish to undergo the same shape change. When the spring undergoes the martensitic transformation under no stress it will exhibit a shape change of approximately 85% of the deformation imposed on it during training. However, if it is forced to undergo the martensitic transformation whilst still under constraint it must suffer a "shape change" of 100% of that imposed during training. It would thus appear that by forcing the sample to adopt during its first martensite transformation after training a shape different from that which it would freely attain interferes with the formation of the single dominant variant and hence a smaller TWSM results.

Thermal cycling then aids the development of the single dominant variant and the TWSM increases somewhat as was observed.

3.2. Thermal cycling

Several experiments were conducted to assess the influence of pre-training heat treatments on the service performance of the shape memory springs. Figure 7 shows the results of thermal cycling on the TWSM of the springs given the pre-training heat treatment which, from the data in figure 1, yields the largest TWSM (i.e. flash heating at 300°C for 35s). Thermal cycling took place over a total period of one month. Between each period of thermal cycles the spring was left at room temperature. The TWSM response is noted not to change appreciably with thermal cycling, in particular there is no decrease in TWSM over the first few thermal cycles, which is often seen [17,25]. After 1100 cycles the TWSM has only decreased by approximately 4% of its original value.

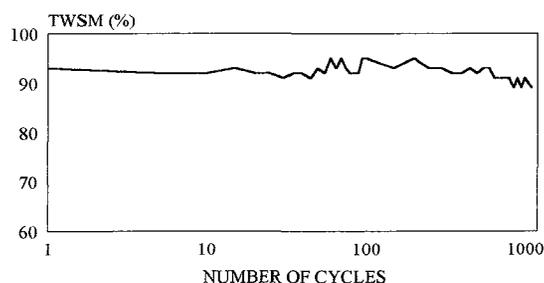


Figure 7 TWSM% as a function of number of thermal cycles for a spring flash heated at 300°C for 35s and trained at 120°C for 30 minutes.

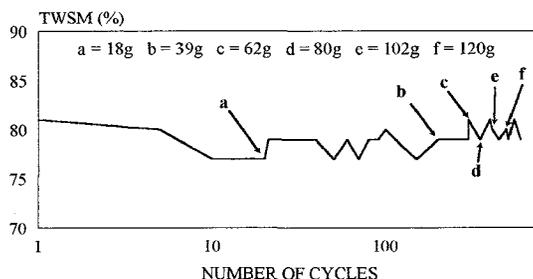


Figure 8 TWSM% as a function of number of thermal cycles for a spring working against various loads.

Figure 8 illustrates the influence of loads applied during cycling on the TWSM response of a spring given a pre-training heat treatment at 300°C for 40s and trained at 120°C for 30 minutes. The loads were applied by placing weights on the compression springs. These weights were maintained on the springs during both the heating and cooling cycles. As can be seen the application of a load of 120g does not have a deleterious effect on the TWSM response of the spring over the 600 cycles studied, the TWSM response being only approximately 2% less when working against a 120g weight after 600 cycles than at the start of thermal cycling under no load.

4. CONCLUSIONS

Pre-training heat treatments can substantially affect the amount of TWSM developed from a given training procedure. The results indicated that an optimum TWSM effect is generated by flash heating at 300°C for 35s. However, the amount of TWSM depends not only on the pre-training heat treatment but also on the precise manner in which constraint ageing is carried out, in particular on whether the spring is unloaded after the training heat treatment, at 100°C, in the parent β phase state, or at room temperature, in the martensitic state. The TWSM developed under the optimum conditions studied is stable on thermal cycling both unloaded and loaded with a weight of 120g.

5. REFERENCES

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