Compressive Training of the Shape Memory Alloy Washer

O. Söderberg, J. Keto-Tokoi, E. Haimi, J. Anttila, and V.K. Lindroos

This paper evaluates the performance and engineering aspects of 44Ti-47Ni-9Nb alloy in a pretensioning washer application. Previously the behavior of this alloy has mainly been studied for tensile predeformation with wires and strips up to 1 mm thickness. The present work investigated the effect of compression deformation and different homogenization temperatures on ring-shaped washers with larger dimensions. The best results with the compression-trained washer were achieved after homogenization at 1073 K where the compression training deformation was -10.4%, the lowest applied. The deformation training was carried out at 213 K near the martensitic reaction start temperature of the material. The expansion method, applied to the commercial reference ring, seemed to be a fairly efficient training method for the studied application, even though the parallel course of the radial surfaces was poor.

Keywords shape memory alloys, Ti-Ni-Nb alloys

1. Introduction

Shape memory alloys (SMA) provide potential advantages in a number of pretensioning applications for coupling bolts that require high but exact prestresses and light tooling due to space restrictions (Ref 1). Pretensioning of coupling bolts can be considered a constrained recovery application, where the force-producing capability is the primary function, even though elongation has to be generated, too.

One of us (JKT) has developed a pretensioning concept based on a comparatively thick, flat SMA actuator washer made of 44Ti-47Ni-9Nb alloy with a temporarily widened transformation hysteresis and with an austenitic reaction start (A_s) temperature that is higher than normal ambient temperatures (Ref 1). The idea is to trigger the shape recovery by active heating. In this way, storage and shipping become possible at normal ambient temperatures, while installation becomes easier and more controlled in mechanical engineering applications (Ref 2). The 44Ti-47Ni-9Nb alloy has a temporarily widened transformation temperature hysteresis (the difference between the shifted A_s temperature and the martensitic reaction start temperature, $A_s' - M_s$, is 130 to 150 K) (Ref 3). The A_s temperature of the first working cycle is shifted to an elevated temperature with predeformation. Deformation causes the structural phases of the material to deform so that the niobium phase deforms irreversibly via slip and the TiNi-matrix by the twin boundary motion. When the material is heated above the A_s temperature, the matrix tries to return to its original shape, but the niobium-rich phase resists the shape recovery process, thus delaying the recovery. According to earlier research (Ref 3-6), the greatest change of the A_s temperature is obtained with deformation from 10 to 12% when tension deformation is carried out at approximately the M_s temperature, i.e., at 183 to 213 K.

A research project was launched to evaluate the performance and engineering aspects of 44Ti-47Ni-9Nb alloy in the pretensioning washer application because there was insufficient published information for compression applications. The behavior of the 44Ti-47Ni-9Nb alloy has mainly been studied for tensile predeformation with wires and strips up to 1 mm thick (Ref 4-7). One of the goals of the research, and the subject of this paper, was investigation of the effect of compression deformation and different homogenization temperatures on ring-shaped washers with larger dimensions.

2. Experiment

The 44Ti-47Ni-9Nb testing material was delivered by Intrinsic Devices Inc. The tested UniLok-rings (model 0505-0177-0354) are designed to work as piping clampers. Their dimensions as delivered were: outer diameter 21.5 mm, inner diameter 12.8 mm, and thickness 8.8 mm. Their free recovered dimensions, according to the supplier, were: outer diameter 21.4 mm, inner diameter 12.1 mm, and thickness 9.2 mm. The shape recovery for these rings was to start at 318 K, and the full recovery should have been achieved after heating above 438 K. The product had been produced by a method in which the ring is expanded in the radial direction. Due to the fabrication method, the axial surfaces of the ring were a little conic instead of parallel. These axial surfaces had to be ground parallel to ensure as large a contact surface as possible between the steel washer, the jig, and the SMA ring.

One ring was used in the delivered state. The others were recovered once and then retrained. The first three specimens were homogenized at different temperatures: 12 h at 973 K (specimen 1), 1073 K (specimen 2), or 1173 K (specimen 3), combined with furnace cooling. Other specimens were homogenized at 1073 K (specimens 4 and 5) in the same way. All heat treatments were carried out in argon atmosphere. After homogenization the specimens were deformed in CO_2-ice at 194 K for different deformations. Deformation was carried out with a hydraulic compressing machine. The compression procedure of retrained specimens 1, 2, and 3 was carried out in steps. The maximum force used was 395 kN and the final deformation in the axial direction was approximately –12.5%. Specimen 4 (axial deformation –10.4%) and specimen 5 (axial deformation –15.5%) were compressed straight to the final deformation with 690 kN. The force difference between these two methods was due to the path dependence of the Ti-Ni-Nb material. The final shape of the retrained specimen resembled that of the homogenized specimen after moderate deformation, except for

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slight bulging of the outer ring wall. When the deformation force was increased, the inner wall also started to bulge. This was observed in the inner diameter values of the specimens, since in stepwise compression the inner diameter increased to some extent, whereas in straight compression it decreased slightly. The dimension changes of these specimens in compression are presented in Table 1.

The behavior of the rings was tested with the apparatus presented in Fig. 1. The prestressing force of the M10 bolt was measured with the Hottinger-Baldwin force-measuring ring KMR60. The KMR60 ring could not be heated above 343 K, so a cooling system for the specimen holder was needed. In assembling the bolt/washer/jig configuration, a small contact force was used to avoid the slack (values presented in Table 2). Heating was carried out by a hot air blaster. The heat income was found to be sufficient, since the resulting final force was approximately the same as the final force measured after a similar construction was heated in a furnace at 473 K.

3. Results

The behavior of the retrained rings was studied in constrained recovery with bolt prestressing tests and also, to some extent, in free recovery. According to the supplier, the free thickness shape change for 0505 rings to the axial direction is 4.3% after heating above 438 K. The free recoveries of the retrained rings (homogenized at 1073 K) proved to be 2.4% with deformation of −13.5% and 1.5% with deformation of −18.4%, after heating at 473 K in a furnace with argon atmosphere.

The test results of the bolt prestressing are given in Fig. 2. The final forces obtained and the other test variables are presented in Table 2. The free length of the bolt was calculated without taking any parts of the nut into consideration. After the test there was no plastic deformation in the bolt. The best prestressing was obtained with retrained specimen 4, which just exceeded the force obtained with the commercial ring, specimen 6. The smallest force values were connected with the specimens that were either heat treated at improper temperatures (specimens 1 and 3) or deformed too much (specimen 5).

Since the retrained specimens were not used until some days after deformation, there occurred a slight dimensional recovery in storage at the ambient temperature. The values given in Table 3 for the shape change were measured just before heating and after cooling and unclamping the construction. In these results the difference between the compressed rings and the expanded commercial ring is clear: the change of the diameter dimensions is much larger in the expanded ring than in the compressed rings. On the other hand, the thickness expansion is approximately the same, and the greatest value is connected with the best obtained prestressing force value with specimen 4.

Table 1 Dimension changes of the samples in retraining

Specimen No.	Homogenization temperature, K	Thickness, %	Outer diameter, %	Inner diameter, %	Area, %	Volume, %
1	973	−12.5	3	2.7	6.3	−7.0
2	1073	−12.5	2.9	1.7	7.0	−6.4
3	1173	−12.7	3.2	0.9	8.6	−5.2
4	1073	−10.4	4.2	−1.3	13.6	1.77
5	1073	−15.5	6.7	−1.4	21.2	2.4

Table 2 Results of the M10 8.8 hexagonal nut head bolt tests

Parameter	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6(a)
Free length of the bolt, mm	58.5	58.5	58.4	58.1	57.5	58.9
Contact force before heating, N	995	1,057	1,182	1,075	1,031	1,057
Force achieved in the test, N (contact force excluded)	4,407	10,735	4,203	14,591	7,002	12,088

Note: Specimen numbers according to Table 1. (a) Commercial specimen

Table 3 Dimension changes of the Ti-Ni-Nb washers after heating in the bolt prestressing test

Specimen No.	Thickness, %	Outer diameter, %	Inner diameter, %	Area, %	Volume, %
1	1.19	−0.54	−0.32	−1.26	−0.09
2	1.48	−0.59	−0.78	−1.01	0.45
3	1.47	−0.79	−0.11	−2.05	−0.61
4	1.94	−0.76	−0.96	−2.83	−0.93
5	1.44	−0.69	0.78	−2.43	−1.02
6(a)	1.70	−2.20	−4.86	−1.59	−1.46

(a) Commercial specimen

The effect of the homogenization temperature on the reverse transformation temperatures can be derived from the difference of the starting moment and end of the austenitizing. With the specimens homogenized at higher temperatures (1073 K, specimen 2, and 1173 K, specimen 3), the transformation occurs faster than it does with specimen 1, homogenized at 973 K. This indicates that the lower the heat treatment temperature, the greater the difference between A_s and the austenitic reaction finish (A_f) temperature. The effect of deformation can be observed in the curves, too. The greater the deformation, the smaller the constrained stress obtained. The effect on the transformation temperatures is not very clear, but the increasing deformation tends to slow down the transformation. The commercial ring obtained its maximum force value faster than the retrained ones, except for specimen 3.

4. Discussion

Ti-Ni-Nb shape memory alloy consists of two major constitutional phases, Ti-Ni matrix and β-phase, although a minor amount of $Ti_3(Ni,Nb)_2$ compound can be present in the structure, too (Ref 8). During solidification the β-phase forms a soft eutectic structure with the Ti-Ni matrix. Annealing and predeformation can be used to affect the final structure and the properties of the alloy.

Piao et al. (Ref 6) confirmed that the A_s temperature rises with increasing annealing temperature. The recrystallization temperature of the material is approximately 673 to 773 K, but even at 873 K, when the matrix grain size is very small, the niobium phase is not totally recrystallizated (Ref 6). To obtain full recrystallization, annealing should be carried out above 973 K, according to Piao et al. (Ref 6). At 1073 and 1173 K, the recrystallized grains are quite large and the thermal martensitic transformation occurs easily (Ref 6). In Ref 6, the measured transformation temperatures of the specimen annealed at 973 K were approximately 20 K lower than the ones associated with annealing at 1173 K, and the austenitizing occurred in the latter case slightly faster. Similarly, in our tests, the recovery of the specimen homogenized at 1173 K occurred faster than with the other specimens. No clear difference in A_s temperature could be observed between the specimens. One reason for this might be the constrained state of the washer, since the small prestress used might slightly affect the recovery properties. One must take into account that according to Bashanova et al. (Ref 9), the A_s temperature increases almost linearly with increasing applied tensile stress for Ni-Ti alloys containing up to 10 wt% Σ(Fe, Nb, Zr). Altogether, the A_s temperature was clearly lower with the retrained specimens than with the commercial one.

The commercial washer ring, the expanded one, obtained its maximum force value faster than the compressed rings. However, the stress values obtained were not very much higher than with the expanded ring. This may be explained by the training history.

The effect of the compressive training can be understood on the basis of the following theory of deforming the Ti-Ni-Nb material with tensile load. If the specimen is deformed at 213 K, stress-induced martensite forms first (Ref 8). Near the M_s

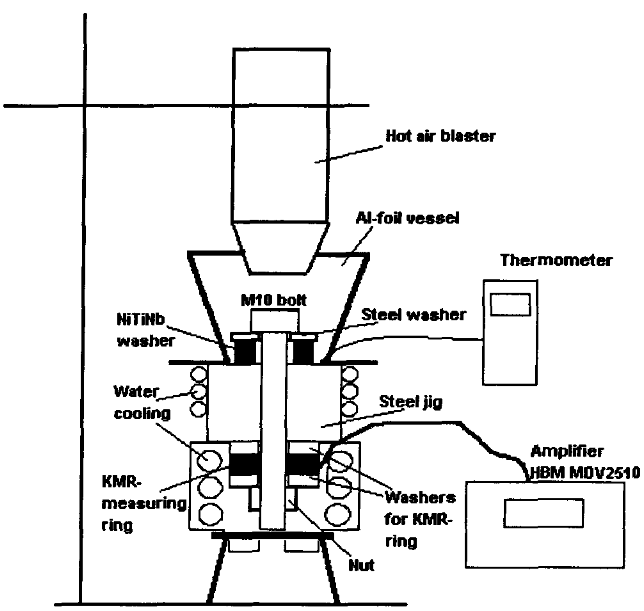

Fig. 1 The testing apparatus

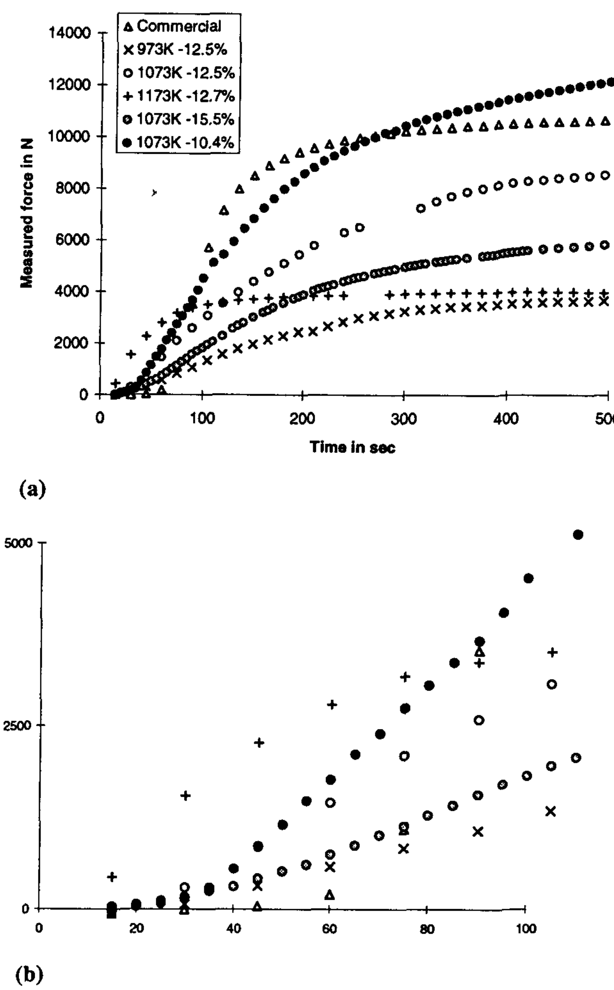

Fig. 2 Stress increase in the bolt at the beginning of heating. (b) Magnification of plot in (a) for 0-100 s

temperature, the yield strength of the β-Nb particles is of the same magnitude as the critical yield stress for the stress-induced martensite transformation (Ref 5). It can be speculated that these two processes occur alternately. If the total deformation is less than 9%, the strain is mainly attributable to the stress-induced martensite production and martensite reorientation (Ref 7). When the stress increases, the β-Nb particles deform plastically (Ref 5, 8). The elastic energy of martensite interfaces is relaxed by the plastic deformation of the adjacent β-Nb particles, and the driving force for the reverse transformation decreases and the transformation hysteresis increases (Ref 5, 8). At the characteristic deformation temperature (approximately 183 to 213 K) and the strain range of 10 to 12%, the critical yield stress for the stress-induced martensite transformation is optimally matched with the yield strength of the β-Nb particles. If the total strain exceeds 14%, the Ti-Ni matrix also deforms irreversibly. The plastic deformation of both the β-Nb particles and the Ti-Ni matrix causes the free recovery strain to decrease rapidly and the residual strain to increase linearly (Ref 5).

In our tests, the recoveries obtained in the axial direction with compressive training were not much higher than those obtained with the commercial specimen that was deformed in the radial direction. This may be due to the high predeformation loads used at the present work. The Ni-Ti matrix tolerated the compression load remarkably better than the tensile load (Ref 10). This led to more massive deformation of the soft niobium particles than was the case for tensile loading, and, accordingly, their frictional resistance in recovery may have been more profound, which may have limited the final axial recovery of the compressed specimen. The degree of deformation clearly affected the bolt prestressing ability of the ring in such a way that the force obtained gradually diminished from the best value, associated with predeformation of 10.4%, to the lowest value, associated with predeformation of 15.5%. The plastic deformation of the matrix also explains the results of the free recovery test, since increasing the deformation from 13.4 to 18.4% decreased the free recovery obtained from 2.4 to 1.5%, respectively.

5. Conclusions

In this study, the performance achieved with compression training was only moderately better than the performance achieved with the expansion method. However, the best performance was achieved with the compression training specimen that was homogenized at 1073 K and had the lowest degree of compression deformation (–10.4%). It is expected that lower degrees of compressive predeformation would yield even better performance. Accordingly, further research will be needed to determine the degree of compressive predeformation that gives the ultimate performance in this particular application.

The expansion method proved to be a fairly efficient training method for the studied application in regard to achievable performance and reasonable cost. The disadvantage of the compression method was the high force needed to produce the required compressive predeformation.

Interestingly, the performance of the retrained specimen was almost identical to that of new commercial rings. The obvious "reloading capability" may potentially be useful in some applications.

Acknowledgments

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