THERMOMECHANICAL TESTS OF SHAPE MEMORY ALLOY BELLEVILLE WASHERS

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Abstract. *This work has the main objective of manufacturing Belleville washers made of shape memory alloys (SMA) and evaluates their performance, aiming applications in smart bolted joints. For this, and using a Ni-Ti SMA previously selected, the actuators have been produced by adapting the Plasma Skull Push Pull (PSPP) process. Once improved the manufacturing technique of SMA Belleville actuators, tests of force generation as a function of temperature were accomplished using a universal testing machine. The obtained results showed a maximum force generation of the order of 14 kN. It has been made also two kind of complementary experiments using a SMA actuator-bolt system, in order to analyze the deformation and force generated on the bolt, keeping in view the load generated by the actuator. All the results indicated a large potential for application of these SMA Belleville actuators for development of real applications, mainly in the oil and gas Industry.*

Keywords*: Shape memory alloys, Belleville washers, smart bolted joints.*

1. INTRODUCTION

Shape Memory Alloys (SMA) are a select group of metallic materials that have the ability to return to the original shape after undergoing plastic deformation with subsequent heating. In general, the shape recovery of these special materials is directly associated with application of a temperature field or of a simple removal of mechanical loading which causes deformation. Those shape recovery phenomena, being related to the temperature at which the material is, cause important changes in some of the physical and mechanical properties.

Thermomechanical actuators made from SMA are receiving a special interest, due to their wide variety of applications. For example, there is a great international tendency to develop smart bolted joints, constituted of SMA washers, which are theoretically able to recover a level of preload eventually reduced due to a relaxation of a bolted joint. Thus, SMA actuators manufactured in shape of Belleville washers, may be adequate to recover this reduced level of preload, avoiding problems with that. For this, the joint must be equipped with a system containing the SMA actuator in shape of Belleville washer pre-deformed in compression, a heating system and a monitoring system. In this way, the monitoring system would be able to detect a critical level, pre-determined, of the coupling force and start the heating system so as to enable the expansion of the actuator by shape memory effect (SME) and, consequently, recovering the coupling force (preload) of the bolted joint (Andersen *et al.*, 1997; Andersen *et al.*, 1999; Ghorashi *et al.*, 2004; Hesse *et al.*, 2004; Peairs *et al.*, 2004; Antonios *et al.*, 2006).

Once developed a manufacturing technique of SMA Belleville washers, one obtains an important component to recovery of pre-load, which equipped with a mechanical assembly and coupled with an appropriate monitoring system, may form a mechanical active system. This system can be installed on machines and/or structures that require intensive maintenance, due to the loosening of some components, caused by factors such as vibration of the system, self-relaxation, etc. In this way, the new maintenance can become simpler and more sporadic, influencing on design issues such as cost reduction with maintenance and simplifying the structure of the system.

Therefore, considering the great application potencial of SMA actuators in shape of Belleville washers in several areas, the objective of this work was to select shape memory alloys that can be used in the Belleville washers manufecturing, in a fusion and plasma machine which uses the *Plasma Skull Push-Pull (PSPP)* process, and study the characteristics of the thermomechanical behavior of the manufactured washers.

2. PROSPECTIVE ANALYSIS

2.1. Belleville washers and shape memory effect (SME)

Belleville washers, patented in France by J. F. Belleville in 1867, are conical washers that have a non-linear relationship between force and deflection, which makes them very useful in some applications. These mechanical elements are extremely compact and can endure large compressive stresses, with very limited deflections. Therefore, these washers are used when high loads occur with small deflections and also when small spaces are required (Norton, 2006).

In this way, a pre-load device for flanged joints is based on actuators of SMA, consisting of a washer of this material, initially pre-deformed in compression which, when heated, it tends to recover its original shape, generating a restoring axial force and causing a load on the bolts of the joint (Park *et al.*, 2003).

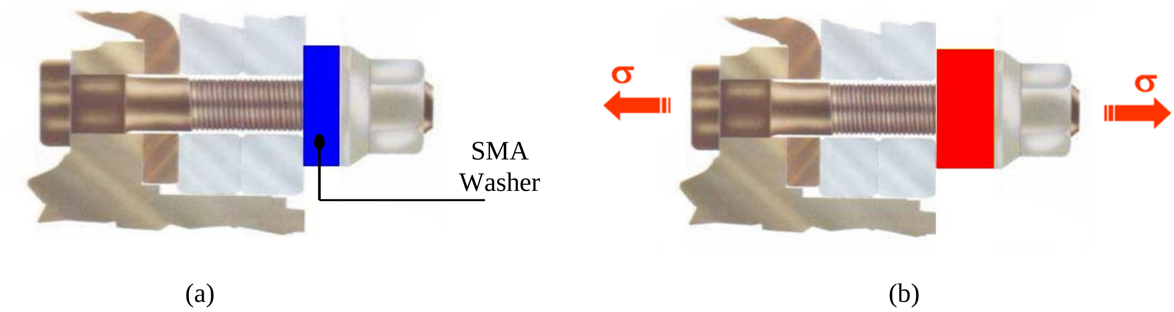


Figure 1. Flange with shape memory washer. (a) SME is not activated. (b) SME is activated, with detail to the tension on the bolt.

Using Belleville washers of SMA instead of that kind of washer illustrated in Fig. 1,the performance of flanged joint can be increased because of them conical shape. These washers have a greater ability to endure great loads with very limited deflections and, besides are extremely compacts.

3. MATERIALS AND METHODS

3.1. Fabrication of SMA Belleville washers using the *PSPP* process

For the fabrication of Belleville washers of shape memory a SMA with nominal composition of 48Ni-38Ti-14Nb (% weight) which has been selected due to its high hysteresis (Zhao *et al.*, 2006). In an earlier work, De Araújo *et al.* (2009) found that the temperatures of beginning and end of the martensitic transformation of that SMA were M_s = -48.0 °C and M_f = -23.1° C, respectively. As for the temperatures of beginning and end of the reverse transformation, it was found A_s = -7.2° C and A_f = 23.6 °C, respectively.

The commercially pure chemical elements (Ni, Ti e Nb) were melted into a plasma melting machine, whose sequence of melting is shown in Fig. 2. The melting was performed with the elements piled, viewed in Fig. 2a, in a copper crucible and underneath a tungsten electrode, using the *PSPP* process (Araújo *et al.*, 2009). In the process, the machine door is closed, as shown in Fig. 2b, and the metal is melted on a thin layer of itself, in an atmosphere protected by argon, turning into in a kind of "button", viewed in Fig. 2c. This "button" is melted four times, in order to achieve a better homogeneity of the final product. Finally, the injection of the liquid material into the metallic mold, which is at the bottom (not shown) of the machine, occurs at the fifth melting. This leads to obtaining of the final designed form. The Figure 2d illustrates a thin layer of material that is, at the end of the injection, weakly stuck on the crucible.

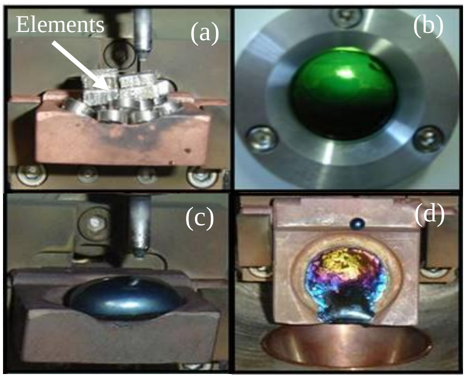
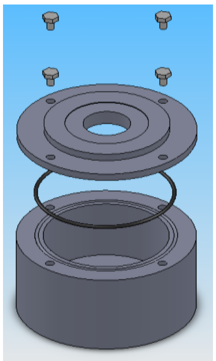


Figure 2. Fabrication sequence of a Ni-Ti-Nb SMA by the *PSPP* process. (a) Pure Ni, Ti and Nb in the copper crucible. (b) Rotating plasma torch. (c) "Button" of Ni-Ti-Nb obtained. (d) Injection of Ni-Ti molten "button" into a metallic mold (not shown).

3.2. Adaptation of the *PSPP* process for Belleville washers fabrication

For the obtaining of the desired shape of a Belleville washer, some adjustments had to be made to the *PPSP* process, shown in Fig. 2. These adjustments have been made by Pereira *et al*. (2010), in a previous work. Thus, an aluminum container was designed, using the 3D CAD Design Software SolidWorks, to adapt the metallic mold in the plasma melting machine, as shown in Fig 3. As illustrated in Fig. 3a, the container cover is fixed using four bolts. To ensure a good seal of the container, it was also used a rubber ring, kind of "O-ring".



(a) (b)

Figure 3. (a) Exploded view of the aluminum container, designed in SolidWorks. (b) Detail of the aluminum container and assembly in the plasma melting machine (Pereira *et al*., 2010).

3.3. Design of a mold for Belleville washers fabrication

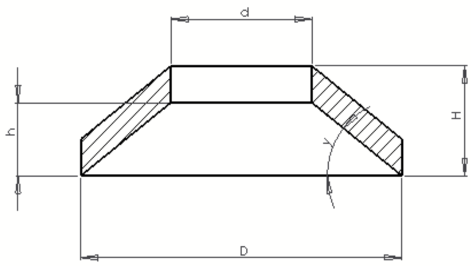
A detailed study of Bellevile washers standardized dimensions has been done by Pereira *et al*. (2010). From this study, Belleville washers were designed in a way that would lead to a satisfactory mechanical response, during the tests. Thus, based on the work of Pereira *et al*. (2010), the Belleville washer dimensions in the Tab. 1 have been used.

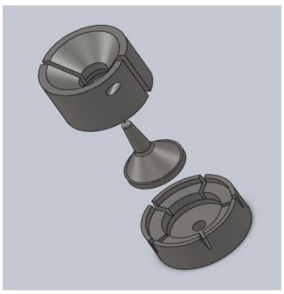
Table 1. Dimensional parameters for a Belleville washer. Source: Pereira *et al*. (2010).

Outer diameter (D)	Tickness (t)	Inner diameter (d)	Small high (h)	Big high (H)	Internal angle (γ)
25	2.5	12.5	7.1	10.8	48.5

(1): measurements in mm and angles in degrees.

The dimensions of the Tab. 1 are related to the dimensional parameters in Fig 4a. Once defined the Belleville washer dimensions, a mold for its fabrication was projected, using the 3D CAD Design Software SolidWorks, as shown in Fig. 4b.





(a) (b)

Figure 4. (a) Dimensional parameters for a Belleville washer. (b) Exploded view, in isometric projection, of the mold components, (Pereira *et al*., 2010).

Using the mold, shown in Fig. 4b, installed in the container in Fig. 3, it has been applied the *PPSP* process described in Fig. 2, for the composition of 48Ni-38Ti-14Nb (% weight) and a total mass of 23 grams . The result of the final product is shown in Fig (5).

(a) (b)

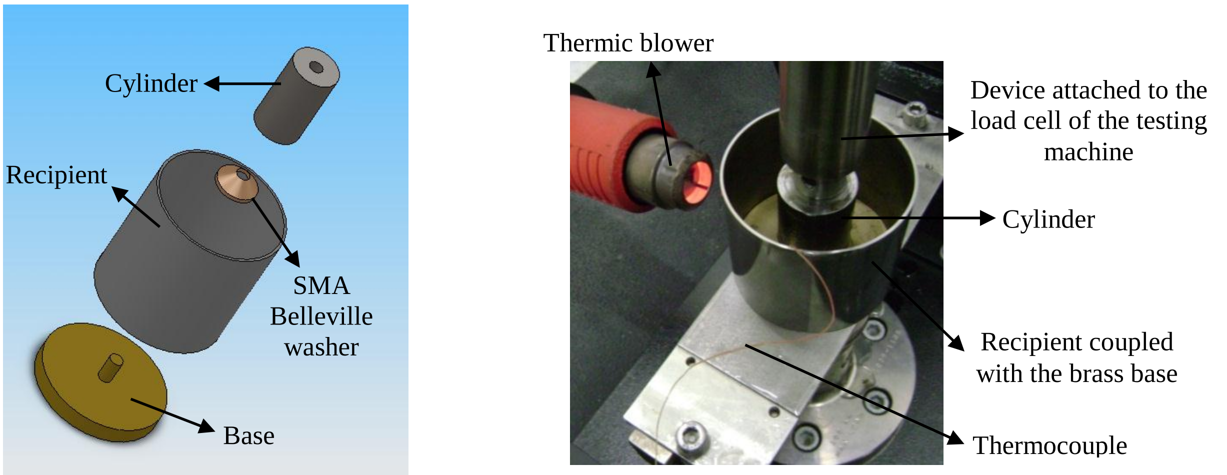
Figure 5. (a) Unfinished final product of the melting. (b) SMA Belleville washer finished.

3.4. Procedure for force generation tests with the manufactured Belleville washer

The procedure for force generation tests was also developed by Pereira *et al*. (2010). In that work, Belleville washers, manufactured by the PSPP process, were tested by a force generation test as a function of temperature. For this test, an universal electromechanical tests machine was used.

For the generation force test is necessary, before to deform the washer, cool it at temperatures below 273 K (0 °C). That is, the SMA washer must be cooled to temperatures at which they are in the martensitic state, and thus they can be submitted to reversible plastic deformations. This procedure is indispensable to obtain the subsequent trend of the washer expansion by SME during the heating.

For the execution of these tests, Pereira *et al*. (2010) projected a range of specific accessories for the measurement of generated force by SME of the washer, using the universal tests machine. In this assembly, shown in Fig. 6, the washer is assembled between the pin, of a bronze base, and a stainless steel cylinder. It was also projected a recipient which serves to contain the liquid nitrogen (N_2) used in the cooling of the washer until the martensitic state.



(a) (b)

Figure 6. (a) Exploded view of the components for force generation tests, designed in SolidWorks. (b) Detail of the test assembly for force generation test of the Belleville washer, (Pereira *et al*. 2010).

In that testing, the cylinder is pressed by a circular device which is connected to a load cell of the testing machine. A thermocouple, type K, is installed on the washer to monitor its temperature during the cooling and heating, using a hot air flow coming from a thermic blower. This experimental arrangement can be seen in Fig. 6b.

The steps of the force generation test can be summarized in the schematic drawing in Fig. 7. As shown in item 1, the thermocouple is welded on the sample and is also connected to a data acquisition system, which will read the values corresponding to temperature during the test. Then, N_2 liquid is deposited in the recipient. That allows the Belleville washer achieves temperatures below 0 °C, in which the SMA will find the martensitic state. The washer is submitted to mechanical compression loading, and when it reaches a strain of 6% (% height), in item 2, the N_2 supply in the recipient is stopped. At this point, a thermic blower is activated (item 3) until the temperature on the washer reaches approximately 60 ^{o}C. In this temperature range, the SMA Belleville washer begins to generate force through trend expanding by SME. Then, in item 4, the washer is naturally cooled to room temperature (approximately 25 °C) and a residual force is measured at this moment (Pereira *et al*. 2010).

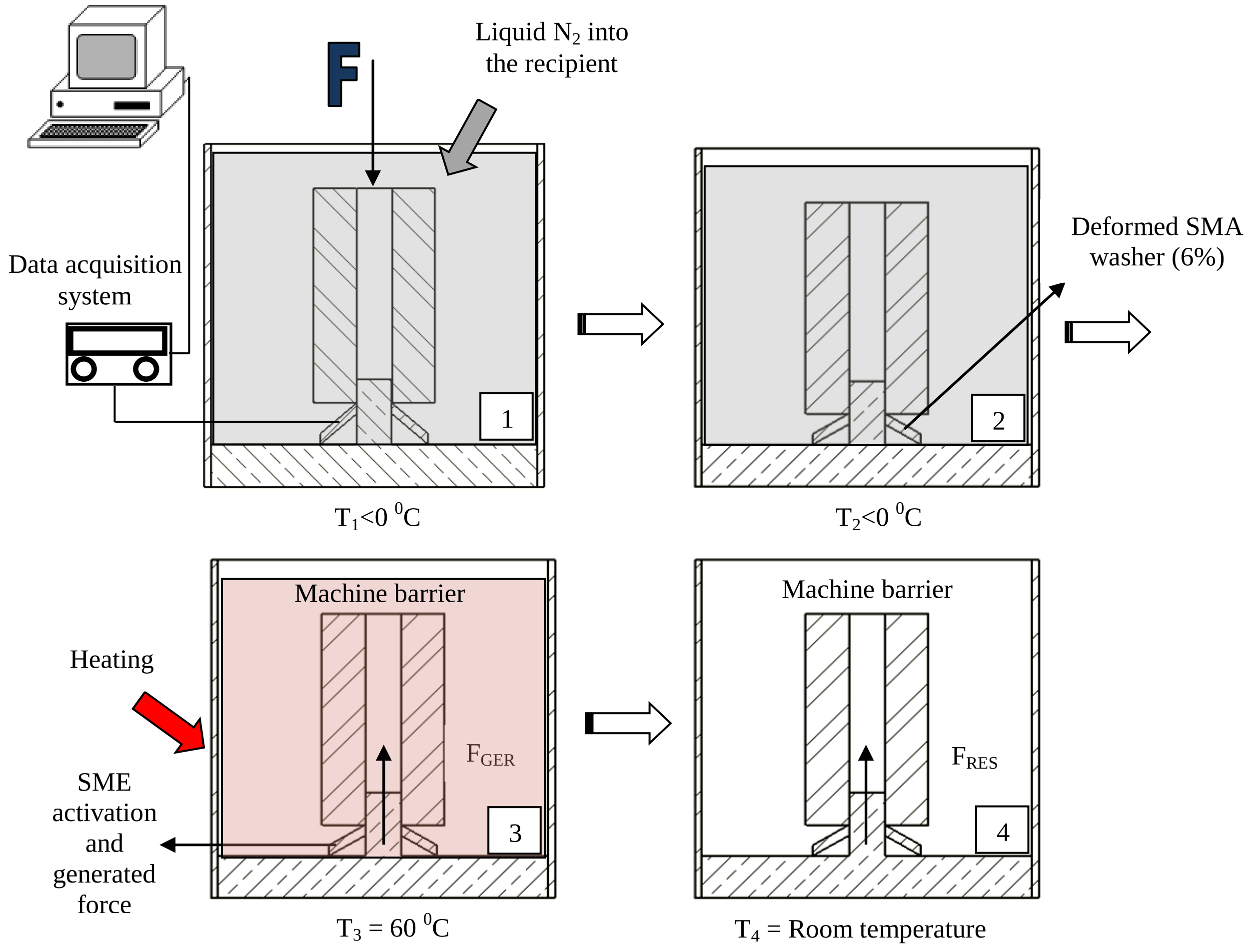


Figure 7. Schematic diagram experimental for the force generation in SMA Belleville washers.

3.5. Procedure for strain tests on a bolt assembled with a SMA Belleville washer and using a LVDT displacement sensor

The objective of this stage is to obtain the deformation which the Belleville washer transmits to the bolt, during activation of the SME. For this, it has been performed the assembly in Fig. 8a. In Figure 8b, the details of the experiment can be seen.

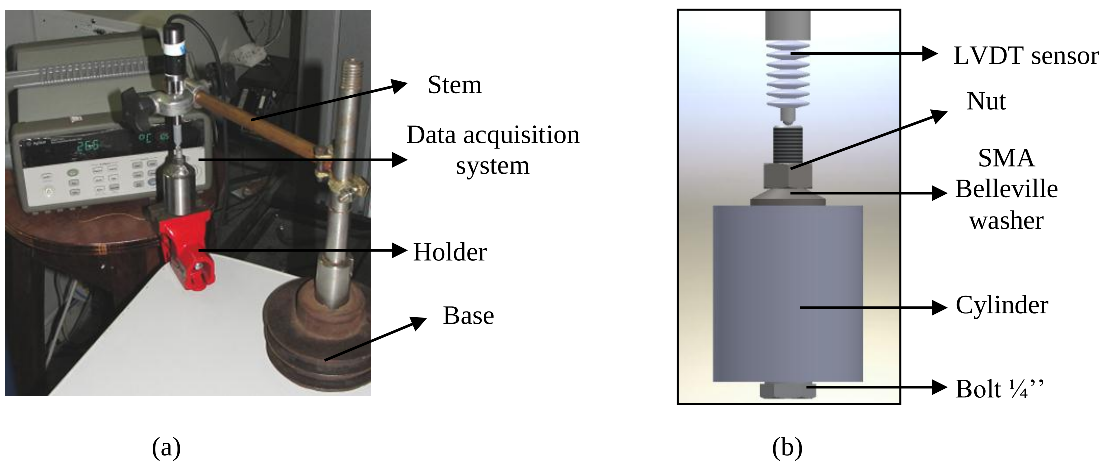


Figure 8. (a) Assembly to measure the deformation of the bolt. (b) Assembly details, designed in SolidWorks.

As can be seen in Fig. 8, a cylinder was designed to be used as a barrier to deformation, so that the generated load by the Belleville washer is transmitted to the bolt. In this way, this cylinder should be sufficiently stiff and, therefore, its diameter must be greater than four diameters of the bolt. Moreover, to ensure a greater stiffness that component has been manufactured using stainless steel. The experimental procedure adopted for the testing is outlined in Fig. 9.

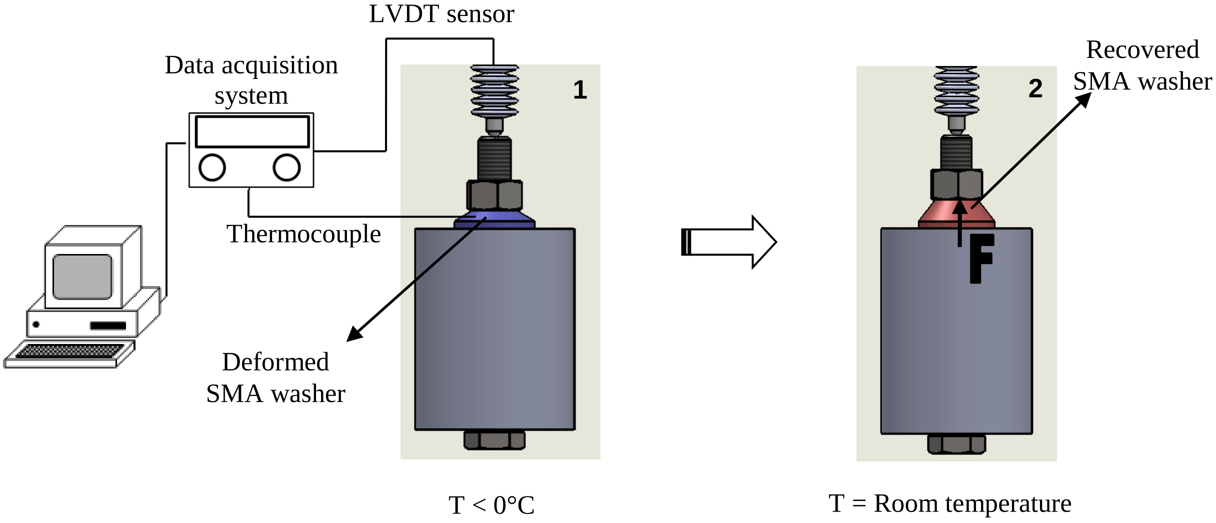


Figure 9. Experimental scheme for bolt deformation assembled with a SMA washer.

After the experimental assembly, it was used the arrangement in Fig. 6a and the procedure in Fig. 7 to promote the same strain of 6% in the Belleville washer. After the strain be applied, the sample has taken to the assembly bolt and the remaining components of Fig 9. As can be seen, the sample was placed between the cylinder and the nut, so that the last one has been put weakly, in a way to not provided torque on the bolt, ensuring that all the strain is provided by the Belleville washer.

The deformed Belleville washer is shown in blue, on item 1 in Fig. 9. After assembly, it was installed a LVDT displacement sensor at the tip of the bolt, in a way to measure its strain. From there, it is expected that the sample reaches the room temperature naturally. During this process, there is a generation of force on the bolt, caused by the SMA washer due to the restriction of the SME. The "recovered" Belleville washer is shown in red on item 2 of Fig. 9.

Throughout the procedure, the sample temperature was measured by a thermocouple, welded in the sample and connected to a data acquisition system. The same thing occurred with the LVDT displacement sensor, which also was connected to the acquisition system, and measured the bolt strain.

3.6. Procedure for force generation tests on a bolt assembled with washer Belleville and using a load cell

This experiment has as main objective to evaluate the force which the SMA Belleville washer generates directly on the bolt, during the SME activation. For this, it has been developed the assembly in Fig. 10.

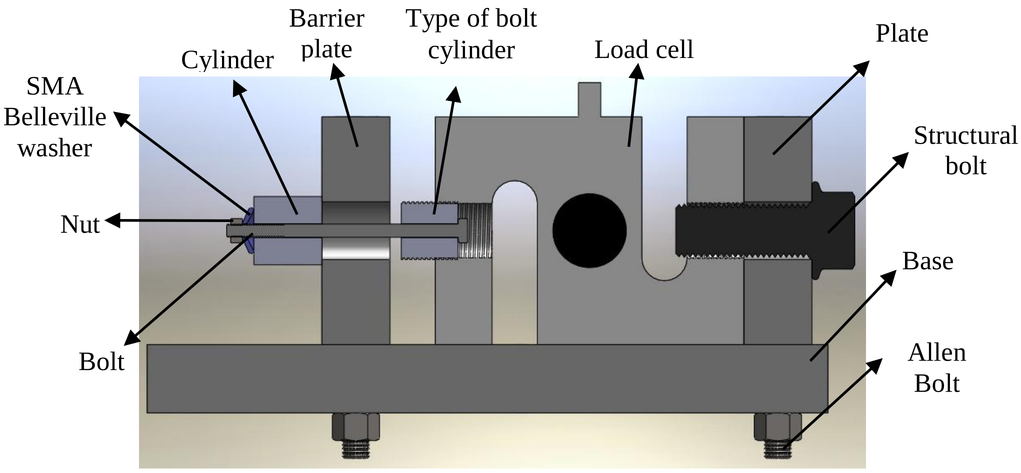


Figure 10. Sectional drawing and description of the components used in the testing of force generation on a bolt.

The set was assembled using two plates attached to a base by Allen bolts. Between the plates was installed a load cell of 5 tons fastened on one side, by a structure bolt, and on other by a type of bolt cylinder. Thus, this cylinder was attached to a steel bolt (length 4" and diameter ¼") that goes through the plate and is attached to a stainless steel cylinder. The scheme in Fig. 11 illustrates the steps of the experiment.

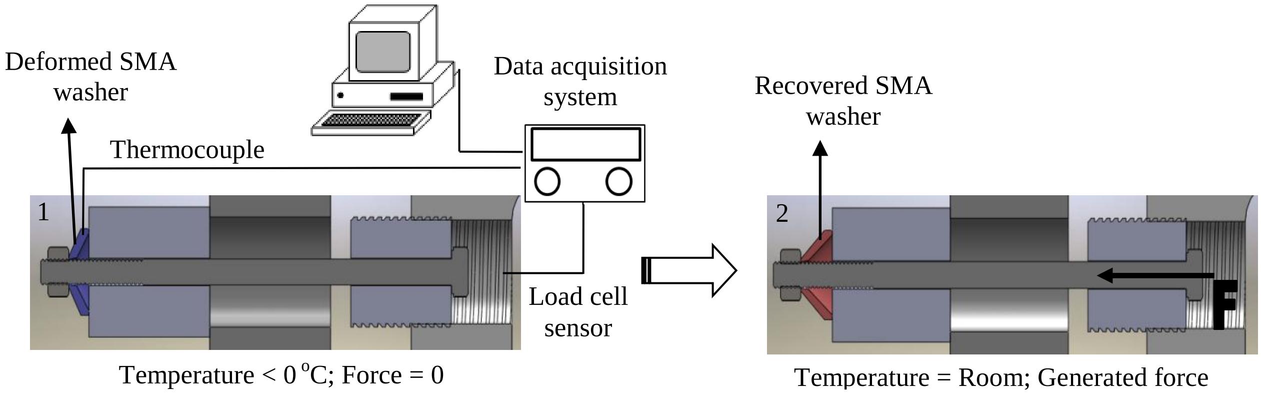


Figure 11. Schematic illustration and detail of the experiment.

After the experimental assembly, the same arrangement in Fig. 6a and the procedure in Fig. 7 to promote the 6% strain of 6% in the Belleville washer. After the strain be applied, the sample has taken to the assembly bolt and the remaining components in Fig 11.

The deformed Belleville washer, shown in blue on an item 1 in Fig. 11, was placed between a cylinder and a nut. That last was tightened with a torque of 19 lb.in (2.15 Nm), using a torque wrench. This torque was promoted in order to minimize assembly gaps, which may influence the experiment results. From there, it is expected that the sample reaches to room temperature naturally. During this process, occurs the force generation on the bolt caused by SME activation of the SMA washer. Throughout the experiment, the sample temperature was measured by a thermocouple welded on it and connected to a data acquisition system. Likewise, the load cell which was connected to the data acquisition system, and measured the load generated on the bolt.

4. RESULTS AND DISCUSSIONS

4.1. Test results of force generation

The force generation test, according to the procedure described in Fig. 7, was made with the Belleville washer of the Fig. 5. The general result can be seen in Fig. 12.

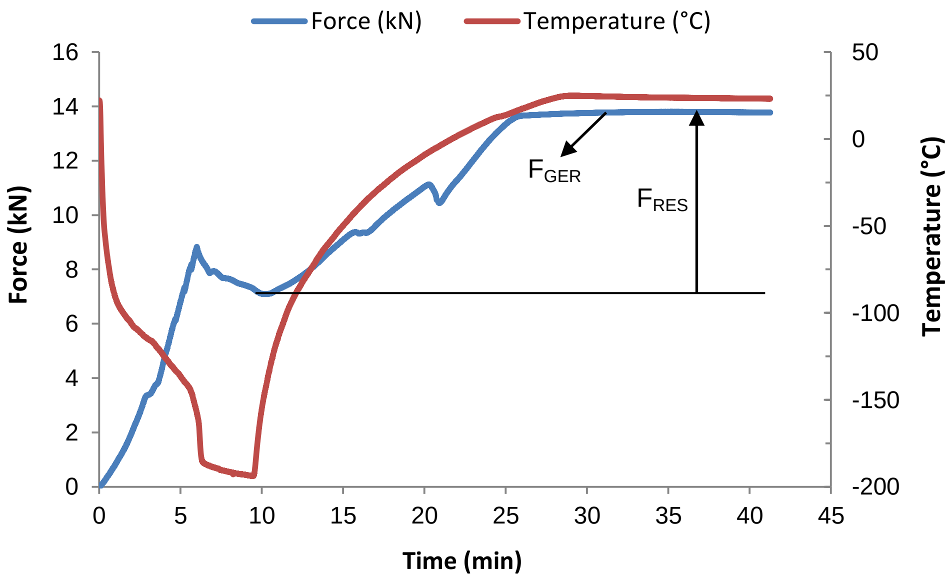


Figure 12. Force generation of a NiTi SMA Belleville washer, showing axis of force, temperature and time.

The experiment was conducted with a deformation of 6% (% height), with a maximum force (F_{GER}), generated by the SME tendency during the heating, of approximately 14 kN. After the "forced" relaxation, it has kept a strain of 6% throughout the heating and return to room temperature, which brings forward a residual force (F_{RES}) of approximately 6 kN. Comparing the value of F_{GER} obtained in this work, approximately 14kN, with that obtained by Pereira et al. (2010), which used a 55Ni-Ti (% weight) SMA and generated a force of approximately 1kN, it has been verified that the washer made in this work has a wider value of generated force.

4.2. Test results of strain on a bolt

The test to deform the bolt, using the Belleville washer in Fig. 7, is described according to the procedure in the experimental setup in Fig. 9. The general result can be seen in Fig. 13.

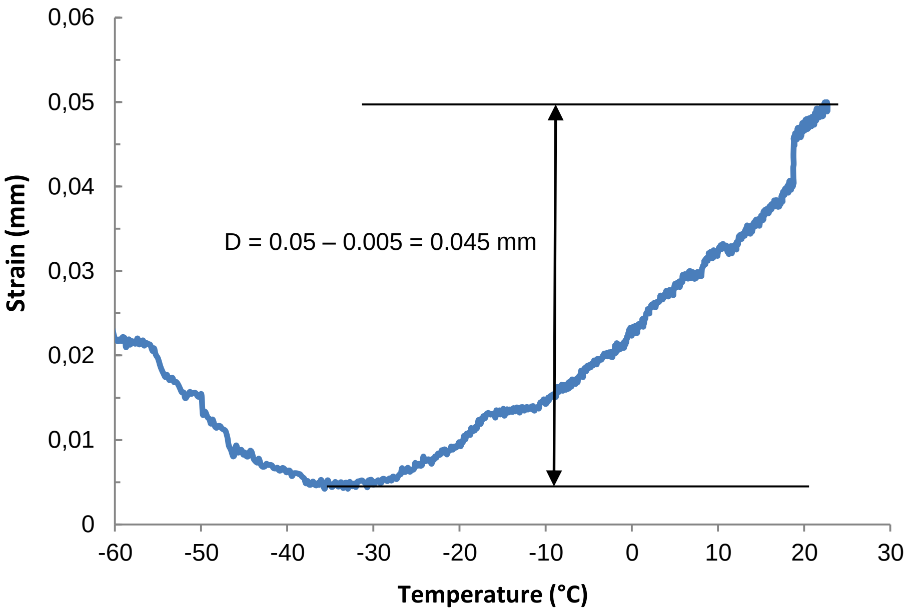


Figure 13. Strain on a bolt due to the SME activation of the Belleville washer.

The experiment was conducted with a strain of 6% (% height). An strain increase was found from the SMA activation of the actuator and the "natural heating" of the sample to room temperature, starting from approximately 0.005 mm to 0.05 mm, which corresponds to a strain level (D) of 0.045 mm.

The Equation (1) (Hibbeler, 2004) was used to calculate the value of force that should be applied on the bolt to cause a deformation of 0.045 mm (on its length), found in the previous experiment.

$$F = \frac{EA}{L}\delta = \frac{E\pi d^2}{4L}\delta \tag{1}$$

Where, the parameters of the equation above are given in the Tab. (2).

Table 2. Value of Eq. (1)'s parameters.

Parameters	Simbol	Value	Units
Modulus of elasticity	E	210	GPa
Diameter	d	6.35	mm
Bolt length	L	50	mm
Strain	δ	0,045	mm

The calculations were made using the value of parameters from Tab. (2) and the value of force obtained was approximately 6kN. This theoretical result, for a strain of 0.045mm on the bolt, has confirmed the experimental result of the Fig. (12), where was found the same value of force when the SMA washer was deformed at the same strain of 6% (% height).

4.3. Test results of the force generation on the bolt

The test of force generation on the bolt, according to the steps of the experimental set in Fig. 11, was also conducted with the Belleville washer in Fig. 7. The general result can be seen in Fig. 14.

The experiment was conducted to the same strain of 6% (% height). As can be seen in Fig. 14, initially the load remains constant at approximately 40 N. This load is due to a small height of the load cell from the base. Due to the initial torque at the nut, the load is increased to approximately 380 N. In this way, the force generated due to torque application (F_{TOR}) is around 340 N.

After the initial torque applying, as the temperature is still below 0 °C, the sample is still on the martensitic state, and so there is a slight load reduction until about 350 N. From there, it is expected that experimental set reaches, naturally, the room temperature (23 ^{o}C) and then the load is measured at about 750 N. Thus, the load generated by the washer restriction (F_{GER}) from the SME is 400 N.

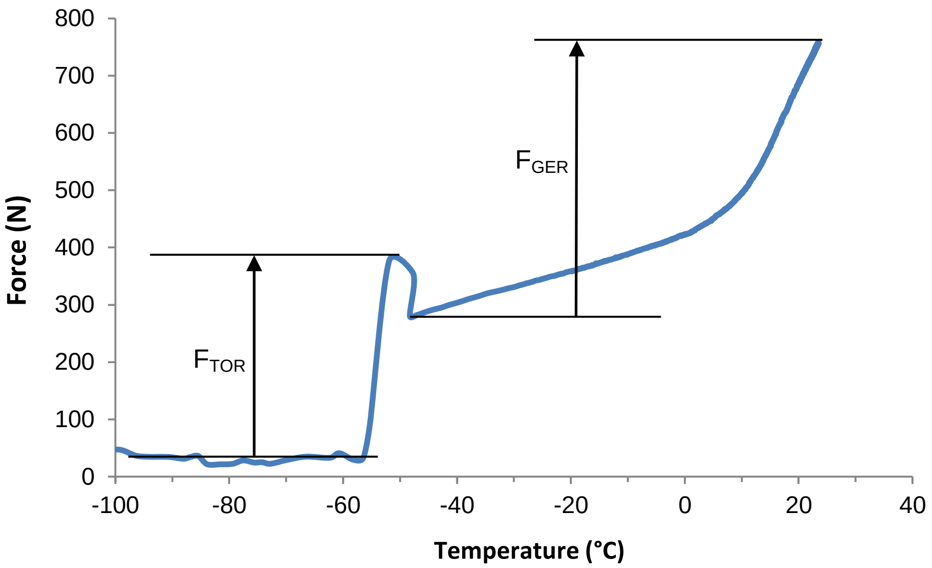


Figure 14. Generated force on the bolt as a function of temperature for a SMA washer.

5. CONCLUSIONS

The Ni-Ti-Nb shape memory alloy used in this study was adequate to generate important forces by restricting of the shape memory phenomenon. Besides, the *PSPP* process for manufacturing of SMA Belleville washer actuators was successfully used.

Regarding to the force generation tests, the Belleville SMA actuator has originated a force (F_{GER}) of 14.0 kN and residual forces at room temperature (F_{RES}) of about 6.0 kN. There were also successfully performed two experimental assemblies to test the SMA Belleville washer and the bolt together. The first experiment showed that the actuator provided an elongation of about 0.045 mm on the bolt. The second revealed that the actuator provided, on the bolt, a generated force of approximately 400 N.

All those results demonstrate that the application of SMA actuators, type of Belleville washers, may have a great importance to recover pre-loads on bolts, for example, as regards the safe transport of oil and gas, when used in joints bolts.

6. ACKNOWLEDGEMENTS

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