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Dynamic Fracture of Ductile Materials

# High Temperature Dynamic Tension Behavior of Titanium Tested with Two Different Methods

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**Abstract**

In this work, the dynamic response of Ti6Al4V alloy at high temperature was studied using the Split Hopkinson Pressure Bar –SHPB- apparatus with two different heating systems. The first device uses direct electric current to heat the sample to the testing temperature in a fraction of a second, whereas the second device uses a furnace to heat the sample and as a consequence, short sections of the bars, in few minutes. Tension tests were carried out at strain rates up to 1500 $s^{-1}$ and at temperatures ranging from room temperature up to 700 °C. The conventional strain gauge measurements from the pressure bars were used to obtain the stress–strain curves and the Johnson-Cook material model was used to fit the results of the tests. High speed photography and digital image correlation were used to quantify the total strain during the test. The plasticity of the titanium alloy clearly increases as the temperature is increased. The maximum strains, obtained from the stress-strain curves, also increase when the temperature is increased from room temperature. DIC results, however, show clear differences in the maximum strain before failure with respect to the values obtained from strain gauges measurements. The maximum strain in the gauge section of the sample prior to failure increases steadily as the testing temperature is increased. At 60 °C, the strains within the gauge section reach values almost 50% just before failure. At 300 °C, the maximum strains are close to 65%, and at 700 °C the maximum strains extend close to 80%.


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*Keywords:* Titanium; high strain rate; high temperature.


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## 1. Introduction

Various industrial and military applications involve dynamic material behavior at high temperatures. Optimal design and development of components requires in-depth understanding of the plastic deformation and failure of materials at these conditions. Nowadays, the most commonly used testing method to study the mechanical behavior of metal alloys at high strain rates is the Split Hopkinson Pressure Bar (SHPB) device. It consists of two long and aligned bars with the specimen sandwiched (compression version) or held (tensile version) between them, and a propulsion device for accelerating a projectile. The striking projectile impacts at the end of one of the bars producing a stress wave which travels along the bars. Strain gauges, amplifiers and oscilloscopes are used to measure the strain wave propagation in the bars and by applying the principles of one-dimensional elastic wave propagation; it is possible to obtain the stress-strain curves of the material, as well as the test strain rate. Moreover, the use of Digital Image Correlation (DIC) technique provides in-depth understanding of the deformation and failure of the specimen by tracking the movement of a surface pattern during testing. Previous research on the dynamic behavior of Ti6Al4V with SHPB devices have been reported [1], including tensile loading [2] and compression loading at high temperatures [3]. However, none has been found involving dynamic tensile loading at high temperatures.

High temperature testing by using the tensile version of the SHPB device is complicated by the fact that the specimen must be firmly fixed to the bars before heating the specimen up to the desired temperature. Because of this, mechanical manipulation of the specimen and the bars is restricted after positioning the specimen. Furthermore, SHPB testing at high temperature presents other difficulties [4]. Due to the length of both bars and the supporting system for keeping bar alignment, it is operationally impossible to heat the entire bar assembly, so a temperature gradient may appear, changing elastic properties of the bars along its length. Consequently, a study of the temperature-gradient effect on the elastic modulus and the longitudinal sound speed should be performed to take into account the corresponding corrections.

High temperature tension tests with the SHPB device can be carried out basically by two ways: heating up the specimen and short sections of the bars to the desired temperature using a furnace [5] [6] [7], or heating up just the sample using, for example, infra-red radiation or direct electric current [8]. Both methods have their advantages, drawbacks, and limitations with respect to the temperature ranges, control of temperature, etc. In fact, no detailed studies have been carried out in the past about the exact effect of the heating method on the obtained final results.

The first method, from now on called furnace method, uses a furnace to slowly heat the sample and inevitably, short sections of the bars, causing some temperature gradient in them. Incident and transmitted bars should be made of a material with a low variation of the elastic properties with temperature to avoid the need for corrections. This method usually implies mechanical clamping since bars are heated up and adhesive degrade its properties at high temperatures. This mechanical clamping could produce disturbances or oscillations in the obtained strain curves.

The second method, which uses direct electric current and called electric method, enables the use of adhesive fixing since the sample is heated up rapidly, so the temperature of the adhesive joint does not increase significantly. Therefore, it would enable to obtain higher quality results. Unfortunately, temperature control of the system becomes difficult since the heating is achieved in less than a second by means of electric current.

There is a third method, which would imply using mechanical devices that brings the room-temperature pressure bars into contact with the heated sample in a fraction of a second before the stress pulse arrives at the end of the incident bar [9] [10]. Regrettably, it is only practical in the case of a compression SHPB test because in tensile SHPB testing the sample needs to be mechanically coupled or adhesively fixed to the pressure bar.

In this paper, the furnace and the electric method are presented and applied to Ti6Al4V alloy.

## 2. Furnace heating method

The furnace method was employed by using the SHPB tensile system of the Department of Material Science at Technical University of Madrid [5]. In this laboratory, the incident and transmitted bars have 4.05 m and 3.85 m length respectively, 19.3 mm diameter, and they are made of the René 41 alloy, a nickel-based super-alloy with optimal high-temperature properties and low dependence of its elastic properties on temperature. The bars have

screwed ends; consequently it was necessary to design a clamp (see Figure 1.b) to attach the flat specimens to the bars.

Samples, whose geometry is shown in Figure 1.a, were mechanically coupled by two pins, which are introduced by the holes at each side of the samples, fixing the sample to two bolts. Then, the bolts are screwed into the bars. Pins and bolts were also made of René 41 alloy.

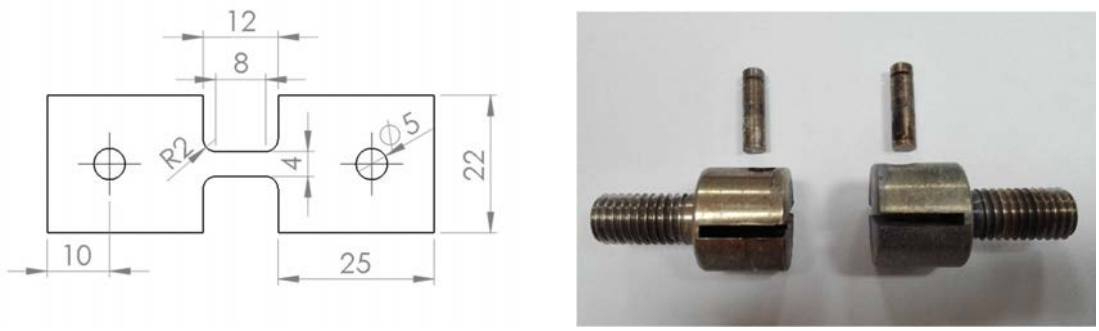


Fig. 1. a. Ti6Al4V samples geometry, Madrid; b. Clamp designed to attach the specimens. All dimensions are in mm.

The furnace, shown in Figure 2, consists of eight resistors and a bar-size opening at each side. It can reach temperatures up to 900 ºC in few minutes. The furnace is supported by a pneumatic system, which enables to remove the furnace to one side of the bars just when the projectile is launched. Therefore, it is possible to visualize and record the tests. Heating rate was set in 30 ºC/min and the heating times were between 5 and 15 minutes. Temperature was acquired by the contact of a thermocouple with the sample.

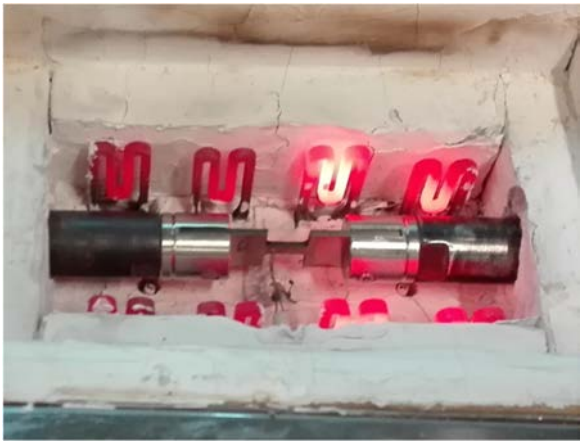

Fig. 2. Resistors system for furnace heating.

Moreover, the system contains two heat-sinks next to the oven and in contact with the bars, where water flows to avoid an excessive heating of the bars and therefore, any damage to the strain gauges.

During testing, the furnace is removed after heating up the sample and while the striker is triggered. Stress waves are registered by strain gauges located at the middle of each bars. The test is recorded by a high-speed camera and DIC technique may be applied if samples have a high-contrast speckle pattern during the test, usually painted with high-temperature resistant paints.

## 3. Electric heating method

In the tensile Split Hopkinson Bar device designed and built at the Department of Materials Science of Tampere University of Technology [8], each bar has 6.3 m in length and 22 mm in diameter. The incident bar is made of a high strength steel (AISI 4340) and the transmitted bar is made of 2007 aluminum alloy, which allows more accurate measurements of low amplitude strain signals. Samples are fixed to the stress bars by gluing them to slits machined at the end of the bars. The adhesive employed was Loctite 480.

The geometry of the samples is shown in Figure 3 and it is quite similar to the ones used in the previous method. It consists of a gauge section, two glue sections and two electrode sections. The gauge section is the central part of the sample and strains during testing. The glue sections, which let the adhesively attachment between the specimens are bars, are the two large sections at the end of the sample. These sections must be large enough to ensure that the shear strength of the adhesive joint is enough to withstand the applied load. The 10-mm-wide electrode sections, are used to conduct electric current into the sample. Specimens only need these extensions on one side; however, they were machined on both sides for the sake of symmetry.

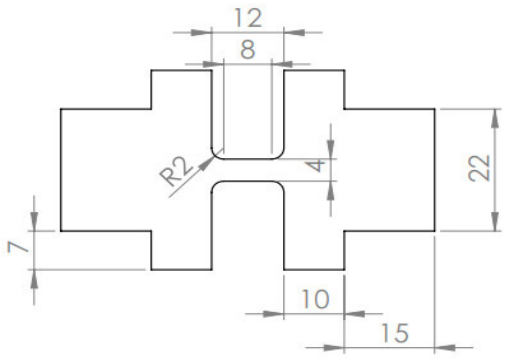


Fig. 3. Ti6Al4V samples geometry, Tampere. All dimensions are in mm.

The heating up system is shown in Figure 4. It consists of four copper electrode pins, with 5 mm diameter, moved by a pneumatic actuator. The pneumatic actuator uses low pressure to move the electrodes up and down and to squeeze these pins to each side of the sample. These four pins, two at each side, are responsible for bringing electric current to heat the sample. Once the heating has finished, the pneumatic actuator retracts away the electrodes, keeping the system far away from the impact. Another reason for taking away the electrodes is that in this way it is possible to use digital image correlation analysis of the sample.

Electric current is provided by a programmable Kempower IMP15 welding transformer, which is controlled by the same computer that controls the SHB device. The transformer uses a low-voltage high-DC-current pulse to heat the sample by Joule's effect. To measure the temperature of the specimen, a thermocouple is previously spot welded to the center point of the gauge section of the specimen and a second high-speed oscilloscope is used to record the temperature. The oscilloscope records the incident loading pulse too. Therefore, the temperature of the specimen can be recorded at the exact moment when the incident loading pulse arrives at the specimen.

Heating times varied between 0.2 and 1 second, enabling to heat only the gauge section (the one with smaller cross-sectional area), while the temperature of the shoulder area, whose cross-sectional area is larger, is not significantly increased and thus, the glue section remains close to room temperature without losing its properties. The electric current and voltage values used for the titanium samples were between 3-5 volts and 300-900 amps. If the maximum current and voltage are kept constant, the maximum temperature of the sample increases almost linearly as a function of the heating time, thus the testing temperature can be estimated before the test by running a series of very short heating experiments. However, when testing different samples the temperatures may vary significantly. It is important to mention that after some heating tests in the same device, the contact between the electrodes and the specimen was lost due to a local melting of titanium. To avoid this problem, a conductive grease was used to improve the conductivity and contribute to better estimations of the temperature.

Although tests were fully computer controlled, there were many things to set up and check before every test, so that we could get accurate timing and control of the different actions. Once the trigger signal is sent, the striker starts moving from resting position until it impacts in the incident bar. Additionally, the electrodes start heating the sample using the DC pulse produced by the transformer. If the heating time is too long and the electrodes are still heating the sample when the wave arrives, the electrodes become damaged. Therefore, electrodes must be taken out before the stress pulse arrives. On the other hand, if the heating time is too short, the specimen may cool down before the stress pulse arrives. Consequently, a heating delay should be set in a way which enables to finish the heating around 50ms before the stress pulse arrives.

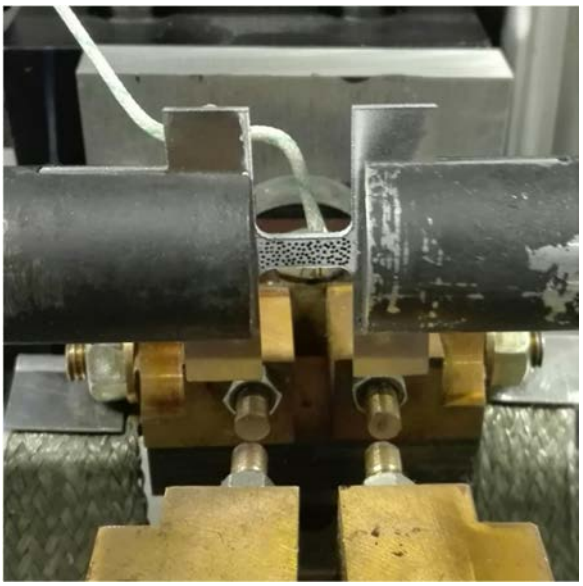

Fig. 4. Four copper electrode system for direct electric heating.

Carrying out this type of test seems much more complex than the previous method, but it is quicker to perform. However, it involves the curing of the adhesive as well as its heating and cleaning with acetone after testing, which limits the use of this method to few daily tests.

## 4. Results

### *4.1. True Stress-True Strain Curves*

Tensile tests using aforementioned methods were carried out at the same temperature and approximately at the same experimental engineering strain rate (1300 $s^{-1}$). Using the data from strain gauges, the true stress – true strain curves at 300, 450 and 700 ºC were obtained (see left plot in Figures 5, 6, 7).

It can be appreciated that curves obtained by electric heating and adhesive fixture (EH & GF) have better signal-to-noise ratio. However, the curves obtained by furnace heating and mechanical clamping (FH & MC) show higher oscillations, especially at the beginning, losing information about the yield strength.

To achieve a better comparison of the curves, they were filtered using a low pass and a median filter. Low pass filter was programmed by Fast Fourier Transforms, which gets the 15 dominant frequencies of the signal and compose the wave again. Then, the median filter was applied and finally, low pass filter was used one more time to avoid the stepped behavior of the curve acquired through the median filter.

Filtered curves are shown on the right of Figures 5, 6 and 7. Now, it can be clearly observed that both methods obtain a similar material response. Analogous material properties are obtained except for 450 ºC, where the flow

stress between both methods differs around 100 MPa. This flow stress difference may be due to a different testing temperature during the FH&MC test (a lower value instead of 450º), probably due to a temperature acquisition error. More tests were not able to do because of the lack of samples, so this hypothesis could not be confirmed. However, the three plots show the same work hardening behavior.

During tests at 300 ºC, a third method, which combined mechanical and heat-resistant adhesive fixing during furnace heating (FH & GF), was employed with the goal of reducing the oscillations at the beginning of the curve. The adhesive employed was Henkel Loctite 638. However, the adhesive did not add any significant improvement, probably because the adhesive deteriorated at that temperature.

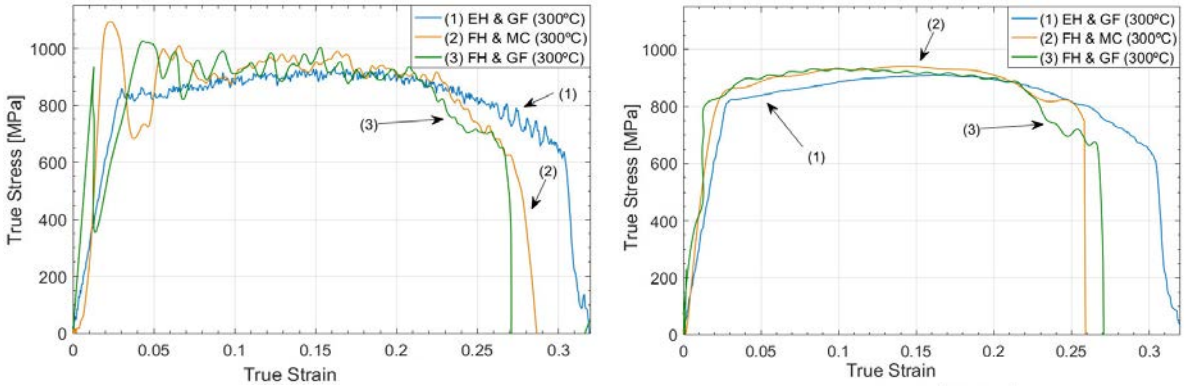


Fig. 5. True Stress – True Strain curves at 300 ºC and 1300 $s^{-1}$ for: electric heating and adhesive fixing (1), furnace heating and mechanical clamping (2) and furnace heating and glue fixing (3) before filtering, left; after filtering, right.

Results from furnace-heating at 450 ºC shown even a higher signal-to-noise ratio than tests at 300 ºC. Higher heating times and temperatures might lead to different thermal expansion between the bar, sample, and pins. Consequently, loosens could appear and lower-quality stress pulses were recorded. The use of adhesive fixing was not feasible at these temperatures in the furnace, but it was by the electric heating method because of the short duration of the heating process (around one second), the room temperature on the glue sections was kept.

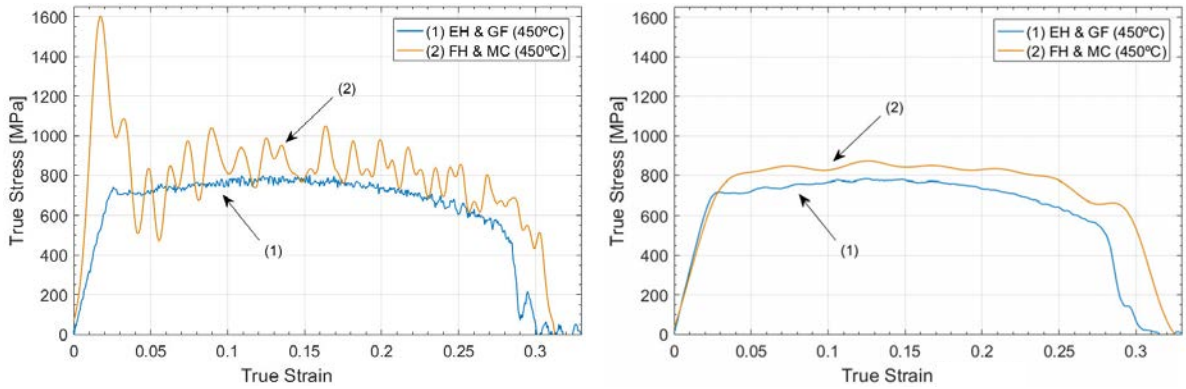


Fig. 6. True Stress – True Strain curves at 450 ºC and 1300 $s^{-1}$ before filtering, left; after filtering, right.

During furnace heating tests at 700 ºC, stress bars were pulled before the withdrawal of the furnace to avoid loosens that may occur during heating. It enabled lower oscillations in the results than 450 ºC tests. The sample spent 15 minutes in the furnace until it heated up to 700 ºC, then the test was carried out. By visual inspection after the test, a thin blue oxide layer could be appreciated on the surface of the sample.

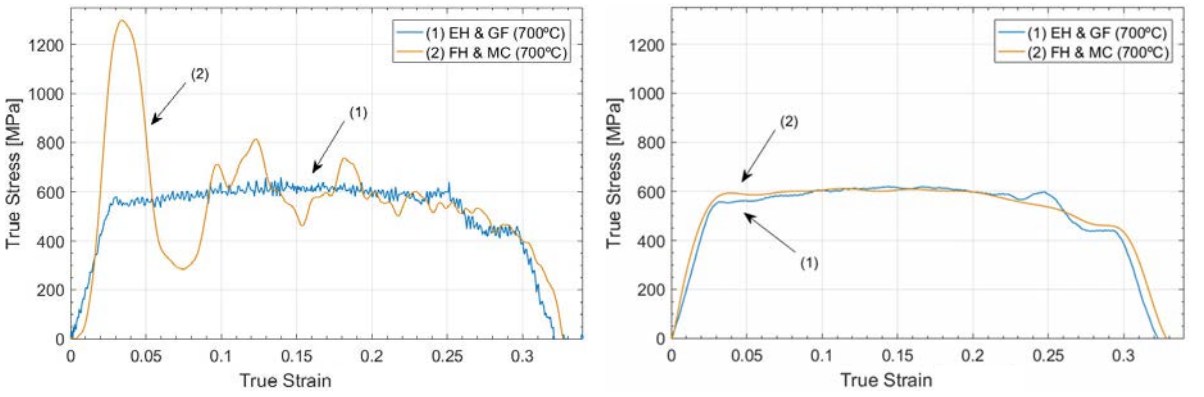


Fig. 7. True Stress – True Strain curves at 700 ºC and 1300 $s^{-1}$ before filtering, left; after filtering, right.

Related to the alloy behavior, previous studies [11] set the yield strength and ultimate tensile strength in tension of Ti6Al4V at room temperature and quasi-static conditions between 900 and 1000 MPa respectively; and around 1200-1300 MPa in dynamic conditions at an engineering strain rate of 1300 $s^{-1}$, showing that flow stress increases with strain rate.

Concerning the temperature effect, experimental results show that increasing test temperature decreases both, the elastic limit and UTS. By increasing the temperature of the dynamic tests up to 300ºC, the flow stress decreases by 30% and by increasing it up to 700ºC the flow stress decreases by 50%. The high UTS of the alloy at 450ºC (800MPa) may explain the use of Ti6Al4V alloy for high temperature applications. However, its use is limited up to 550 ºC [12], because, as we saw after a few minutes at 700 ºC, an oxide layer appears due to the high interstitials affinity of titanium.

### *4.2. Adjusted material model*

In order to predict the material behavior, a Johnson-Cook material model was adjusted [13] considering the adiabatic softening. At high strain rates, adiabatic heating takes place since it is not possible to dissipate such amount of plastic energy to the surroundings during the short duration of the test, so a temperature increment of the sample occurs. The Johnson-Cook model is defined in equation (1):

$$\sigma = \left(A + B\,{\varepsilon_p}^n\right)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \qquad (1)$$

The first, second and third term of previous equation define the influence of the deformation, strain rate and temperature, respectively, in the material behavior. $A$ is the yield strength of the material at quasi-static tests, $B$ and $c$ are parameters that define the evolution of the flow stress as a function of the equivalent plastic strain $\varepsilon_p$ , $C$ and $m$ define the strain-rate and temperature sensitivity of the material, respectively.

$\dot{\varepsilon}^*$ and $T^*$ are given by equations (2) and (3):

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \qquad (2)$$

$$T^* = \frac{\mathrm{T} - \mathrm{T}_{room}}{T_{melt} - T_{room}} \qquad (3)$$

where $\dot{\varepsilon}_0$ is the reference strain rate (quasi-static tests), $\dot{\varepsilon}$ the strain rate of the test, T is the temperature of the specimen, which may increase due to adiabatic heating (see Equation 6) , $T_{room}$ is the room temperature and $T_{melt}$ the temperature at which the material does not show mechanical resistance against deformation.

The parameters employed in the adjustment of the model are shown in Table 1. The adjustment was performed by least-squares fitting and a comparison with the experimental results at three different temperatures is shown in Figure 8. Material model is plotted up to diffuse necking and after this point it is represented with dash lines.

Table 1. Johnson-Cook parameters value.

| A | B | n | $T_{room}$ | $T_{melt}$ | m |
|---|---|---|---|---|---|
| 800 MPa | 700 MPa | 0.096 | 25ºC | 1400ºC | 0.65 |

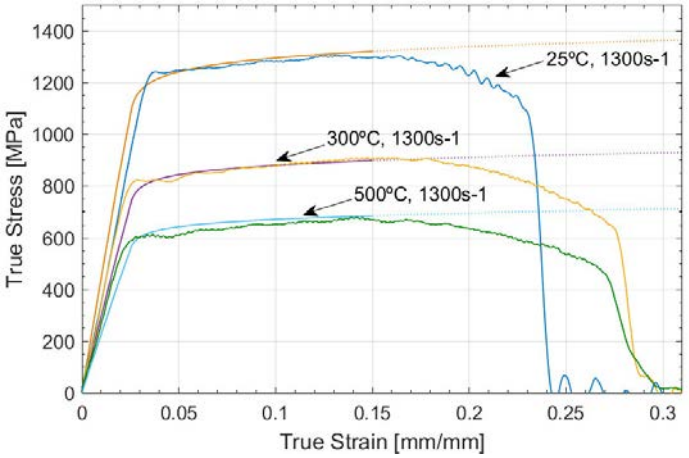


Fig. 8. Comparison between the adjusted Johnson-Cook material model and the experimental results.

The curves include the adiabatic heating, in which the thermal softening is considered. Temperature increments are calculated through the First Law of Thermodynamics and the Taylor Quinney coefficient λ (around 0.9 for metals), showed in equations (4), (5) and (6).

$$dQ = dW_p \tag{4}$$

$$\rho\, C_p\, dT = \sigma\, d\varepsilon \tag{5}$$

$$\Delta T = \frac{\lambda}{\rho\, C_p} \int \sigma\, d\varepsilon \tag{6}$$

*4.3. Digital Image Correlation results.*

DIC analysis was only possible with direct electric heating method. During the furnace heating, although a heat resistant paint was used, the paint dried excessively, losing its elasticity and causing the appearance of cracks in the paint that affected DIC results.

The observation at slow motion showed (140000 fps were recorded) a bottle neck behavior of the samples before breaking, thus localization occurs in the middle of the samples. Videos were processed, deformation fields were obtained and last frame of every sample was extracted (see Figure 9) to clearly show the strain localization.

A plot of strain over the length of specimen with fixed time in between two curves shows how the specimen has locally deformed with time. This was done by drawing a horizontal line in the center of the samples with the software, and extracting its strain during the different frames. Then, it was possible to see how strain was localized usually at the center of the sample. Curves at 700ºC are shown in figure 9.

Finally, by comparing the last frame of three samples at different temperatures as in Figure 10, it can be observed that the maximum strain in the gauge section of the sample prior to failure increased steadily as the testing temperature was increased. At 60 °C, the strains within the gauge section reached values almost 50% just before failure. At 300 °C, the maximum strains were close to 65%, and at 700 °C the maximum strains extended close to 80%. Therefore, the use of DIC shows a high deformation localization of the samples, and clear increments of the deformation when the temperature is increased.

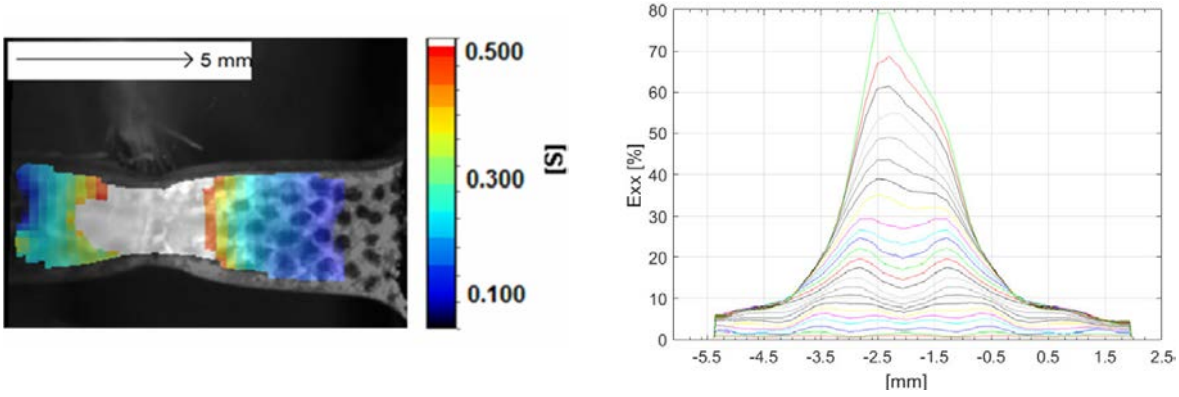


Fig. 9. Last strain field frame before final cracking at 700ºC, left; Strain distribution along the length at 700ºC, right.

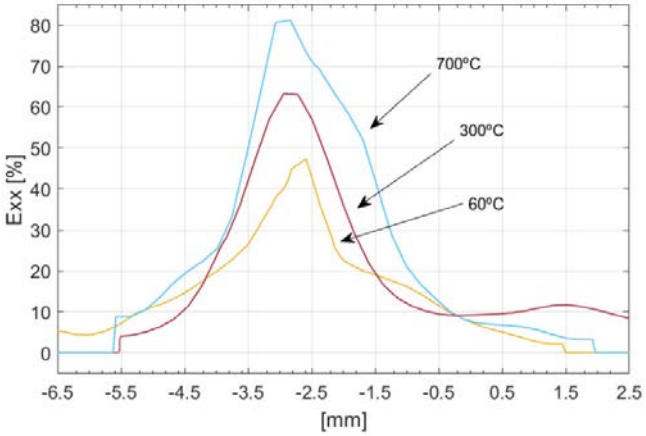


Fig. 10. Comparison of last frame strain distribution along the length of specimens at different temperatures.

## 5. Conclusions

Dynamic tensile loading at high temperatures on Ti6Al4V have been carried out by two different methods.

The noise on the waves obtained by furnace heating method increased with the test temperature, probably, because of the different thermal expansion between the bars, samples, and pins, which produced loosens in the

mechanical fixture of the samples. However, by using numerical filters it was possible to obtain similar results to those from electrical heating.

Waves obtained by electric heating method and glue fixture showed less oscillations than the ones from furnace method and were less influenced by the heating temperature. Besides, they allowed us to obtain temperatures up to 700 ºC without influencing the adhesive temperature and therefore its properties.

Glue was also employed on the furnace method up to 300 ºC to reduce the oscillations of the results. However, it did not reach the oscillation-free results of the electric heating method.

Temperature prediction resulted complex in electric heating method as it required short heating times and linear approximation. Moreover, it became more difficult due to local heating over the titanium samples-copper electrodes interface. As a solution, conductive aluminum grease was added to the interface.

Fixture and removal of the samples in the electric heating device involved the curing of the adhesive before testing as well as heating and cleaning with acetone after testing to carry on a new test, which limited the number of test to two or three per day.

Finally, the use of DIC showed a high deformation localization of the samples, and clear increments of the deformation when the temperature is increased.

## Acknowledgements

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