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CREEP-TESTING MACHINE RETROFIT FOR Ti-6Al-4V ALLOY STUDY

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Abstract. *The Nuclear and Energy Research Institute received two Creep-Testing Machine frame donated from Technological Institute of Aeronautics in nonfunctional mode. These apparatuses has arrived with structure, lever arm and tube furnace. However, they came with no strain gage and no temperature controller. In order to back the machinery to active mode, this work developed a Creep-Testing Machine modernization suite. In fact, this study developed a new PID controller hardware, based in an Arduino open platform. In addition, it used a LVDT developed in Brazil, by Technological Research Institute, to capturing the specimen strain. After the modernization suite implementation, it evaluated the creep strain-rate of the Ti6Al4V alloy at 873 K in 319 MPa. Moreover, compared the results of the same lot material tested in another two ones apparatuses. This open technology was able to maintain the specimen temperature in the set point, getting and saving the test results in a text file and it got results close to the most modern equipment.*

Keywords: *creep-rupture, retrofit, materials, characterization, titanium*

1. INTRODUCTION

The response of a part is presumed when the mechanical behavior of the component material is known for a stress circumstance. In order to obtain these characteristics, specimens are tested apps walk preset effort conditions on samples to determine their reactions, defining the design parameters able to predict failures (Garcia, Spin, & Santos, 2012). The most noted damage is fractures and unwanted deformations (Rhoads, [200?]).

The devices are also subject to merge of external factors. Which, even in the elastic zone, can cause problems with prolonged use. The combination of stress and temperature rise accelerate a breakdown, usually a rupture, precipitated by a phenomenon called creep (Callister, 2007). It is the permanent, time-dependent deformation of a solid under constant load. (American Society for Testing and Materials, 2011). It is a macroscopic reaction occasioned by the movement of disagreements in the microstructures of matter that make up this body (Rhoads, [200?]). The temperature contributes to this atomic level movement. The rise in heat causes the increase in steady state creep rates. (American Society for Testing and Materials, 1996).

Isothermal creep test consists of applying a static uniaxial stress on a sample. In a fixed temperature, between 0.4 and 0.7 of the absolute melting point. The strain is recorded as a function of time. And three regions characterize the elongation curve. In the first one there is an almost instantaneous response, followed by a decrease in the deformation rate. The secondary stage is where the strain increases linearly, this region is called the steady state, from a practical point of view, is the most important. Finally, in the tertiary the deformation increases rapidly until a catastrophic failure. Typically, the secondary strain rate estimate the creep resistance of a solid. By calculating and evaluated as a function of the applied load or stress. The elevation of temperature, load, or both, results in increased instantaneous deformation and the creep rate at steady state, in addition to decreasing the time to failure (Garcia, Spin, & Santos, 2012; Rhoads, [200?]; Callister, 2007; American Society for Testing and Materials, 2011; American Society for Testing and Materials, 1996; Frost & Ashby, 1982).

Most load devices apply the force of dead weight to the sample via lever arms. Generally, these devices type have no ability to compensate for changes in the cross-sectional area of the sample. However, it is satisfactory for long time creep tests and for creep tests where the total deformation before rupture is small. The short-term creep tests or constant stress creep tests require a variable load capacity machine. The United States Army Test and Evaluation Command (1968) also require 1% accuracy on applied stress and instructs to avoid twisting or bending in the sample. Long rods or flexible joints can prevent eccentricity.

The Center for Materials Science and Technology (CCTM) of the Institute for Nuclear and Energy Research (IPEN) received two inoperative creep-testing machines from the Aeronautics Technology Center. Manufactured by the "Electronic and Mechanical Engineering Co. Ltd." (EMEC) contains two devices: i) the G35 is a constant uniaxial tensile loading mechanism in a sample. Basically, it is a lever arm that amplifies the force employed by dead weight; ii) the G28 is a cylindrical furnace with three distinct heating zones. However, these apparatus came without strain gauge and without temperature controllers.

The electric furnace and the temperature regulating device are the most important items of the equipment. The furnace heater usually consists of nickel-chromium (NiCr) wire wrapped around a refractory tube. Keeping windings closed reduces the temperature gradients in the sample. An insulating cover is placed windings are closed, so that around the furnace to conserve energy and prevent temperature fluctuations.

Among the various automatic process control techniques, Proportional-Integral Derivative (PID) is the most common solution for practical problems. Proportional and integral action controllers have been reported to have been used in windmills and steam engines. However, the current format emerged with pneumatic controllers in the 1930s. Development was accelerated when, from the 1980s, microprocessor implementations emerged. (Åström & Hägglund, 2006).

The advantage of the digital controller over older temperature regulators is that more advanced furnace heating techniques can be applied to keep the temperature within ± 2 K for testing below 1273 K established. ASTM E139-11. To do so, the PID needs to be tuned and one of the most commonly used procedures is the Ziegler & Nichols (ZN) heuristic methods. (Ziegler & Nichols, 1942) open or closed mesh. Teixeira & Jota (2007), Gwak & Masada (2008), Beifei (2009), Nayak *et al.* (2012), Kumar *et al.* (2013) and Xie & Long (2015) proposed modified PID methodologies, which aimed to minimize the variability in furnace temperature in the most diverse processes. All are based on ZN tuning methods and computational implementation as described by Åström and Hägglund (2006).

The creep test consists in obtaining a strain curve, or its first derivative as a function of time. Therefore, it is necessary to measure the specimen elongation. Since the test is performed at temperatures between 773 K and 973 K, extensometer frames are employed to reproduce deformation on the outside of the furnace. So that a sensor can capture deformation without suffering thermal effects. The extensometers are made of material with low coefficient of thermal expansion and oxidation resistant, to prevent readings from being compromised.

One of the sensors used to measure the linear displacement is Linear Variable Differential Transformer (LVDT). It has numerous advantages over potentiometric transducers. These include measurement with very low friction, infinite mechanical life, excellent resolution and great repeatability (Al-Sharif, et al., 2011).

This special type of transformer measures displacement indirectly. While a common transformer consists of just two windings arranged where the variable magnetic flux produced in the primary winding acts on the secondary one (Boylestad, 2012). In the case of LVDT the amplitude in the flux variation is due to the variation in the magnetic permeability due to the moving ferromagnetic embolus that moves inside it. These sensors are based on the principle of mutual induction, but have a primary winding, which is excited by an alternating voltage, and two secondary windings, which should ideally be identical. When the core is in the central position, the two secondary windings have the same inductance (Drumea, Vasile, Comes, & Blejan, 2006) and the same voltage. This center point is called null point. With the change in position of the ferromagnetic core, the electromotive force induced in the secondary is no longer symmetrical. Measuring the induced voltage difference between the secondary windings provides the displacement.

Commercially, LVDTs are available to cover ranges from ± 0.25 mm to ± 75 mm. They are sensitive enough to be used to respond to displacements below 0.5 µm. and a maximum non-linearity of 1% of full scale (Eren, 1999). Its nominal sensitivity determines the value of the output voltage for each 1 V excitation in its nominal displacement.

In this context, the general objective of this work was to modernize the creep test machine, through electronic temperature control, automated collection of variables, which facilitate the obtaining of graphs, and produce reliable test results.

2. METHODS

2.1 Furnace Temperature Control

In order to determine the electrical characteristics of the furnace, a TRUE-RMS AC/DC digital clamp meter, model POL-08 manufactured by Politerm, was used with ± 1.0% accuracy for current measurement and ± 0.8%. for resistance or voltage measurement. To determine the thermal characteristics of the furnace, three solid-state relays (SSR) controlled the heaters. JNG Materiais Elétricos SSRs have a current carrying capacity of 25.0 A, rated voltage of 240.0 V in alternated current, and a peak output tolerance of up to 800.0 V. The K-type thermocouples, AWG 24, manufactured by Salcas Indústria e Comércio LTDA., Collected the instantaneous temperature in the center of each zone.

Boards with the Maxim MAX6675 integrated circuit (IC) transformed the thermocouple's electrical signals into digital information. These Analog to Digital Converters (ADCs). With a 12-bit data response, they are capable of reading temperatures between 273 K and 1,296.75 K, with 0.25 K resolution. The IC has a second internal temperature sensor to make cold junction compensation.

An Arduino Nano development platform combined the reading of the three zones into a single data packet and sent it to a personal computer (PC) to store the comma-separated text (CSV) read values. The Arduino has a CI microcontroller ATMEGA328P model, manufactured by Atmel. The microcontroller also managed SSR activation, each duty cycle had an average duration of 351.0 ms.

In order to obtain the heating and cooling curves, the following routine was performed: start data collection, turn on SSRs, wait 90 minutes, turn off SSRs, wait 140 minutes, and finally end data collection. From the collected data, the open-loop method was applied to determine the constants and tune the PID controller. The code embedded in the microcontroller acted in the heating process in order to maintain the internal temperature of the furnace around the SP. For this, the reading of the thermocouples fed the control system that acted on the controlled variable through the fraction of time the heater remains on. This fraction was updated in 3s cycles (approximately 0.34 Hz).

2.2 Specimen Elongation Measurement

For the deformation data, it used a Linear Variable Differentials Transformer (LVDT), model TD 43, which has a stroke of 38.0 mm and was produced by the Institute of Technological Research (IPT). The calibration assembly was performed using a micrometer with a measuring range from 0 mm to 25 mm and a resolution of 0.01 mm. The micrometer arc was removed so that both could be fixed concentric on a longitudinal axis, so that the movement of the movable backrest varied across the LVDT core.

In order to determine the null point, the LVDT course was extended and displacements were produced. With an Icel inductance meter, model RLC-410, with ± 2% accuracy, the position was found where the inductance of the two secondary ones was identical. At this point the sensor was connected to the signal conditioner, model GSTD 43, also produced by IPT, specific for this LVDT, and the conditioner output was set to 0 V voltage.

The signal conditioner was connected to a Texas Instruments ADC model ADS1115 and it was connected to the microcontroller that recorded the displacements in 0.5 mm intervals. Within the most linear range, ± 7.5 mm, from the null point, a linear equation was fitted by the least squares method.

2.3 Data logging

The equation was added to the embedded code in the microcontroller and provided the displacement with 1 µm precision. Four temperature sensors, three for the furnace zones and one for the sample. Data was received on a PC by free software Processing, which plotted graphs and saved the information to a file with the extension CSV, with updates every 588 ms. The microcontroller smoothed all the data with adjacent-average filter with 100 window points.

2.4 Comparison of Results

The evaluation of the improvements was obtained by direct comparison in performed tests. Assay conditions were determined so that assays were less than one hour based on Briguente (2011) studies. In this sense, we opted for the voltage 319 MPa, temperature of 873 K; in constant load mode. Deformation curves, in millimeters per millimeter, were plotted against time in seconds. The primary creep time parameter (t_p), secondary creep rate $(\dot{\varepsilon}_s)$, final fracture time $\left(t_f\right)$ and the fracture deformation $\left(\varepsilon_f\right)$ were compared in the tests performed in the object of this study and in two other apparatuses.

The first was manufactured by Denison Mayes Group (Mayes) and there is little information available. The retrofit was performed by the company BSW Tecnologia, Industrial e Comércio Ltda., Which in the modernization process inserted an update set and a thermal process controller of the Coel brand and model HW4200. The set is still composed of an electronic board and a software called Antares, capable of managing multiple devices on a single computer. The test data is based on one K Type Thermocouple (chromel/alumel) and one LVDT. Both installed in the sample. The capture board together the software records the furnace's internal temperature and specimen elongation. The furnace inside temperature is governed by the process controller from the feedback (feedback) of a second thermocouple. All thermocouples are type K and staying near the sample, but without touching it. The equipment belongs to the Mechanical Testing Laboratory (LEME) of the Materials Division (AMR) of the Aeronautics and Space Institute (IAE) of the Aeronautics Technology Center (CTA), located in São José dos Campos, SP. It was used by several authors (Reis, 2005; Barboza, 2001; Barboza., Moura Neto, & Silva, 2004; Briguente, 2011) in their research with the Ti-6Al-4V alloy.

The second equipment was a Kappa 10DS, manufactured in 2015 by the German company Zwick-Roell (Zwick). It has components from other manufacturers, namely the Eurotherm model 2604 temperature controller for independent control of three furnace zones; HBM LVDT and model 1-WA/50MM-T, with 50.0 mm stroke and 80 mV/V sensitivity at its nominal stroke; the servomotor Stegmaier-Haupt brand and model RX330CR1 with IGD26H-2500-V05-0 encoder 58 V supply voltage, electric current of 9.4 A, can provide torque of 1.54 Nm, in order to apply the load to the sample. Other parts and components have the Zwick-Roell brand, namely split furnace, with three heating zones and total electric power of 3500 W; R Type thermocouples (platinum/rhodium-platinum) to control the temperature of each zone; type N (nicrosyl—nisil) thermocouples for recording temperature in the sample; servomotor transfer device by two ball screws to the table holding the sample; load cell model Xforce K with nominal capacity of 10 kN and sensitivity of 2 mV/V; a proprietary software called “testXpert II”.

3. RESULTS

During the prototype implementation phase of the modernization set, some aspects were observed, which are described below.

3.1 Electric and thermal aspects of the furnace

The furnace heaters have 63.5 Ω in the upper and lower zones, in the central, 63.8 Ω. When supplied with its nominal voltage (220.0 V) provides a thermal power 2283.0 ± 18.5 W. When considering the margin of error of the measuring instrument, it is possible to infer the rated power is 2300 W. The temperature data as a function of time presented as exponential curves. Regression provided the maximum theoretical furnace temperature of 1,143.0 K above room temperature. Controller parameters were only assisted with Proportional (18.46) and Integral (295,457.0). Even so, in the temperature tests the controller could keep the sample variation below ± 2 K, as Fig. 1 display.

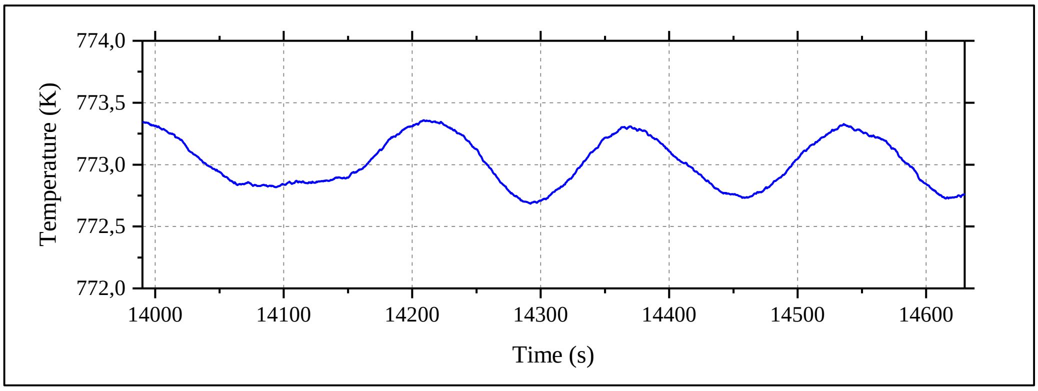

Figure 1. Preliminary heating test for 773 K set point, with 600 seconds temperature cutout.

3.2 LVDT Calibration

The set formed by the GSTD-43, ADC and microcontroller recorded digital values every 0.5 mm of displacement. A plot with the ADC readings as a function of displacement produced the graph shown in Fig. 2. The least squares linear regression provided the equation of displacement from the ADC reading as shown in Eq. (1).

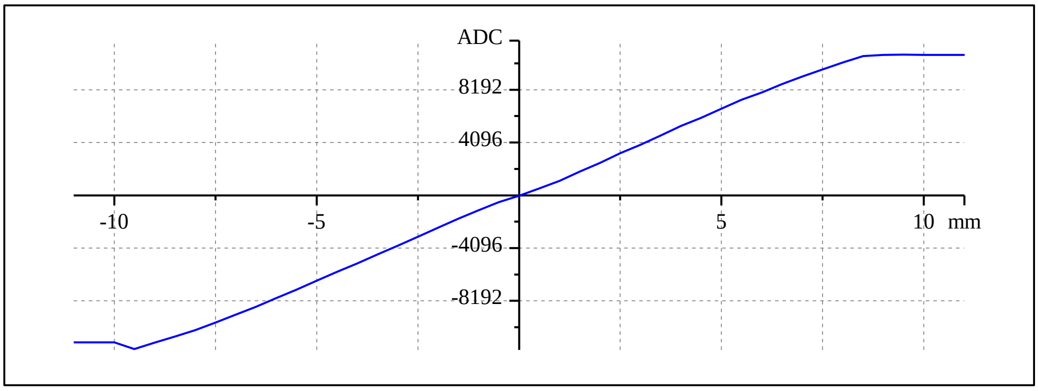

Figure 2. ADC (dimensionless) connected to the signal conditioner and LVDT, as a function of displacement.

$$x = ADC(7{,}564 \times 10^{-4}) - 4{,}392 \times 10^{-3}\ [mm] \quad (1)$$

3.3 Creep test

The Tab. 1 shows the creep-test results for specimens with equiaxial microstructure. It shows the primary creep times (t_p), the secondary creep rate ($\dot{\varepsilon}_s$), the final fracture time (t_f) and the fracture strain (ε_f).

Table 1. Creep data at 873 K and 319 MPa of Ti-6Al-4V alloy.

Tests	$t_p\ (s)$	$\dot{\varepsilon}_s\ (s^{-1})$	$t_f\ (s)$	$\varepsilon_f\ (mm/mm)$
Mayes (CTA)	39	5,04 x 10^{-4}	321	0,2412
Zwick (Mackenzie)	-	2,85 x 10^{-4}	615	0,2808
EMEC (IPEN)	52	2,71 x 10^{-4}	619	0,2986

There is a great similarity between the results of EMEC and Zwick. On the other hand, there is a divergence in rupture times and steady flow rate with Mayes in the order of 60%. However, only one test was performed for each equipment. Possibly, Mayes's temperature control was the critical point in its retrofit. Only a temperature point for the controller feedback is insufficient. This simplification did not take careful with the three heating zones. It can cause gradients into zones.

The variation of creep rates in the tests indicates that there are differences between the equipment. Although the load application on Zwick is through the spindle. The load is oscillated, even when the constant load method is selected, as shown in Fig. 2. There were no substantial differences between Mackenzie and IPEN results.

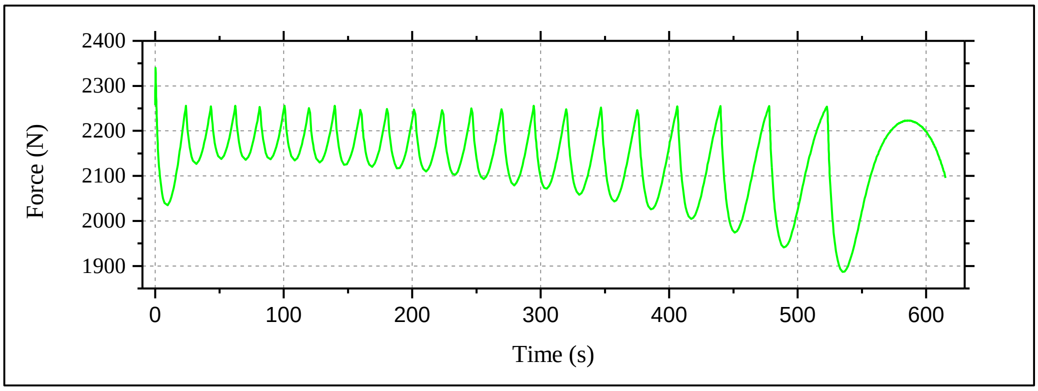

Figure 2. Force oscillation in Zwick apparatus while creep testing.

In the EMEC creep test, the temperature varied more than during the heating tests, as shown in Fig. 3. One possibility is that the control thermocouples needed to be moved to fit the extensometer frame to which the LVDT is attached. Another point is that this is another body transmitting heat out of the furnace. In this sense, it can be stated that the PID tuning has been compromised. The Fig. 4 shows the creep curves of Ti6Al4V alloy at 873 K and 319 MPa, tested in the three apparatus.

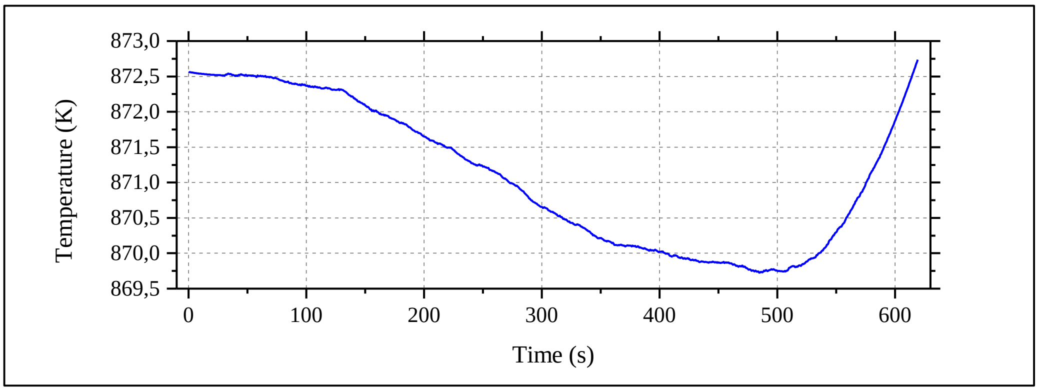

Figure 2. Temperature variation while testing, which could be visualized a deviation from 873 K setpoint.

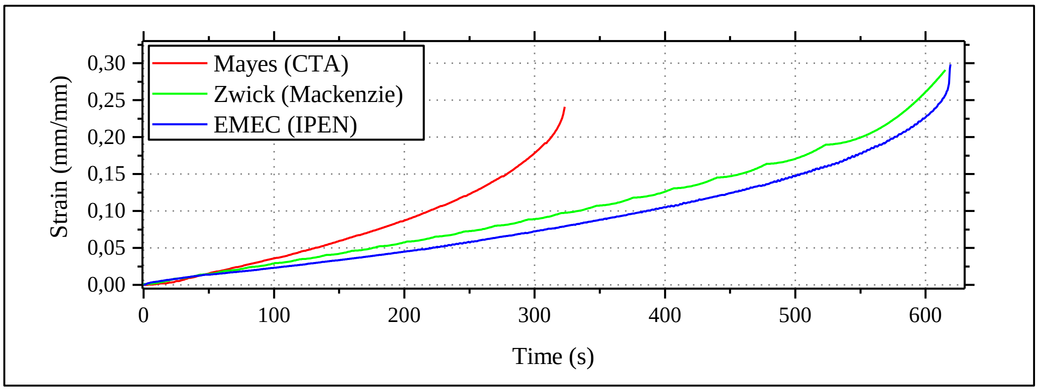

Figure 4. Overlapping strain curves as a function of time

4. CONCLUSION

Finally, the technological sophistication with a low-cost controller obtained results close to the most modern equipment. The application of advanced techniques could control and maintain the furnace temperature within the limits established by ASTM E139. Another positive point was the integration of all devices. The controllers and sensors in a single hardware allowed the recording of the test data in digital media in text format. In addition to the use of electronic devices in the deformation reading, the Creep-Testing Machine, which also, facilitating further analysis. The set can be reproduced free of charge because it uses open technology.

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