Stress-Dependence of Young´s Modulus of Ti 6242S at High Temperatures during Uniaxial LCF Tests

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Abstract

In several practical cases the material's elastic behaviour is very well described by Hooke's law. However, in alloys that exhibit a low Young's modulus and at the same time a high yield strength, such as the high-temperature near-alpha Titanium alloy Ti 6242S this is not the case. Ti 6242S is utilized mainly in the high-pressure compressor of jet engines. In such an environment the material undergoes fatigue loads. It is therefore necessary to ascertain the cyclic properties of the material at service temperature in order to guarantee safe life of the components. During low cycle fatigue tests at elevated temperatures (350; 450; 550 and 650°C) the elastic part of the deformation was calculated. The shape of the stress vs. strain response was not linear, as might have been expected, but rather crescent-like. This observation may be attributed to the fact that the elastic modulus is stress-dependent as a consequence of non-linear effects. This dependence was determined quantitatively. In order to establish the usual linearity of the elastic behaviour, Hooke's law was expanded by a quadratic term. In such a way it is characterized by two constants. While the Young's modulus remains a function of temperature, the second constant, named “K”, neither alters its value with temperature nor applied stress or strain amplitude. For Ti 6242S the value of K was calculated to be 210,000 MPa.

Key words: Low cycle fatigue, hysteresis loop, k factor, Young´s modulus, Hooke´s law.

Resumen

En varios casos prácticos el comportamiento elástico del material esta descrito muy bien por la ley de Hooke. Sin embargo no es el caso, en aleaciones que exhiben bajo módulo de Young y al mismo tiempo elevada resistencia a la cedencia, como lo es la aleación de titanio para elevadas temperaturas cuasi-alfa Ti- 6242. Ti-6242 son utilizadas principalmente en el compresor de alta presión de motores a reacción. En tal ambiente el material experimenta cargas por fatiga. Es por ello, necesario precisar el comportamiento cíclico del material a la temperatura del servicio para garantizar la vida segura de los componentes. Durante los ensayos de fatiga de bajo ciclaje a elevadas temperaturas (350; 450; 550 y 650°C) fue calculada la componente elástica de la deformación. La forma de la histéresis esfuerzo vs deformación no fue lineal, como lo esperado, sino en forma de *crescent-like*. Esta observación puede ser atribuida al hecho que el módulo elástico es esfuerzo dependiente como resultado de efectos no lineales. Esta dependencia fue determinada cuantitativamente. La ley de Hooke fue expandida por un término cuadrático con el fin de establecer la linealidad usual del comportamiento elástico. De tal manera es caracterizado por dos constantes. Mientras el módulo de Young esta en función de la temperatura, la segunda constante, denominada "K", no es afectada por la temperatura ni por la amplitud de la deformación y esfuerzo aplicado. Para la aleación Ti-6242 se calculó el valor de K estando en el orden de 210.000MPa.

Introduction

In order to investigate thoroughly the low cycle fatigue behaviour of Ti6242 it is recommended to conduct isothermal as well as thermomechanical tests under plastic strain control. Usually one can express plastic strain in the following way

$$\varepsilon_{pl} = \varepsilon_{mech} - \frac{\sigma}{E} \qquad (1)$$

However, titanium alloys show a stress-dependence of Young’s modulus, i.e. it is not a constant value anymore. Therefore Hooke’s law has to be expanded by a polynomial of the second degree

$$\sigma = E_0(T) \cdot \varepsilon_{el} + k \cdot \varepsilon_{el}{}^2 \qquad (2)$$

Equation (2) is only valid for single crystals. The elastic behaviour of polycrystalline material results from a complex superposition of the potential curve as a function of the atomic distance, since the elastic recovery is due to the action of interatomic and intermolecular forces.[1,2]

The extension of Hooke's law is especially relevant for materials with low young's modulus and high yield strength as this conventional titanium alloy, (at room temperature: E = 114 GPa, $R_p0.2$ = 980 MPa).

Ti-6242 is a near-alpha titanium alloy currently used in the compressor part of jet engines. According to this, such material is subjected to dynamically load during service. So it is necessary to assess the material's response to cycle stress. Normally the range of loading above the limit of pure elastic deformation is of special interest; because repeated microplastic or plastic deformation can lead to failure of the component by fatigue damage (this regime is called low cycle fatigue). Thus, the lifetime is governed by the plastic strain amplitude. In order to ascertain the control parameters, the contribution of the k factor to plastic deformation has to be recognised.

Lightweight alloys for high-temperature application on the basis of titanium alloys will contribute to the demand for the worldwide decrease of greenhouse gases (Kyoto Protocol, 1997). Such alloys will improve efficiencies of engines (e.g. gas turbines)[3]. One way to achieve this goal is increasing service temperature.

Therefore plastic-strain-controlled low cycle fatigue tests on this material are necessary to ascertain the applicability at elevated temperatures. Considering the contribution of the k factor to the control signal is the incentive of this work.

Experimental

A schematic sketch of the experimental set-up consisting of a sample in the MTS machine is shown in Fig. 1[4]. Fatigue tests were carried out in a MTS servohydraulic test system. A vacuum recipient allowed eliminating air's contribution to the fatigue process. The specimens were heated by radiation (induction furnace coupled around the specimen) Temperature was measured and controlled using a calibrated thermocouple type K attached to the centre of the gauge length. The parameters were controlled and the data collected by using the MTS programme Advanced Cyclic

Fatigue in LCF. The dimension of the specimens are 16mm of gauge length and a diameter of 8mm. Ti6242 specimens were tested both at room and elevated temperature in the range of 350-650°C. LCF tests were carried out in total ($\Delta\varepsilon_t/2$ = 0.7%) and plastic ($\Delta\varepsilon_p/2$ = 0.2%) strain control and under stress control ($\Delta\sigma/2$ = 400 and 600 MPa). All experiments were performed applying a triangular command signal for plastic or total strain control and temperature. For calculation the stress- strain hysteresis loop response the true plastic strain was not measured directly, instead it was calculated continuously by the computer program during the test using the following equation:

$$\varepsilon_{pl} = \varepsilon_{tot} - \varepsilon_{el} \qquad (3)$$

Where ε_{tot} is the measured total strain, ε_{el} is the elastic strain calculated by extension of Hooke´s law (eq.2) [5,6].

Results & Discussion

Calculation of Young’s modulus’ temperature dependence

Due to the elastic modulus’ change with the temperature, this was calculated experimentally. These results were compared with the literature [5,6] and also with the calculated using the empiric equation developed by Rösler et al., 2003 (eq.3) [7], in order to check the accuracy of our results.

$$E(T) = E\,(0\ K)\,.(1\text{-}0{,}5\ T/T_m) \ldots (4)$$

T, is the current temperature, T_m, melting temperature in absolute grade.$T_{mTi6242}$ K = 1978 K, E_{Ti6242} $(0\ K)$ = 123,3 GPa [6]

(Figure 2)

Calculation of Plastic Strain Low Cycle Fatigue test (LCF)

For tests under total strain or stress control, the absolute maximum and minimum values are the control parameters. However, if the test takes place in plastic strain control, then one has to make sure that the plastic strain range at zero-stress corresponds to the control parameters. Therefore it is necessary to make sure that the arms of the plastic hysteresis are absolute vertical when only elastic deformation occurs. If the Young's modulus is stress-dependent then it is necessary to quantify this dependency before running the test in plastic strain control. In this study the calculated k-factor was - 210,000.

$$\varepsilon_{tot} = \varepsilon_{mech}$$
$$\varepsilon_{el} + \varepsilon_{pl} = \varepsilon_{tot}$$
$$\varepsilon_{pl} = \varepsilon_{tot} - \varepsilon_{el}$$

$$\varepsilon_{el} = \frac{-E + \sqrt{E^2 + 4 \cdot k \cdot \frac{F}{A}}}{2 \cdot k}$$
$$k = -210.000 MPa$$
$$A = 50{,}2655 mm^2$$

$$\varepsilon_{pl} = \varepsilon_{tot} - \left[\frac{-E + \sqrt{E^2 - 16.711{,}2632 \cdot F}}{-420.000} \right]$$

- Hysteresis loops. LCF under total strain control (Figures 3-4)
- Hysteresis loops. LCF under plastic strain control (Figure 5)

In figures 3 and 5 (c) it is possible to consider the k-factor as constant for this alloy at all temperatures.

Figure 6 shows an example of the effect of the k-correction under plastic strain condition. At higher loads the stress-dependency of the Young's modulus can be seen in the way that the hysteresis's axis becomes vertical. (Figure 6)

- LCF Stress strain response under Stress control

It is possible to show the stress-dependency of Young's modulus very well by cyclic testing at small amplitudes (in this case stress-control is better than strain-control). The hysteresis will have a crescent-like shape. With the k-factor it is possible to "make" the hysteresis straight. Figure 7 gives an example of a hysteresis loop obtained under stress control condition.The effect of the stress dependency of the young's modulus can be seen clearly if a specimen is loaded with little deformation. Then, if a constant young's modulus is expected, the plastic strain hysteresis will become crescent-shaped. (Figure 7)

The fig 8 shows the hysteresis loops response whit k factor correction included. (Figure 8)

Conclusions

Engine components are exposed to low-cycle fatigue. This regime is governed by plastic-strain amplitude. In this study it has been shown that for materials with low Young's modulus and high yield strength, it is not correct assuming a constant Young's modulus in the elastic regime. Instead, the modulus of elasticity becomes a function of stress. This stress dependency can be considered by an extension of Hooke's law. This correction is an essential prerequisite for conducting tests under plastic strain control. In this study it was demonstrated how to obtain this expression for the extended Hooke's equation for the near-alpha titanium alloy Ti6242.

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