LMECA2410 – Mechanics of Materials

Material Selection Project

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Project Overview

1 Damage Parameter

In this part we analyzed the damage of TiAl6V4 Metal, which is an alpha-beta titanium alloy known for its high specific strength and excellent corrosion resistance. Our analysis was for the damage of this metal under tensile yielding.

1.1 Parameter Formulation

By definition we have: $D = \frac{A - A_{eff}}{A}$ so $A_{eff} = A(1-D)$

we know that $\sigma = \frac{F}{A}$ and $\sigma_{eff} = \frac{F}{A_{eff}}$

Based on Hooke's law:

$$\sigma = \varepsilon E \Rightarrow \varepsilon = \frac{\sigma}{E} \quad \text{and} \quad \sigma_{eff} = \varepsilon E_{th} \Rightarrow \varepsilon = \frac{\sigma_{eff}}{E_{th}}$$

So:

$$\frac{\sigma}{E} = \frac{\sigma_{eff}}{E_{th}} \Rightarrow \frac{\cancel{F}}{\cancel{A}.E} = \frac{\cancel{F}}{\cancel{A}(1-D)E_{th}}$$

Finally we obtain:

$$E = E_{th} - E_{th} D \Rightarrow \frac{E - E_{th}}{E_{th}} = D$$

Figure 1: Damage parameter formulation as a function of the effective Young's modulus

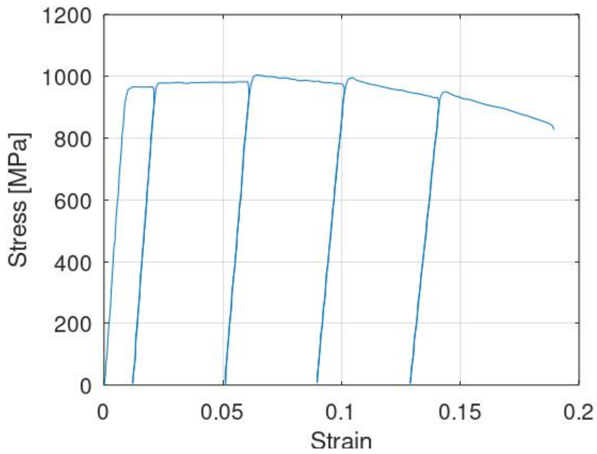
1.2 Stress Stain Curve

This report presents an analysis of stress-strain curve experimental data obtained from a material subjected to tensile loading. The material was loaded incrementally until reaching its yield point, then unloaded, and subsequently loaded again until reaching its yield strength. This loading and unloading process was repeated until the material fractured. Below are the experimental results in figure 1 and figure 2.

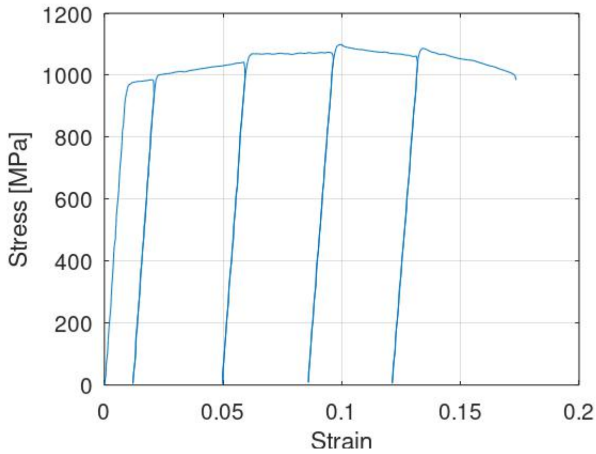
Comments:

- We can observe that the engineering stress-strain curve has a higher strain before rupture. This is because the engineering stress-strain curve doesn't consider the reduction in cross-sectional area during deformation. As a result, the calculated stress values tend to be higher, and the calculated strain values tend to be lower compared to the actual conditions of deformation. This results in higher apparent strain values and different stress values compared to the true stress-strain curve.

- For the rest of our analysis we will use the true stress strain curves because it represents better the material behaviour.



(a) Engineering Stress Strain Curve



(b) True Stress Strain Curve

1.3 Damage Parameter Calculation

The Damage Parameter were calculated using the formula obtained above using the Young's modulus (Slope of the elastic region of the stress strain curve). E_{th} was the Young's Modulus from the first loading and E was the Young's modulus of the subsequent loading after deformation. Since there were four subsequent loading after deformation we obtained 4 damage parameters which were calculated as shown on table 1

	Damage [%]
1	0.5122
2	2.1054
3	6.8512
4	9.7744

Table 1: Values of damage

Comments:

- We can observe that the Damage is increasing after subsequent loading after yield. This makes sense as the material is undergoing plastic deformation on every subsequent loading which damages the material.
- We can also observe that the Fracture happens after the 4th loading where the material has around 10 percent damage.

2 Brittle to ductile transition

2.1 Heat Treatment Analysis

In this part we will be analyzing the suitable heat treatment for the Stainless steel 17-4 PH (AISI 630), that is typically used in Nuclear control rods. The goal of the treatment is to provide the material with high mechanical strength and toughness.

We will be analyzing the 3 different modes of heat treatment namely: Quenching, Anealing at 450°C and Annealing at 600°C

2.1.1 Mechanical Strength Analysis

Below are the stress-strain curve of the heat treatments:

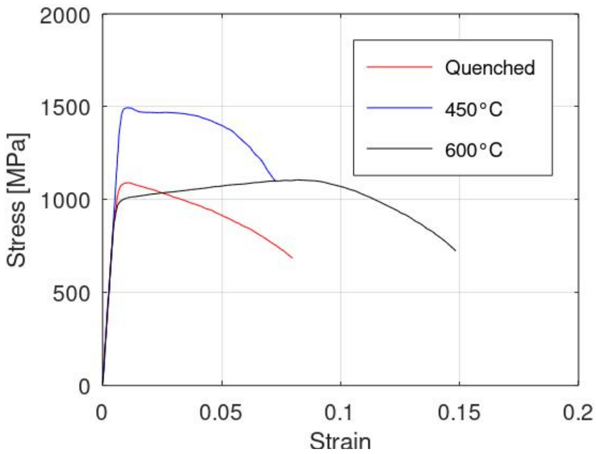


Figure 3: True Stress-Strain Curve

Comments: We can see that the 450 has high yield Limit, but the 600 has higher deformation before fracture. Based on this first graph, the heat treatment at 450° seems to better suit our specifications because we are looking for a material with good mechanical resistance

2.1.2 Mechanical Toughness Analysis

The operation temperature for the nuclear control rod application we are studying is around 280°C and 330°C

Below are the Ductile to brittle transition curve of the heat treatments:

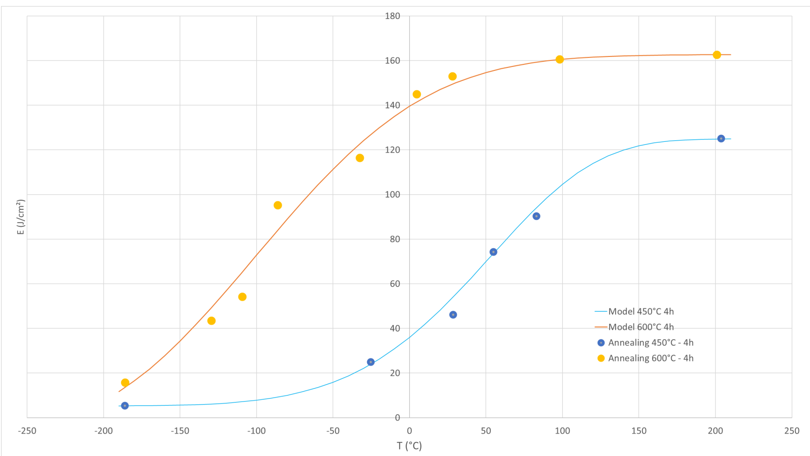


Figure 4: Fracture Energy Graph

Comments: At the temperature range of operation, we can see that the Crack Fracture Energy is higher for the Annealing 600°C 4h that is around 162 J/cm^2 whereas for the Annealing 450°C 4h it is around 125 J/cm^2. Fracture energy, or toughness, is an important measure of a material's ability to absorb energy before breaking. A difference of $40J/cm^2$ suggests that the heat treatments at 600°C gives the material a better ability to resist fracture and absorb energy. High temperatures can also affect the thermal stability of the material, which can influence its resistance to heat and corrosion. Finally, heating a material can modify its micro-structure and so its mechanical properties. Therefore we will prefer heat treatment at 450°C for its high yield limit.

2.2 Brittle Fracture Explanation

In this part, we will attempt to explain the sudden brittle fracture of an annealing at 450°C for 4h Steel. This fracture came at after a sock during maintenance when the material had 10 years of service.

2.2.1 SEM Image analysis

After aging at 450°C for 50h and shock testing, we notice grains of relatively large size and quite numerous, those are manganese sulfides, we suppose. After aging at 450°C for 100h and shock testing, we also notice a phase change in places where the aggregates become homogeneous. After 150 hours, the granular structure completely disappeared, and has been replaced with crystals. More precisely we can identify the first image where the material is ductile, the second as a transition phase and the last the material has become fragile. On the other hand, due to the crystalline structure of the aggregates, the atomic bonds along certain planes may be weaker than others, as well as leading to bigger stress concentration factors, which in the end causes a lower energy of fracture to break those samples (brittle behaviour).

2.2.2 Effect of Aging on Fracture Energy

The changes in fracture energy due to aging show a decrease in energy absorption with increasing aging time. After 4 hours, the material allows a greater quantity of fracture energy to be stored due to its granular configuration and can therefore be plastically deformed (ductile behaviour). We also note that at maintenance temperature (25°C) the absorption energy is significantly higher after 4 hours than after 170h. In addition, still at 25°C, we notice that the material is ductile for 4 hours while after 170 hours it becomes fragile. So the curve confirms the hypotheses that we had made just before concerning the transition from ductile to brittle of the material.

2.2.3 Effect of Aging on Yield Stress

Knowing that the yield stress is proportional to the hardness ($H \approx 3\sigma_y$), it can be suggested that they follow the same evolution, as the aging time increases. For small aging times (<50h), the impact is important, as the yield stress quickly rises. For long aging times (>50h), the evolution is softer, and it almost becomes non-significant at some point.

If we assume cleavage stress is constant, but the hardness is increasing, we can suppose that the material will become more fragile, as explained in the documents given, When the cleavage stress falls below the elastic limit of the metal, the fracture occurs in a brittle manner, without macroscopic plastic deformation. This results in a low absorbed energy in Charpy testing. On the contrary, if the elastic limit is lower than the cleavage stress, the metal undergoes plastic deformation before fracture (ductile fracture), leading to a high absorbed energy.

2.2.4 Effect of Aging on Concentration of Elements at the surface of grains

We can see that the aging has had the effect of the segregation of elements on the edges of the grains and in particular phosphorus. A high segregation of phosphorus at the grains boundaries lead to a change of mechanics properties. The impact of the segregation may cause a drastic decrease of the interface energy, favouring intergranular decohesion and so the material become more brittle.

2.2.5 Explanation of the Brittle Fracture

Essentially, the material undergoes a transition from ductility to brittleness. This change can be triggered either by the segregation of phosphorus atoms along grain boundaries, that lead to surface deterioration. The second way is by an increase in hardness, thus induce a reduction of shock resistance.