# Some Remarks on Low Cycle Fatigue Testing and Evaluation Procedures

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***ABSTRACT:*** *One of the basic design parameter of the engineering structures are operating at high temperatures under cyclic loading conditions is the low-cycle-fatigue (LCF) properties of the materials. These parameters can be determined in experimental ways. Two types of experiments are widely used, i.e. the **soft type** or the **stiff type** loading conditions. In the case of soft type loading condition the load amplitude is constant during the test in the stiff type condition the strain amplitude is constant. This last testing procedure can be performed with either constant **axial** or constant **diametrical** strain amplitude. The paper emphasises the advantage of the diametrical strain controlled testing procedure performed on the hour glass specimens.*

## INTRODUCTION

One of the basic design parameter of the engineering structures are operating at high temperatures under cyclic loading conditions is the low-cycle-fatigue (LCF) properties of the materials. These parameters can be determined in experimental ways. Two types of experiments are widely used, i.e. the **soft type** or the **stiff type** loading conditions. In the case of soft type loading condition the load amplitude is constant during the test in the stiff type condition the strain amplitude is constant. This last testing procedure can be performed with either constant **axial** or constant **diametrical** strain amplitude [1]. The testing results are evaluated analytically. The most widely used relationship between the stress (strain) amplitude and the lifetime is the power type relationship, the Manson-Coffin law contains two parameters.

If we are speaking about the *fracture conditions* in principle it can be formulated in term of the ***stress, strain*** (deformation) and ***absorbed energy***. The first two are vector quantity the last is scalar one, which includes both the stress and strain field of the fractured volume that is why the application of the energy criteria is most suitable. The absorbed energy in the investigated volume at LCF testing can also be determined experimentally.

This is approximately equal to the sum of the hysteresis loops shown in Fig.1.

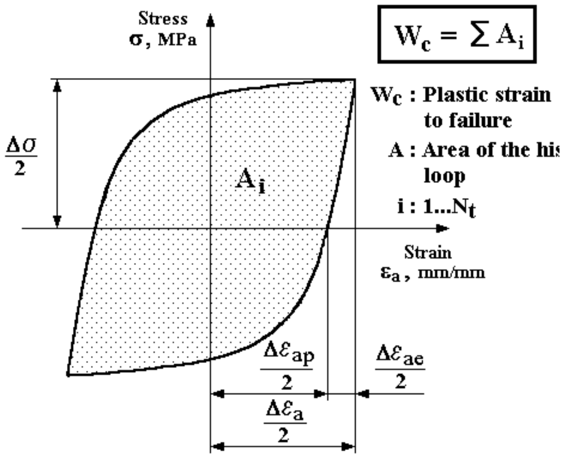

Fig 1. The energy criteria for fracture as the sum of the hysteresis loops

The most widely used specimen types are schematically explained in Fig. 2. i.e. the cylindrical or hour glass types. The cylindrical specimens are either bulk or tubular type. The experimental determination of the absorbed energy till to fracture has some basic problems. One of them belongs to the failure criteria, i.e. the criteria to cancel the testing procedure, the other is belonging to the loading parameter (stiff type or soft type loading), and the third problem is the type of the specimen. It is obvious that the testing results have to be transformed to the designed engineering elements, i.e. for

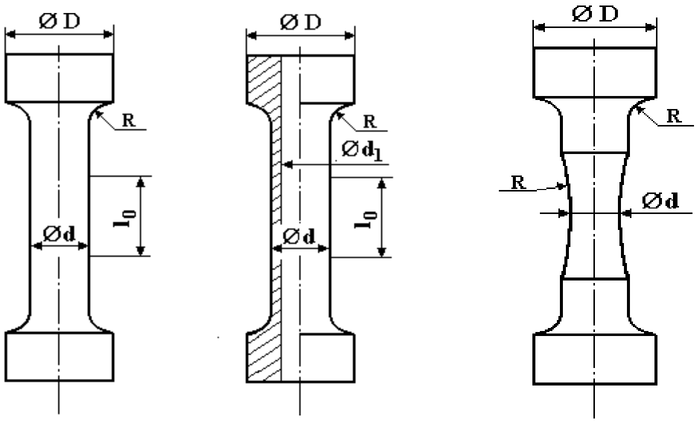

Fig.2. The most widely used types of the specimens for LCF testing

instance the parameters of the Manson-Coffin law determined experimentally on specimens can be used in lifetime prediction if the stress-strain field in the component is determined by numerically (using numerical methods of continuum mechanics).

For the total sum of the hysteresis loops as the function of the plastic strain amplitude in literature in general that type of function can be found which is shown in Fig.3.

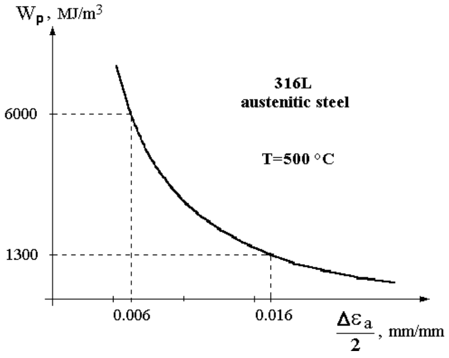

Fig.3. The sum of the areas of the hysteresis loops till to fracture vs. plastic strain amplitudes

According to the Fig.3. the absorbed energy till to fracture is not constant, it depends on the plastic strain amplitude, i.e. this work can not be regarded as the material property, as a fracture criteria because its value depends on the testing procedure.

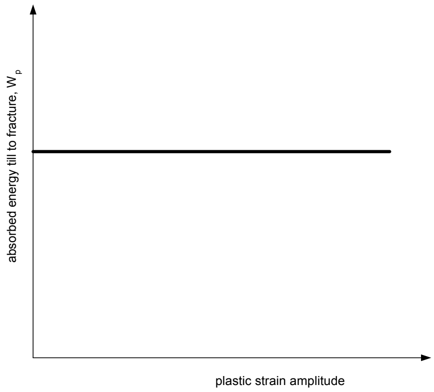

Fig.4. The shape of the sum of the areas of the hysteresis loops till to fracture vs. plastic strain amplitudes if the absorbed energy a material property is.

If the absorbed energy is independent of the loading conditions, i.e. of the strain amplitude, than material parameters, i.e. for instance of the Manson-Coffin parameters are material properties and they are transferable to the engineering components. From this it follows that the following basic question needs to be answered: ***the difference in shapes of the Fig.3 and***

***Fig 4. can be connected with the testing conditions or not?*** This question can be answered by analysing the testing and damage conditions, which takes place during the testing performed on different specimen types with different control conditions. Basically two types of control can be used, i.e. either axial or diametrical control. Reference volumes of the specimens are defined by each of them. In the case of axial control this volume for the cylindrical specimen is

$$V_R = \frac{d_0^2 \pi}{4} L_0,$$

in the case of diametrical control for the hour glass specimen the reference volume is

$$V_R = \frac{d_0^2 \pi}{4} dL_0,$$

where $d_0$ is the initial diameter of the specimen at the strain controlled region.

The absorbed energy in both cases are measured on these volumes, i.e. the total sum of the hysteresis loops are referenced to these volumes. Considering the damage processes take place in these reference volumes can be roughly divided into two parts, i.e. into the ***uniform*** and ***localised*** damages. This is illustrated in Fig.5. At the beginning of the testing the specimen has no any damage. After a given number of cycles ($N=N_1$) a uniform damage takes place in the reference volumes as it is illustrated in Fig.5. Continuing the tests to the number of loading cycle of $N=N_2$ the measure of the uniform damage increases. The sum of the hystersis loops reflect to the absorbed energies of the reference volumes defined on the specimens. After a given number of the cycles ($N=N_3$) the damage is localised. Using hourglass type specimen this localisation takes place in the smallest section of the specimen where the testing procedure is controlled. Using smooth cylindrical specimen the places of the damage localisation and testing control are not absolutely the same. Continuing the tests the localised damage value is increasing. The sum of the hysteresis loops reflects to the average value of the damage. The further behaviours of the locally and uniformly damaged volumes are influenced by cyclic behaviours of materials. If the material cyclic hardening is than the damage of the uniformly damaged volumes slightly increases both in axial and diametrical control conditions. If the testing is carried out on the smooth cylindrical specimen the damage can also localised another place(s), section(s) as well while the propagation of the small crack can be stopped. If the material cyclic softening is than the uniformly damaged volumes are approximately constant, only the further damage localisation takes place in both types of specimen. From the above mentioned facts it follows that the sum of the hysteresis loops after the appearance of the damage localisation reflects to some kind of average damage of the reference volumes. In the case of hourglass specimens this reference volume is smaller than at the axial controlled and there is no possibility of the appearance different damaged centres as in case of the smooth cylindrical specimens. That is why the sum of the hysteresis loops, i.e. the value of the measured absorbed energy is higher at the axial controlled testing performed on smooth cylindrical specimens than diametrical controlled ones. The possible damage situations are schematically illustrated in Fig.5.

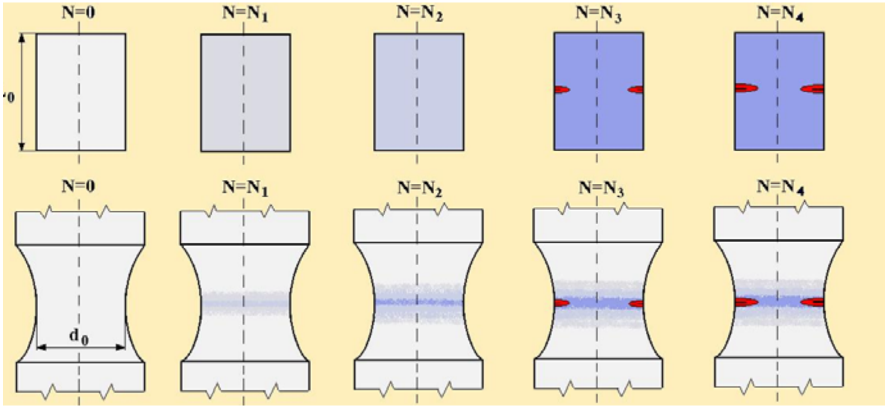

Fig.5. The damage localisation process on axial and diametrical controlled LCF testing

It is obvious that the ratio of absorbed energies used for uniform and localised damages depends on the loading amplitude. If the loading amplitude is high, than the localisation of damage – the appearance of the main crack - will be attained after some loading cycles. In this case there is no chance of the creation some more localised damage centres, i.e. the measured „average damage value" at higher strain amplitude will be smaller than at lower strain amplitude. In this last case namely the main crack will originated from any of the localised damage centres, so in the average damage value the creation of some more localised damage centres will also be included. The above mentioned thought is absolutely reflected in Fig.3., where the total sum of the hysteresis loops, i.e. the value of the absorbed energy till fracture is decreases with increasing the stain (loading) amplitude. Considering the above mentioned thoughts and the Fig.5. the following conclusions can be drawn:

- In the total sum of the hysteresis loops, i.e. in the absorbed energy are reflected all the damage processes which take place in the reference volume.
- The reference volume is higher of the axial controlled testing procedure using smooth specimens than diametrical controlled testing method on hourglass specimens.
- In case of axial controlled testing procedure in the total sum of the hysteresis loops are included the absorbed energies which are used for creation of uniformly damaged volume, of some localised damaged volumes in the reference volume and the initiation of the main crack.
- In case of diametrical controlled testing procedure using hourglass specimens the possibility of creation more localised damaged volumes in the reference volume is smaller, so the measured average value of the absorbed energy till fracture is smaller.
- The average value of absorbed energy till fracture in principle decreases with increasing the strain (loading) amplitude in case of **axial controlled** testing procedures on smooth cylindrical specimens. The tendency depends on the cyclic behaviour of material (i.e. cyclic hardening or softening). The more considerable decreasing of the absorbed energy can be expected for cyclic hardening materials.
- In principle the constant average values of the absorbed energy (if the energy criteria of fracture is accepted [2,3]) can experimentally be measured on diametrically controlled hourglass specimens with different loading amplitude, except in case of a remarkable cyclic hardening behaviour. In this case the reference volume (in which the damage occurring) continuously increasing during the test.

The above mentioned through has been experimentally verified on a KL9 type of steel with the following chemical composition: C=0.14%, Mn=0.58%, Si=0.25%, Cr=0.86%, Mo=0.45%, S=0.03%, P=0.04%. The testing temperatures are: 20, 450, 500 and 550 $^{o}$C. The testing has been carried out using MTS universal servohydraulic system with 250 kN load capacity. The shape and dimension of the specimens is illustrated in Fig.6. The controlled parameter was the strain measured in diameter ($\varepsilon_d$). The LCF testing has been carried out in the following ranges: $\varepsilon_d=\pm 0.0012$ - 0.0058 mm/mm, with a loading (asymmetry) factor of R=-1. The frequency was 0,5 Hz sinusoidal. The fracture criteria were defined as the 25% loss in load in the pull regime [4].

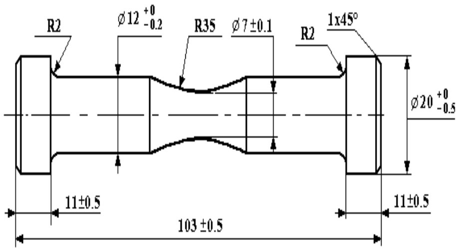

Fig.6. The shape and dimensions of the specimens

The load and the value of the diameter have been continuously measured and saved during the tests The absorbed energies values measured at different temperatures and strain amplitudes are plotted in Fig. 7a. – 7d. In Fig.7a-7d. it can exactly be seen that the absorbed energies measured at 450, 500 and 550 $^0$C are approximately constant, i.e. their values does not depend on the strain amplitude, they are depends on the temperatures only. Their values decreases with increasing of the temperature, which is in agreement with the fact that at higher temperature the contribution of thermofluctuation process to plastic deformation is higher. The total sum of the hysteresis loops, i.e. the absorbed energy depends on the strain amplitude only at room temperature. Considering the schema, which is illustrated in Fig. 5. and the fact that the investigated steel has a cyclic hardening behaviour (especially at room temperatures) it can stated that the reference volume cyclically increases, i.e. the damaged volume continuously increases even at diametrical controlled testing conditions.

## SUMMARY

On the basis of the speculations related to the uniform and localised damage of the reference volume of material, which is selected to be strain controlled region at low cycle fatigue testing the following conclusion can be drawn:

1. The absorbed specific energy till fracture experimentally can be measured in principle on hourglass specimen using diametrical controlled testing procedures. If the absorbed energy is not a constant value (i.e. depends on the strain amplitude) at a given temperature than the reference volume increases due to the cyclic hardening behaviour of the tested material.
2. The absorbed specific energy till fracture, i.e. the sum of the hysteresis loops measured on smooth cylindrical specimens in regime of axial strain control decreases with increasing of the strain amplitude because of the appearing of some localised damaged volumes. The appearance

probability of the inhomogen localised damage volumes is smaller if the strain (load) amplitude increases.

3. The absorbed energy till fracture of the investigated CrMo steel measured on hourglass specimen at 450, 500 and $^{0}$C using diametrical controlled LCF testing procedure decreases with increasing of temperatures.

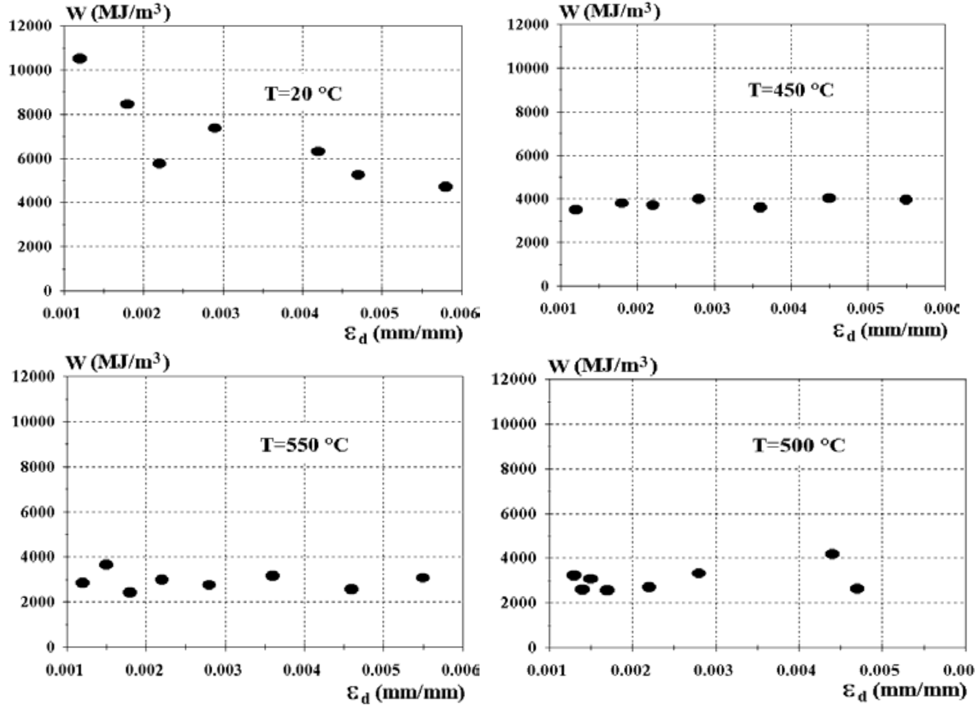

Fig 7a. – 7d. The absorbed energies values measured at different temperature with different strain amplitude

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