Determination of the fatigue limit by semi static tests

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ABSTRACT. Following the first experimental results concerning the possibility to estimate the fatigue limit by quasi-static traction test, the authors give a physical explanation about the process of the failure of a specimen. It was put in evidence the link between the complete thermo-elastic phase under traction stress and the beginning of the punctual plastic deformation in the zone of the classic stress strain curve yet distant from the yield limit of the material. The tests carried out on the AISI 304 steel by thermal analysis, confirmed the good approximation between the values of the fatigue limit estimated by fatigue test and by the quasi-static test. The results shoed the importance of the thermo-analysis of the part of the stress-strain curve (distant from the yield point) where only in macroscopic terms the behavior is perfectly elastic.

KEYWORDS. fatigue, plastic energy, infrared thermography, mechanical characterization of steel.

INTRODUCTION

In previous work, the authors, proposed a methodology to find the fatigue limit of the materials by means of a thermo-analysis of the specimen surface during a classic mono-axial traction test. Following the results, the aim of this work is the use of the procedure for a different material (in terms of released heat under stress) and, in the same time, the use a more complete approach to verify the validity of the method.

The calorimetric effect associated to elastic deformation and plastic deformation is observed by different researchers. The thermoelastic effect was studied By lord Kelvin [1] and the termoplastic effect was analyzed by Taylor and Quinney [2]. With the possibility to read the surface temperature of specimen during tests by infrared image processing, many authors worked to use the thermoplastic effect to define mechanical characteristics of materials. In 2000, Chrysochoos and Louche [3] analyzed the surface temperature by infrared camera during static traction test of a flat and thin parallelepiped sample. They using infrared image processing, based on Fourier's techniques, observed a sudden dissipative effect due to the propagation of the Luders band during local plastic deformation. In 2009 Plekhov and Naimark [4] with use of high sensitivity infrared camera demonstrated that in static traction test the plastic strain localization are accompanied by emergence of heat waves and their propagation over the specimen surface. In all literature examined never it was been linked the heat released to the dynamic failure of the specimen. A. Risitano and G. Risitano [5] noted that the slope changing in the temperature vs strain curve was linked with the first plastic local deformation (local necking). Knowing that fatigue failure happens for a load able to induce in the specimen (or mechanical component) local plasticization, they

defined as the fatigue limit, the stress corresponding to the slope's change of the temperature curve in a static traction uni-axial test and proposed to find the fatigue limit by a simple classic test accompanied to the analysis surface temperature or analysis of the released heat.
In [6]it is indicated how it could be possible to evaluate the limit stress of the thermo-elastic phase of deformation by thermo-analysing the surface of the specimen during a static traction test. Adding the temperature curve measured on a small area of the surface (the hottest) to the classic stress-strain curve, it is possible to evaluate a limit temperature T_0 coincident with the beginning of the non linear trend of the curve. The corresponding stress value is coincident with the fatigue limit of the analyzed component.
In this work, the authors are continuing the experimental thermo-analysis of the curve zone between the origin and the yield stress during tensile traction test that is rich of indication about the fatigue failure process. Using AISI 304 steel specimens, they compared the fatigue limit found by the thermoanalysis of the static stress-strain curve wiht that found by thermo-analysis of the specimen surface during fatigue test. Particularly, after a thermal characterization of the material using static test and fatigue test, as confirm of the fatigue limit found, they carried out, on other equal specimens, static traction test and acquired the temperature surface of the specimen for all time of the test. During the test, they were observing the trend of the temperature of the hottest point and they stopped the load application when they estimated a changing in the slope of the temperature vs displacement curve. In this way, according to what was found in the past works [5, 6], they evaluated the corresponding stress σ_0 as the fatigue limit. For this one specimen, the test continued with the loading of the specimen by oscillating stress (load ratio R=-1) higher than σ_0 until the failure. Also during the fatigue test the temperature surface was recorded and the post processing images permitted to find the fatigue limit and the fatigue curve to compare with those found in the characterization phase.

THE TEMPERATURE IN STATIC TENSILE TEST

When a material experiences an external load not all its crystals reach their elastic limit at the same time due to a number of irregularities (crystal orientation, dislocation, etc.). Consequently, the elastic deformation of some crystals will lead to the plastic deformation of others.
With reference to a metal test sample under load, its behaviour can be subdivided as follows:

I. The load is so low that all the crystals are elastically stressed.
II. The load is such that most crystals deform elastically, but in some parts there is plastic and elastic deformation together so when the sample is unloaded the metal regains its shape. Macroscopically, the sample has behaved perfectly elastic.
III. The load is such that some crystals deform elastically together with plastic deformation so that once unloaded the sample does not regain shape – it is permanently deformed.
IV. The load has reached levels where the plastic deformation is such that most crystals are plastically deformed. The elastically deformed ones steadily decrease as the load continues to be applied and when the load ceases the permanent deformation becomes all the more obvious.

The yield value represents the transition between phase II and III. In some apparently perfect metals, phase I is very limited.
The internal stresses between the zones deformed elastically and plastically give rise to an 'after-elastic' effect in polycrystalline metals. This effect is linked to elastic hysteresis.
It is known that fatigue failures occur at those points where the local stress is able to give plastic deformation. In fact, in the points where there are micro-defects (structural or superficial) the stresses are intensified in comparison to the average stress value (load/area) and are reached local stress conditions that result in fatigue failures. Therefore, in different manner than the traditional definition, we can define as fatigue limit of the material, the average value of stress (load/area) in a monoaxial traction test, for which, at some point of the material, plastic local conditions are reached, conditions which are not visible by classic instrumentation, but only through a deep thermal surface analysis.
During a static tensile test, the micro-plasticization process zone is the II in Fig. 1. In terms of thermal behaviour of the material during a tensile static test, we can distinguish two phases:

- ✓ the first phase in which all crystals are deformed in an elastic field (zone I in Fig. 1). In this phase, the relation stress-strain is linear in macroscopic and microscopic terms.
- ✓ the second phase in which not all crystals are deformed in an elastic field, and only some are deformed in the plastic field (zone II in Fig. 1). In this phase in macroscopic terms the classic stress-strain curve is a straight line yet.

In the first phase, the behaviour of the material follows the thermo-elasticity theory.

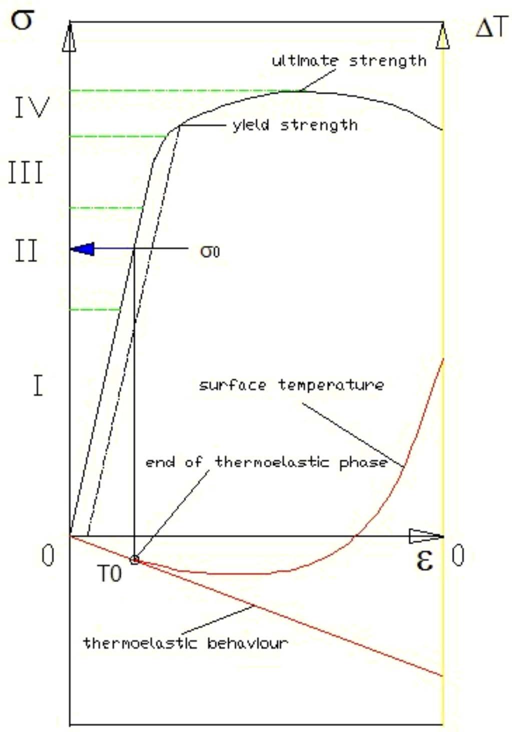

Figure 1: Stress-strain and temperature curve.

If we would be able to capture the first plastic heat in relation with the external average stress applied, we could find the stress that produces the first plastic damage in the specimen and therefore the conventional fatigue limit for R=-1. Therefore by a static traction test, using adequate instrumentation and test conditions, it is possible to find the fatigue limit stress σ_0 (average value of the external applied stress) through the determination of the "temperature limit" T_0, where T_0 is the temperature for which in a stress (strain) vs. temperature curve the linear trend (thermo-elastic phase) finishes, therefore, for the first time, a variation of the derivate is noted (Fig. 1). According to what was said before, a direct comparison, between the value of the fatigue limit by static test and by fatigue test, is performed.

TESTING PROCEDURE FOR THE EXPERIMENTAL DETERMINATION OF T_0 AND σ_0

Following what it is said above, it is possible to have an experimental definition of temperature T_0 and consequently of the zone where the plasticization appears for the first time. The increase in temperature depends on the material characteristics (for steel at an ambient temperature of 23°C there is an increase of approximately 0,1 °C, for each 100 N/mm² of stress), on the sensibility of the thermal sensors, on the image analysis quality, on the signals synchronization of the three parameters (load, elongation and surface temperature). As a general indication, we can say that during the first phase (perfectly elastic) for which at any point of the surface is $\Delta T = -K_m T\ \sigma_m$, the temperature variations are proportional to the thermo-elastic coefficient K_m (approximately 3,3x10^{-12} [Pa^{-1}] for steel and 10x10^{-12} [Pa^{-1}] for aluminium alloy) and to the point value of the stress. The temperature variations are more evident near the high stress concentration point. As reported in [5, 6, 7], to estimate the fatigue limit for R=-1, it is sufficient to perform a classic static test and recorder the temperature surface during the static test by means of a adequate remote system. The subsequent image processing permits one to define the end of the thermo elastic behavior and permits to estimate the T_0 temperature as the beginning of the local micro-plasticization. The authors applied this procedure and they found the value of σ_0 and compared the values to those determinate by Risitano's methods [8] for R=-1.

The method was applied to steel AISI 304 (Allegheny Ludlum Stainless Steel Chromium-Nickel Type 304, 10% Cold Rolled - UNS S30400. Yield Stress 517 MPa. Ultimate Stress 676 MPa) specimen with a rectangular section (12x5 mm) and length of 90 mm (see Fig. 2). The testing machine was an Instron model 8501 100 kN Servo Hydraulic Machine and the thermographic scanner was Flir System model SC-3000. The image processing was also performed by Flir system. The frequency of image acquisition was 1 Hz. The minimum measurable value of temperature was 0.02°C. The emissivity coefficient was 0,98. Tab. 1 summarizes the all test programmed.

Specimen	Static Test	Max Stress in Static Test [MPa]	Broken in Static Test	Speed Crossbar in Static Test [mm/min]	Fatigue Test	Max Cycles Number in Fatigue Test	Broken in Fatigue Test
Mean value for 3 specimens in the static characterization phase	yes	717	yes	1,421	no	-	-
Mean value for 3 specimens in the fatigue characterization phase	no	-	no	-	yes	4,76E+05	yes
Specimen 1	yes	192	no	0,207	yes	1,16E+06	yes
Specimen 2	yes	328	no	0,402	yes	1,23E+06	yes

Table 1: Summary of all tests.

With the first tests, the material was characterized. Therefore 3 specimens, for the static and thermo-static characterization, were used and other 3 for the thermo-fatigue characterization. The Fig. 3, for the sake of brevity, reports only one of the classic traction load-displacement curve of the three specimens tested. The other two had a very similar trend. In the diagram of Fig. 3, the temperature of the hottest surface point recorded during the test, is reported. Fig. 4 is a zoom of Fig. 3. The temperature curve has an evident inflection point for 7 kN (corresponding stress of 117 MPa). For what has been said above, this value can be considered an estimated value of the fatigue limit of the material. In Tab. 2 are reported the static parameter of the AISI 304.

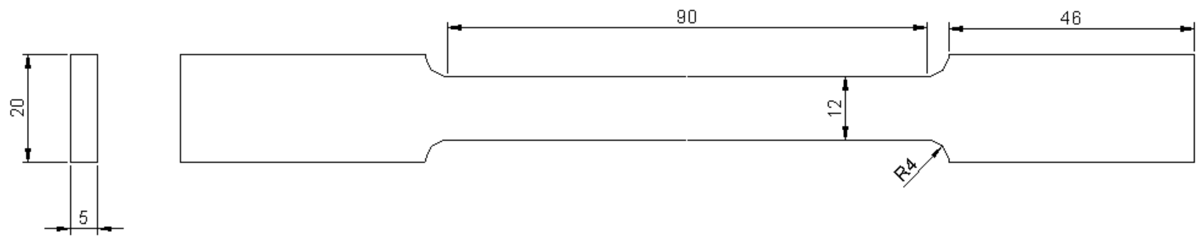

Figure 2: Specimen dimensions [mm].

Yield Stress [MPa]	Ultimate Stress [MPa]
525	692
Literature Yield Stress [MPa]	Literature Ultimate Stress [MPa]
517	676
Yield Stress Error %	Ultimate Stress Error %
1,50%	2,30%

Table 2: Comparison between experimental values (specimen 3) and literature values.

Other 3 specimens were subjected only to the fatigue test until they were completely broken (in Tab. 1 the average number cycles at failure is reported); the specimens were loaded with a load ratio R=-1. To determine the fatigue limit, we used the method Risitano and for each step of load, the stabilization temperature has been measured. Fig. 5-a, shows the temperature variation as average value of the temperature acquired for the three specimens tested. For each load step, the difference between the average value and the others was not more than 1,2%. According to the Risitano method, the mean values of the stabilization temperature were reported as a function of the square of the load (stress) and the intersection of the trend line with the x-axis is the value of fatigue limit (Fig. 5-b). The mean fatigue limit σ_0, for the 3 specimen, is 102 MPa. Finally, the Wohler diagram using the data of Fig. 5-a and according to the previous mentioned method, was created (Fig. 5-c). In this way we have characterized the material in static and fatigue terms. As it is possible to note, the difference between the found values of the fatigue limit (105 MPa and 102 MPa) is very low.

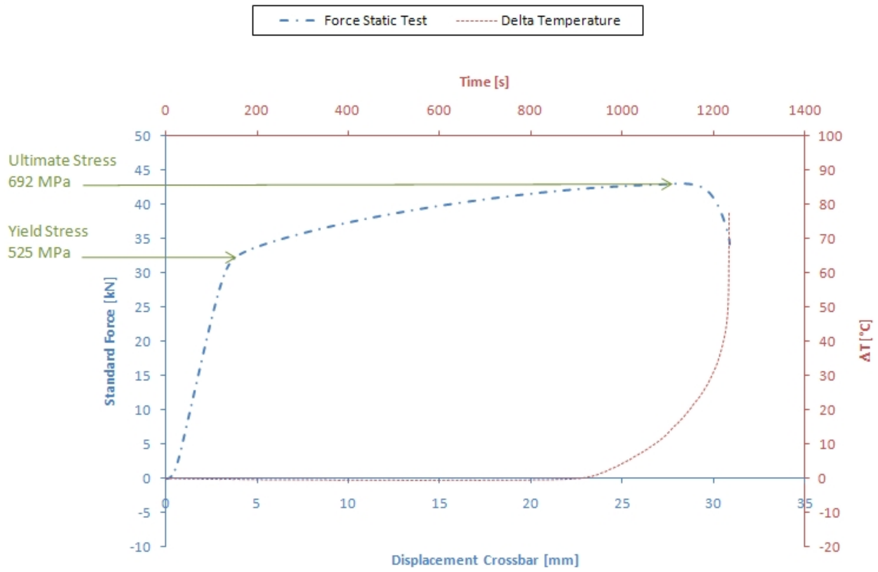

Figure 3: Monoaxial Tensile Static Test. Standard load vs displacement of crossbar (blue line) and ΔT vs time (red line).

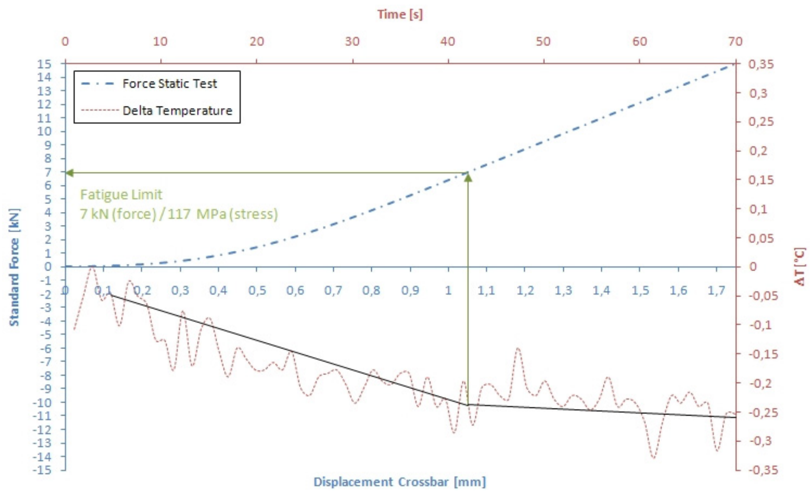

Figure 4: Zoom of Fig. 3.

Following the material characterization, the tests continued in the form that we said before. Other two specimens (1 and 2 in Tab. 1) were tested with a different approach. Particularly, the specimen 1 was tested with a mono-axial tensile load (speed of crossbar 0,207 mm/s) up to a stress of 192 MPa (much lower yield stress 517 MPa). In Fig. 6 there are the standard load vs displacement of crossbar (blue line) of Istron Machine and the ΔT (difference in temperature of the specimen between the i-th time and the initial time) vs time (red line).

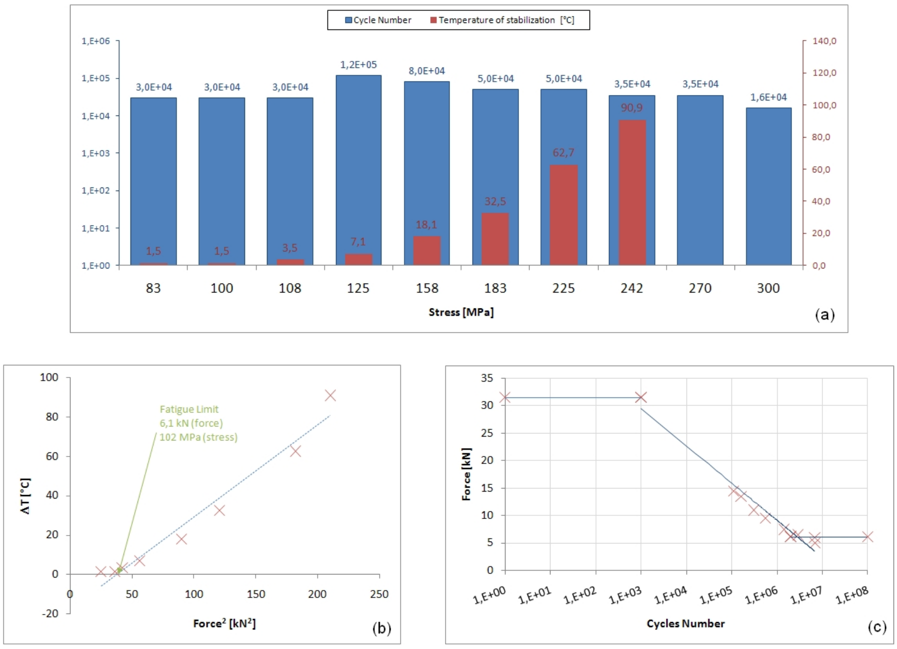

Figure 5: (a) Mean values of acquired cycle number and temperature stabilization; (b) Determination of fatigue limit; (c) Wohler Diagram.

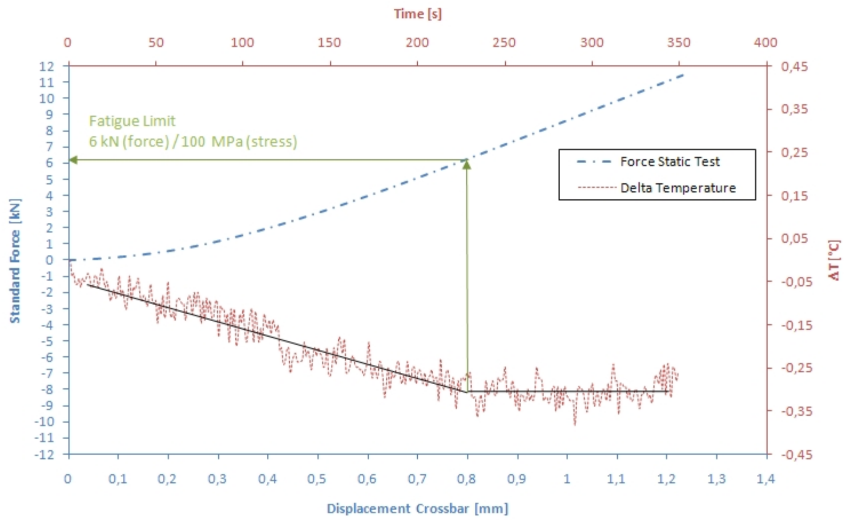

Figure 6: Specimen 1; Monoaxial Tensile Static Test. Standard load vs displacement of crossbar (blue line) and ΔT vs time (red line).

The temperature curve has an inflection point at 6.5 kN (corresponding stress of 108 MPa); for what has been said above, this value is the value of fatigue limit of the material. In fact, at this point, the thermoelastic phase for all crystals, finishes and the plastic phase, begins with releasing of heat by some plastic deformed crystals. This produces a changing in the slope of the curve. After the static test, the same specimen (1) was subjected to a fatigue test (Tab. 1). The applied load started from a stress value under the fatigue limit previously estimated (108 MPa), increasing step by step until reach the failure. The ratio load was R=-1. Also in this case, we used the method Risitano (Fig. 7-a). According to this method, for each step of load, temperature stabilization has been measured (Fig. 7-b). The values of temperature of stabilization have been reported as a function of the square of the load (stress), the intersection of the trend line with the x-axis is the value of fatigue limit (Fig. 7-c). Finally, the Wohler diagram of the specimen 1 was created (Fig. 7-d).

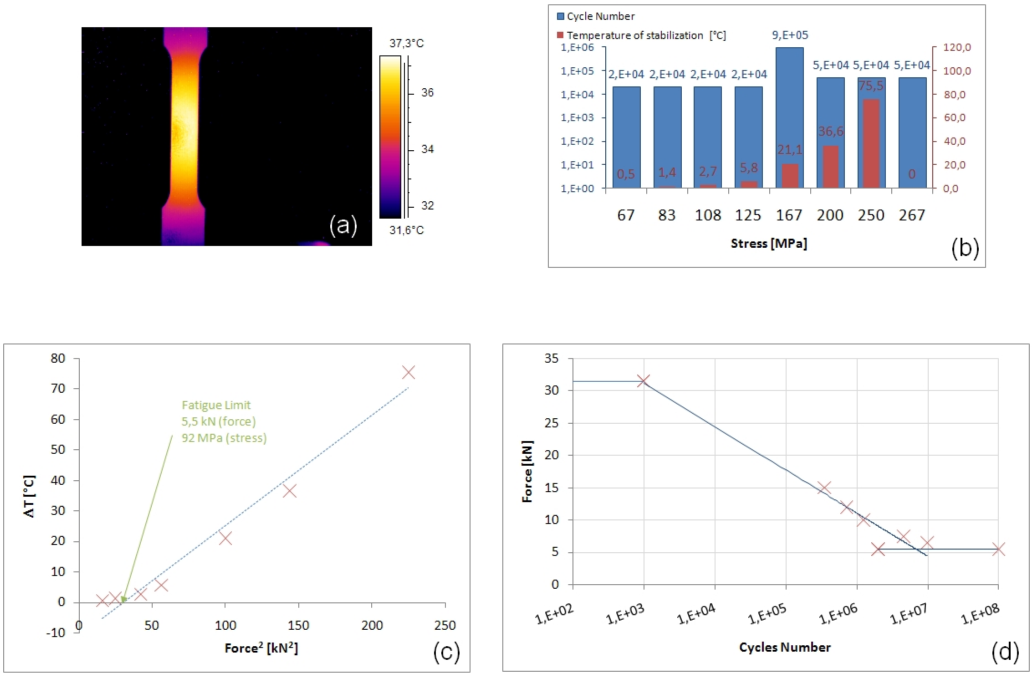

Figure 7: Specimen 1; (a) Thermographic image of specimen 1; (b) Temperature stabilization; (c) Determination of fatigue limit; (d) Wohler Diagram.

In the fatigue test, the fatigue limit, for specimen 1, was 6,0 kN (100,0 MPa). The fatigue limit obtained by the tensile test is similar to the fatigue limit obtained by the fatigue test. The two values differ by 8%, which falls within the normal difference of data for dynamic characterization test. It is important to observe that, after the applied static stress, the specimen is practically undamaged or very low damaged (1 cycle and maximum applied stress distant from the macroscopic yield stress).

Similarly, the specimen 2 was tested with a monoaxial tensile test (speed of crossbar 0,402 mm/s; twice that of specimen 1) up to a stress of 328 MPa (much lower yield stress 517 MPa, but bigger than specimen 1). The temperature curve has an inflection point for a stress of 125 MPa. Fig. 8 shows for the specimen 2 a similar trend of specimen 1. The changing slope is less evident than the specimen 1 and is near to 7,0 kN (117 MPa). In this case, the changing of the slope of the curve temperature vs load is not always evident. This can depend of the physic characteristic of the material but also of the crossbar speed. In these cases, following the indication of A. Chrysochoos , we suggest a analysis of the acquired image not only in temperature but in terms of heat released [7] also. Working in this way, the individuation of T_0 and the related value of $\Delta\sigma_0$ is more easy to estimate.

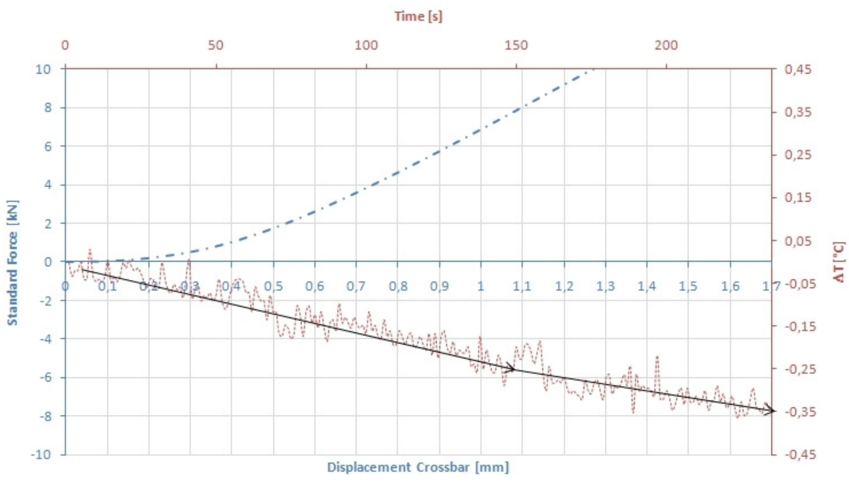

Figure 8: Specimen 2; Monoaxial Tensile Static Test. Standard load vs displacement of crossbar (blue line) and ΔT vs time (red line).

Following the static test, the specimen 2 was subjected to a fatigue test similar to specimen 1. For each step of load, temperature stabilization has been measured (Fig. 9). The applied load began from a stress value lower than the fatigue limit previously estimated (117 MPa), increasing step by step until reach the failure. The increasing in temperature began only for the load higher than 5,8 kN therefore the estimated fatigue limit for specimen 2 is the corresponding stress 97 MPa, as can be seen from Fig. 9.

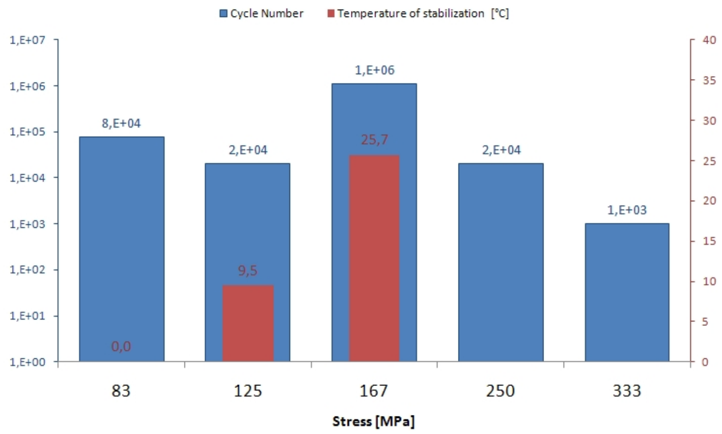

Figure 9: Mean values of acquired cycle number and temperature stabilization.

Specimen	Fatigue Limit Load [kN]		Fatigue Limit Stress [MPa]		
	Static Test	Fatigue Test	Static Test	Fatigue Test	
Mean value for 3 specimens in the static characterization phase	7	-	105	-	
Mean value for 3 specimens in the fatigue characterization phase	-	6,1	-	102	
Specimen 1	6,5	6	108	100	
Specimen 2	7	5,8	117	97	Error %
		Average	110	99	10%

Table 3: All results obtained during tests.

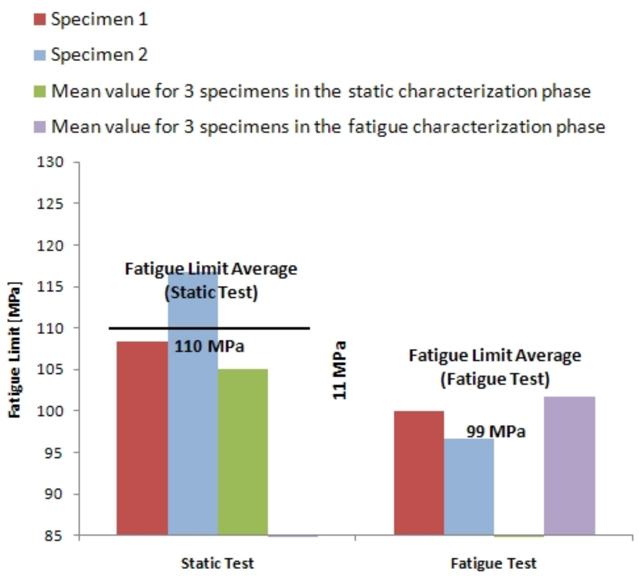

Figure 10: Fatigue limit obtained during Static and Fatigue Test.

Tab. 3 and Fig. 10 summarize all results obtained during tests. As one can see the average value of fatigue limit obtained by static tests is 110 MPa, whereas the average fatigue limit obtained by dynamic tests is 99MPa. The difference between these two values is 11 MPa and corresponds to an error rate of 10%. These differences are typical in the field of experimentation for the determination of fatigue limit of metallic materials. The results of the two last specimens (1 and 2) confirm in evident way the validity of the method to find the fatigue limit by a simple static test. The same values found with the subsequent fatigue test (specially for the specimen 2), bring to suppose that the lightly lower value found is caused by a possible damage produced during the static test.

CONCLUSIONS

The Authors, in recent works, proposed a method to estimate the fatigue limit of a material (or a mechanical component) by thermographic analysis of a simple traction static tests [5, 6, 7]. In this work, they have carried out tests to verify the methodology with a steel characterized by different released heat under stress, compared those used in other applications. The tests conducted were of two different types. Using 6 specimens, 3 were performed as static tests and 3 as fatigue tests. After this, other 2 specimens are loaded in different way to confirm the previous results. The material has been used for the specimens was AISI 304 (Allegheny Ludlum Stainless Steel Chromium-Nickel Type 304, 10% Cold Rolled - UNS S30400).
The method that the authors are carrying out is completely different from the others proposed by other authors that use cyclic loading to find the fatigue limit of the material. In different way of other researchers, the authors are analysing the part of the classic stress strain curve between the end of the completely (for all crystals) elastic phase and the beginning of the macroscopic plastic phase (near the yield stress). The method is based on the acquisition of the temperature variation on the specimen surface by remote system. In fact, the fatigue limit can be found by the individualisation of stress able to produce the first plasticization at which internal heat is released and consequently a change of the linear trend of the surface temperature occurs .
According to this method, the traction stress σ_0 corresponding to the end of the linear decrease of the local temperature of the most critical point (the hottest), is a good approximated value of the fatigue limit for R= -1. In fact, the results were excellent. The dispersion of the data found, confirmed by the literature shows that the difference between the fatigue limit obtained by static monoaxial tensile test and the fatigue limit determined by thermal fatigue tests (Risitano method) is in the order of 10%.
In this application the reading of the fatigue limit is clear and is a good approximation with that found by the traditional method and by the Risitano method.

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