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Surface factor assessment in HCF for steels by means of empirical and non destructive techniques

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Abstract

The fatigue limit value in steels is strongly influenced by many factors, among them the surface finish. In particular, the fatigue limit decreases with increasing the surface roughness, referring to standard grinded specimen.Technical literature provides an empirical correction factor, named surface factor, to be used if surface roughness is different from standard specimen conditions. This factor is traditionally lower than 1 and it reduces the fatigue limit value corresponding to the material in standard conditions. This coefficient may be obtained from literature graphs and it can be identified by means of two parameters: materials ultimate tensile strength and surface finish R_a.Aim of the present paper is to evaluate the effectiveness of fast procedures to assess the surface factor. The reference is the Murakami model, which estimates the fatigue limit by means of roughness parameters other than R_a.In the present paper the fatigue limit estimations related to specimens with sanded $R_a$have been obtained by utilizing empirical destructive and nondestructive methods and then have been compared each other.Experimental testing was carried out on a structural steel specimens by means of axial alternate fatigue testing with two different surface roughness.The results obtained referring to Murakami model have been compared with those obtained by means of both thermographic and Staircase method.The Murakami model results to be easy to use and non destructive.The corresponding fatigue limit estimations match with the thermographic ones above all when surface roughness is elevated.

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Keywords: Fatigue; Roughness; Surface factor, Thermography; Fatigue limit

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1. Introduction

High cycle fatigue damage is a phenomenon which occurs in the material structure (Roushdy and Kandeil (1990)) and cracks can nucleate on the surface or subsuperficially or inside the component (Kuroda et al. (2005)). The genesis of these damaging phenomena substantially differs. Structural related damage evolution can be detected by means of nondestructive testing and termographic measurements (Maquin and Pierron (2008), Connesson et al (2011),Risitano and Risitano (2010), Chysochoos et al (2010), Doudard et al. (2004)) or hysteresis cycle analysis (Curà and Sesana (2014), Charkaluk et al. (2002), Meneghetti et al. (2013)).In case of structural material fatigue damage, the presence of local microplastic phenomena (Lazan (1968), Connesson et al (2011), Doudard et al. (2004)) involves local microdissipations and a local thermal increment which, in a thermal conductive material, causes a global surface temperature increase. Microplastic sites are statistically activated in relation with loading amplitude values.By means of experimental testing, it can be observed that specimens with rougher surface finish show lower fatigue limit values. This phenomenon is probably due to the local notch effect related to surface finish, which can cause surface cracks to arise even for very low loads.In case of surface finish, the edges of surface roughness can act as crack initiators and the stress distribution, in the volume of material around microcrack tip, leads to local plastic dissipations involving a high thermal increment. The phenomenon is uniformly distributed on the surface of the specimen.The effect of surface finish on high cycle fatigue behavior of steels has been widely experimentally investigated during the decades. In design practice, to take into account the decrement of fatigue limit for rough specimens, an empirical correction parameterC_f, generally known as surface factor (McKelvey and Fatemi (2012), Juvinall and Marshek (2006), Hanel et al. (2003)), can be used to estimate the fatigue limit of a materialor component due to surface roughness effect. In research studies, traditional experimental approaches have been used to investigate the influence of surface finish on fatigue limit values, that is the fatigue limit of sets of specimens with various surface roughness have been assessed by means of experimental fatigue loading of specimens. The fatigue limits thus obtained have been compared each other, in order verify the influence of surface roughness on high cycle fatigue characterization.

In literature the causes of this influence have been mainly investigated by means of microscopy techniques in order to analyze both fracture surface and fatigue crack growth. As an example in Itoga et al. (2002) a deep study about the effect of surface roughness on fatigue life of high resistance steels has been presented; in particular, a traditional experimental investigation (bending rotation fatigue tests) has been carried focusing on the fatigue limit and a related microscopic analysis of fracture surfaces.A great attention has been also dedicated to the transition phase between superficial and subsuperficial crack nucleation. It is observed that for high cycle regimes the crack nucleates subsuperficially and fatigue life is not affected by surface finish. The opposite happens for low cycle regimes. In this and other papers it has been stated that surface roughness acts as a small defect and a parameter related to the defect size is proposed to predict the fatigue limit. In Javidi et al. (2008) the effects of surface roughness and residual stresses on fatigue life are compared for a steel alloy with the same methods.In Kasarekar et al. (2008) the effect of surface roughness on fatigue life in contact problems has been studied by means of a Smith Watson Topper multiaxial damage approach and it results that surface roughness increments the value of the damage parameter.In Kuroda and Marrow (2008)surface finish is identified as the direct source of damage and then as an active damage site distributed on the material surface.

Murakami (2002) describes roughness as distributed micro notches which, having approximatively the same dimensions and being continuously distributed on the surface, cause lower damage than single notches due to their interactions. His theory is based on the analysis of a defect equivalent area parameter, $\sqrt{Area_R}$ which takes into account of notch pitch and depth. The roughness parameter R_y (maximum peak to valley height) represents the microcrack depth.By means of this parameter it is possible to estimate the fatigue limit of some samples of specimens with a controlled roughness. His research focused on medium carbon steels.Itoga et al. (2002) applied the Murakami method on a high resistance steel with actual roughness, obtaining results with percent differences of15% ÷24% with respect of experimental fatigue limit. Some correction can be applied to $\sqrt{Area_R}$ to improve the fatigue limit estimation.

Furthermore, in literature many researches are described related to the estimation of HCF damage and HCF limit for steels by means of thermal and mechanical parameters. In particular, the evolution of both thermal increment and hysteresis cycle area (Chrysochoos et al. (2010), Curà and Sesana (2014), Meneghetti (2001), Meneghetti et al. (2013), Kim and Jeong (2010)) are good parameters to be related with the damaging phenomena taking place in the structure of the material. Generally speaking, the thermographic approach to the analysis of fatigue of steels has been utilized from the eighties by several international research groups.The general fatigue damage approach described by Doudard et al. (2004) predicts a damage due to microplasticization statistically activated related to load amplitude and cycles. The thermographic approach well adapts to measure the effect of energy dissipation due to microplasticization in elastic loading.In particular, a damage accumulation approach has been proposed. According to Javidi et al. (2008), surface roughness can be considered as a microcrack. A microplasticization field is located at the edge of a crack, even if load is in the elastic field. The thermal increment measured on the specimen surface (same material, same loading condition, different surface roughness) may be generated only by the microplasticization located at the edges of the roughness. This way, the thermal increment can be considered as a damage evolution parameter

In the present paper the two different techniques have been compared, Murakami and thermal approaches for the estimation of the fatigue limit.

In particular the fatigue limit estimations obtained with the different methods give surface factors estimations which are compared with literature ones.

2. Materials and methods

The investigated surface roughness parameters are R_a, Rz and R_t according to UNI EN ISO 4287. To this aim a statistical analysis has been carried on to find out the adequate number of measurements for an effective roughness measurement. The same analysis has been performed on Murakami parameter. This statistical activity is not presented in this paper. In total, 13 specimens have been measured, 10 laminated (specimens B) and 3 sanded (specimens X). Measurements have been performed by means of a ALPA TL90 instrument. Sand processing allows to avoid any preferential orientation in surface finishing. All specimen surfaces have been sanded. Specimens were made of C40 (1.0511)4 mm laminated sheet in dogbone shape, according to ASTM E466-72 and UNI 3964. Specimen dimensions are reported in Figure 1.C40 mechanical properties have been obtained in previous tests (Curà and Sesana (2014))and are reported in Table 1. Fatigue limit value has been obtained on polished specimens (R_a< 0,8 μm), according to UNI 3964.

Table 1: C40 mechanical properties

R_m [MPa]	R_{P02} [MPa]	E [GPa]	σ_{D-1} [MPa]
500	380	210	240

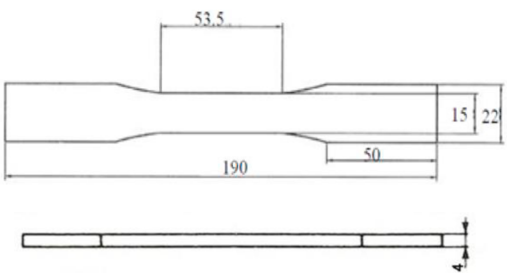

Figure 1: Specimen geometry, dimension in mm.

High cycle fatigue testing have been run according to ASTM E466-72 and UNI 3964 by means of constant amplitude loading tests and step loading tests. The procedure is consolidated for the assessment of fatigue limit for standard and notched specimens (Ling (2001), Itoga et al (2002), Curà and Sesana (2014), Kordatosa et al. (2013)). In particular, thermal and mechanical data have been processed by means of TCM (Two Curves Method,Curà et al

(2005)), which relies on ((Curà and Sesana (2014), Luong (1995), Meneghetti and Ricotta (2012), Curà et al (2012)). This method is implemented by means of linear and exponential curves.

Residual stresses measurements have been performed on specimens by means of drilling hole method according to ASTM E837-13.Residual stresses measurements have been performed before and after fatigue testing.

Hardness HRB measurements have been performed on specimen by means of a Galileo A-200 durometer, $(^1/_{16})'$sphere. Four measurements have been performed on each specimen surface, for 2 B specimens and 2 X specimens. Afterwards, according to ASTM E140, HRB measurements have been converted in HV values as required by Murakami model. Specimens have been fatigue tested as follows. A step loading procedure has been applied with loading ratio R=-1 and axial loading. Loading blocks lasted 10^6 cycles and increments of 10 MPa have been applied in the following blocks until failure, in load control. Testing frequency was 10 Hz for the first 10^5 cycles and 30 Hz for the remaining cycles. An Instron 8010, 100 kN load cell and hydraulic grips testing machine has been used for fatigue testing. A IRtech Radiamatic TImage Mk4 termocamera whas been positioned in front of the specimens during fatigue cycling. Specimens were black painted to maximize thermal emission. Acquisition frequency was set to 1 Hz.

Thermal data have been processed to obtain stabilization thermal increment for each specimen and each loading block, for 10 and 30 Hz. Then these increments have been processed by means of One Curve Method (Fargione et al (2001), Two Curve Method (Curà and Sesana (2014), Curà et al (2005)), Modified Staircase (Zhao and Yang (2008), CIMAC (2009)) and Murakami method (Murakami (2002)) to estimate fatigue limit.

Fatigue limit of specimens has been also estimated by means of literature $C_f$factor.In particular, starting from the fatigue limit σ_{D-1} of the material obtained by means of Standard specimens (surface finish Ra=0.8 μm) and Standard tests, it may be calculated as follows the corresponding σ^*_{D-1} for specimens with higher surface roughness:

$$\sigma^*_{D-1} = C_s \times \sigma_{D-1} \tag{1}$$

The C_f factor can be obtained by means of literature data. In Rossetto (2000) a diagram, reported in Figure 2, is obtained processing Standard UNI 3964 indications.The values selected for the present research will be named $C_{f(St)}$Another way to estimate the surface factor is reported in (Budynas and Nisbett (2008), Noll and Lipson (1946)) as a power low function of the UTS of the material, where a constant proportional factor and an exponent are material parameters available in tables for ground, machined or cold drawn, hot rolled and as forged steels.A similar parameter is defined in FKM German guidelines (Hanel et al. (2003)). Due to lack of data, the $C_{f(Noll)}$estimation has been done with parameters related to hot rolled materials.McKelvey and Fatemi (2012) also processed literature data and obtained graphs similar to Figure 2 to for the same previous groups of materials. $C_{f(Fatemi)}$was then obtained from that graph.

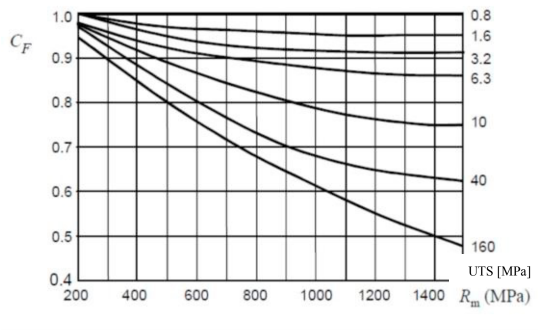

Figure 2: C_f diagram (Rossetto (2000))

A further fatigue limit estimation has been performed by means of Murakami method (Murakami (2002)).

According to Murakami, fatigue limit values can be obtained basing on two parameters: one related to material properties (UTS, Yield stress, HV) and one related to geometry of defect. HV has been selected due to easiness of measurements and to Garwood et alii (1951) linear relation between HV and fatigue limit which, up to 400 HV showed very little scattering. For what concerns defect geometry parameter $\sqrt{Area_R}$ has been selected according to Murakami (2002).

$$\sigma_w = \frac{1,43(HV+120)}{\left(\sqrt{area_R}\right)^{1/6}} \tag{2}$$

In particular in R_y is proposed as the parameter related to defect depth, i.e. the worst case. In the present paper $\sqrt{Area_R}$ was calculated by means of R_a, R_z and R_y to compare the different results.

For what concerns residual stresses in Itoga (2002) it is stated that for hardened alloy steels, residual stresses do not affect fatigue life. In Javidi (2008) a quenched alloy steel show a strong relation between residual stresses and fatigue limit Murakami suggests an equation taking into account of residual stresses whose effect can be assumed as local mean stress effects and to take into account of means stresses the formula is:

$$\sigma_w = \frac{1,43(HV+120)}{\left(\sqrt{area_R}\right)^{1/6}} \cdot \left(\frac{1-R}{2}\right)^{\alpha} \tag{3}$$

where R is the stress ratio resulting from the mean and amplitude applied stresses. In the present research the stress ratio was calculated adding the residual stresses to applied stress values.

In the present research the following roughness parameters have been selected for the calculation of $\sqrt{Area_R}$: R_t=a and R_{sm}=2b according to the model indications. From a statistical point of view, Murakami parameter has been processed as roughness parameters ones. In particular, to obtain a reliable parameter value, stabilization of standard deviation of measurements takes place after 15 measurements per specimen side.

For what concerns hardness measurements, two specimens per each sample have been measured and on each specimen 4 measurements per side have been performed. Then the measured values average has been calculated on each side and on the whole set of measurements to check for inhomogeneities and to obtain the final value.

Acquired and TCM processed parameters have been related to surface temperature obtained at 10 and 30 Hz fatigue testing frequency. The obtained fatigue limits have been compared with calculated results related to both laminated and sanded specimens.

3. Results

Roughness measurements and residual stresses measurements results are reported in the followingTable 2.

These measurements showed that residual stresses are present only in the near surface layer and for both sanded and grinded specimen, new and fatigue tested ones, the value is approximatively 200 MPa. It then results that the sand process does not affect the residual stress state thus allowing assessing that the following results related to surface effect are not affected by the sand process.

Table 2: surface measurements results

	R_a [µm]	R_z [µm]	R_t [µm]	Max residual stress [MPa]	Min residual stress [MPa]
Laminated new	1,5	8,6	11,67	213/248	-166/-272
Laminated fatigue tested	-	-	-	264/258	-212/-213
Sanded new	2,9	16,8	20,4	215/223	-176/-195
Sanded fatigue tested	-	-	-	205/161	-138/-275

Hardness measurements give the following results: 116 HV for grinded specimens and 117 HV for sanded ones. These results allow to assume that sand processing do not influence the hardness status on the specimens. The same can be assumed for residual stresses both for sand processing and fatigue loading

3.1. Fatigue limit calculation

The calculated C_f factors are reported in Table 3.

The results of fatigue limit estimation are reported in Table 4: columns 2 and 5 show the results of the fatigue limit estimation according to the different methods for laminated and sanded specimens respectively; columns 3 and 6 show the corresponding percent difference with respect to SM calculated values; columns 4 and 7 the obtained C_f values obtained as the ratio between the corresponding estimation and the SM estimation

Table 3: C_f calculation

	Laminated	Sanded
$C_{f(St)}$	0,98	0,96
$C_{f(Noll)}$	0,67	-
$C_{f(Fatemi)}$	0,55	-

Table 4: fatigue limit calculation. By means of C_f (Rossetto (2000)) (SM), Modified Stair case method (MSC), Murakami Method with R_a without (MM R_a) and with Residual stresses (MM R_a RS), Murakami Method with R_z without (MM R_z) and with Residual stresses (MM R_z RS), Murakami Method with R_t without (MM R_t) and with Residual stresses (MM R_t RS),

	Laminated			**sanded**		
	σ^*_{D-1} [MPa]	% diff	C_f	σ^*_{D-1} [MPa]	% diff	C_f
SM	235,2			230,4		
MSC	230	-2,1	0,96	235	2,0	0,98
OCM	238	1,3	0,99	160	-30,6	0,67
TCM	211	-10,2	0,88	166	-28,0	0,69
MM Ra	258,7	10,1	1,08	235,3	2,1	0,98
MM Ra RS	224,0	-4,7	0,93	204,0	-11,5	0,85
MM Rz	196,5	-16,4	0,82	182,5	-20,8	0,76
MM Rz RS	170,0	-27,7	0,71	158,0	-31,4	0,66
MM Rt	185,4	-21,1	0,77	174,4	-24,3	0,73
MM Rt RS	161	-31,5	0,67	151	-34,5	0,63

4. Discussion and conclusions

An investigation on the applicability of different rapid and non destructive methods for the estimation of the fatigue limit for a low resistance steel in presence of surface roughness is presented. The different methods were compared both for what concerns the estimation results and from an experimental point of view.

For what concerns fatigue limit estimation by means of the modified stair case method (MSC), sanded specimens showed failures at scattered numbers of cycles above all for loading values close to the fatigue limit. This made the calculation of the corresponding fatigue limit complex and uncertain and it can be justified with the roughness which acts as already nucleated microcracks: as soon as the threshold value is reached, their propagation is activated. These results agree with Dixon et al (2016).

For what concerns the fatigue limit evaluated by means of thermal methods, sanded specimens showed very low thermal increments for low loading amplitudes and elevated ones (higher than 40 °C) for elevated loading amplitudes.

More in detail, the fatigue limit estimation provided by OCM has been easily obtained, being required only the stabilization temperature value which has been generally reached for about 10^5 cycles and the following cycles to failure scattering did not influence the results. For TCM, the estimation calculated by processing experimental data measured at 10 Hz has been complex, due to very few data available at low amplitude loads, then increasing the estimation uncertainty. So, the estimation has been performed only with 30 Hz data. It has to be noted that the experimental procedure applied a step loading starting from loading levels close to the fatigue limit and two loading frequencies to speed up the tests. Temperature data for low loading levels were then few.

Murakami method returns the higher percent differences. In case the roughness parameter is R_t, the more conservative estimation has been obtained. The use of the roughness high averaged on 10 peaks and valleys (R_z) decreases the value of $\sqrt{Area_R}$ reducing the gap with the reference fatigue limit estimation, with a still conservative result. The use of Ra, that is the mean arithmetic difference, already discussed by Itoga, is the procedure which, for this low resistance steel, gives the best estimation. Considering an average roughness value (R_a) instead of a value closer to the higher peak value (R_t) can simulate the interaction effect between the distributed micro notches mentioned by Itoga, resulting in a better estimation of the fatigue limit. These obtained percent differences agree with Itoga results.

All the methods return conservative C_f values and the comparison with $C_{f(St)}$ results far from it. This comparison is not reliable as the $C_{f(St)}$ is obtained from a generic graph which can be used for any steel and for generic processing and surface roughness. It also refers to R_a which has been demonstrated to be a not optimal parameter to estimate fatigue behaviour (Gadelmawla et al. (2002)).

This leads to state that the definition of the C_f needs a deeper investigation, with dedicated testing and models taking into account of materials, processing and loading conditions, as for example in McKelvey and Fatemi(2012). In particular, according to Shareef and Hasselbusch (1996), if dedicated tests are performed it gives reliable estimations, else it gives general indications and, as in the case of the here investigated carbon steel, it can also underestimate the fatigue limit.

For what concerns non destructive approach to Cf and fatigue limit, Murakami method is a fast and non destructive method to estimate the fatigue limit in presence of surface roughness. It needs an accurate procedure for a correct roughness estimation (20-30 measurements per material).

Thermal methods, and in particular TCM, give results comparable and better, of fatigue limit and Cf despite the more complex testing activity required to obtain the estimation.

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