Application of different fatigue strength criteria on shot peened notched parts. Part 2: nominal and local stress approaches

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1. Introduction

Although beneficial effects of shot peening (SP) on fatigue strength in terms of induction of compressive residual stresses and its work hardening effect on the subsurface layer of treated material are well recognized, yet its contribution is generally underestimated by the design codes. Still a universally accepted theoretical model for assessing the fatigue strength of shot peened components that can be sufficiently robust to deal with various conditions is not available.

This work critically evaluates the criteria available in the literature that have been applied to shot peened notched specimens. This is the second part of a study on a series of recognized fatigue strength evaluation methods to assess the fatigue strength of shot peened specimens and perform critical comparison of the results obtained from these methods (used in case of uniaxial fatigue loading). The first part [1] consisted in evaluating fracture mechanics based approaches, whereas this second part focuses on methods based on nominal and local stresses. All criteria are applied to well known different experimental data obtained for notched specimens subjected to rotating bending tests (RBT) and axial fatigue tests (AT).

Eichlseder [2,3] introduced a method based on the stress gradient obtained from a linear elastic FE calculation for fatigue life evaluation of notched components. Olmi et al. [4,5] have implemented the Eichlseder approach [2] on shot peened notched specimens.

Other applied approach is the one proposed by FKM [6], a well-known German design guide for analytical static and fatigue strength assessment of components in mechanical engineering.

This method is applicable in a very schematic way and requires the definition of a few parameters, such as the tensile strength of the material, the coefficient of average roughness and a work hardening index derived from the intensity of peening. This method can be applied using nominal stresses and also local stresses defined on the basis of FE analysis.

In this paper a brief description of these two approaches is presented. Both criteria are applied to two different experimental campaigns: RBT and AT. These specimens were shot peened with different conditions. X-ray diffraction measurements, surface roughness measurements and fatigue tests were performed on RBT and AT series. The results obtained from application of the Eichlseder and FKM approach to the experimental data are then compared. This comparison highlights the restrictions of each approach and the field in which they can be successfully applied;

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Nomenclature

R	stress ratio
Local fatigue method	
σ_{bf}	fatigue limit in bending
σ_{tf}	fatigue limit in tension
χ'	relative stress gradient (RSG)
b	un-notched specimen diameter
K_D	material parameter
σ_f	fatigue limit
FKM approach	
$K_{\mathrm{WK,zd}}$	design factor for axial loading
$K_{\mathrm{WK},b}$	design factor for bending loading
$K_{f,\mathrm{zd}}$	fatigue notch factor (tensile loading)
$K_{f,b}$	fatigue notch factor (bending loading)
$K_{R,\sigma}$	surface roughness factor
K_V	surface treatment factor
K_S	coating factor
$K_{\mathrm{NL},E}$	constant for material behaviour
$K_{t,\mathrm{zd}}$	stress concentration factor according to type of stress (tensile loading)
$K_{t,b}$	stress concentration factor according to type of stress (bending loading)
$n_{\sigma(r)}$	K_t–K_f ratio for the component under normal stress as a function of r
$n_{\sigma(d)}$	K_t–K_f ratio for the component under normal stress as a function of d
r	notch radius at the reference point
d	diameter or width of the net notch section
$\bar{G}_\sigma(r)$	stress gradient as a function of r
$\bar{G}_\sigma(d)$	stress gradient as a function of d
R_m	material tensile strength
a_G	material constant
b_G	material constant
φ	coefficient for the notch effect
$a_{R,\sigma}$	constant related to material
R_z	roughness parameter according to DIN4768
$\mathrm{R_{m,N,min}}$	material minimum tensile strength
S_{WR}	fatigue limit for $R=-1$
$\sigma_{W,\mathrm{zd}}$	material fatigue limit for $R=-1$
$K_{\mathrm{AK,zd}}$	mean stress coefficient
$K_{E,\sigma}$	welding factor
$f_{W,\sigma}$	material constant
$S_{m,\mathrm{zd}}$	mean stress
M_σ	mean stress sensitivity factor
a_M	material constant
b_M	material constant
$\bar{K}_F$	material constant
σ_{1a}	stress amplitude in the reference point
σ_{2a}	stress amplitude at a neighbouring point below the reference point
Δs	distance between the reference point and the neighbouring point

where possible, appropriate corrections are introduced in order to obtain a better agreement with the experimental results.

2. Fatigue assessment criteria

In this section a review of the local stress based methods that were applied for calculation of the fatigue strength of notched components subjected to SP is provided. Since the general concepts of these approaches are well known, details are not included; the reader can refer to the respective references for a deeper look at each criterion.

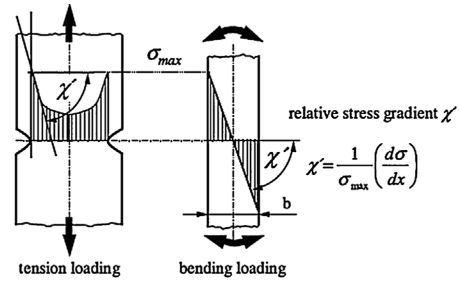

Fig. 1. Stress gradient in notches and bending specimens.
Source: [2].

2.1. Fatigue analysis by local stress concept

This model proposes interpolation of fatigue limit in bending (σ_{bf}) and in uniform stress loading conditions (σ_{tf}) on un-notched specimens (with diameter b) made of the same material, to describe the local fatigue limit of components with arbitrary stress gradients. Eichlseder [2,3] characterizes an exponential relationship between fatigue limit and stress gradient as a function of the relative stress gradient (RSG) (see Fig. 1 and Eq. (1)), described in Eq. (2) (for stress ratio $R=-1$).

$$\chi' = \left(\frac{1}{\sigma_{\max}}\right)\left(\frac{d\sigma}{dx}\right) \tag{1}$$

$$\sigma_f = \sigma_{tf}\left[1+\left(\frac{\sigma_{bf}}{\sigma_{tf}}-1\right)\left(\frac{\chi'}{2/b}\right)^{K_D}\right] \tag{2}$$

in which the exponent K_D describes how σ_f behaves between σ_{tf} and σ_{bf} and is characteristic of material type. K_D can be assumed to be 0.3 for alloyed steel materials [2].

Olmi et al. [4] have implemented the Eichlseder approach on shot peened notched specimens considering the effective distribution of stresses at notch root as a sum of the stress due to the external load at its maximum value (obtained by FE structural analysis) and the residual stresses due to SP (measured experimentally); then adjusting the obtained fatigue limit, considering the actual mean stress of the cycle and consequently the modified R, by constructing the Haigh diagram (Goodman linear model) [4].

Since the gradient in correspondence to the notch effect can be very sharp, it is often difficult to determine the exact value of the gradient, unless a very fine mesh is used in the FE model, which in turn raises the calculation time and computational costs. However, Eichlseder model is not linear and its trend is similar to that of a logarithmic curve; for this reason it has a relatively good robustness. Olmi et al. [4] report that for 30% error in RSG calculation, the fatigue predictions is affected by just 1–3% errors.

2.2. FKM method

FKM Guideline is a German guide reference for the design of mechanical components [6] that allows the assessment of fatigue strength considering nominal stresses as well as elastically determined local stresses derived from FE analyses. A uniformly structured calculation process is provided by FKM for both cases. The calculation process is almost completely predetermined. Both nominal and local stress approaches were applied in this paper and the results are discussed as following.

2.2.1. *Calculation of the fatigue limit through the nominal stress approach*

The design parameters included in this approach are the fatigue notch factor, considering the design of the component (shape, size and type of loading) as well as the roughness factor and the surface treatment factor through which the respective surface properties are accounted for. By specific combination of all these factors a summary design factor is calculated. The design factor for a rod shaped not welded component under tensile and bending stresses are defined as (the subscript *zd* stands for tensile and *b* for bending) [6]:

$$K_{\mathrm{WK,zd}} = \left(K_{f,\mathrm{zd}} + \frac{1}{K_{R,\sigma}} - 1\right)\frac{1}{K_V * K_S * K_{\mathrm{NL},E}} \tag{3}$$

$$K_{\mathrm{WK},b} = \left(K_{f,b} + \frac{1}{K_{R,\sigma}} - 1\right)\frac{1}{K_V * K_S * K_{\mathrm{NL},E}} \tag{4}$$

in which K_f is the fatigue notch factor depending on the component design and is to be calculated from stress concentration factors or experimental values. $K_{R,\sigma}$ refers to the surface roughness state, K_V considers the application of surface treatments including also SP, K_s refers to the presence of coatings and finally $K_{\mathrm{NL},E}$ accounts for the non-linear elastic behaviour that for steels is regarded to be equal to 1. The mentioned coefficients are defined as following for case of tensile and bending stresses [6]:

$$K_{f,\mathrm{zd}} = \frac{K_{t,\mathrm{zd}}}{n_\sigma(r)} \tag{5}$$

$$K_{f,b} = \frac{K_{t,b}}{n_\sigma(r) * n_\sigma(d)} \tag{6}$$

where K_t stands for stress concentration factor according to the type of stress, $n_\sigma(r)$ represents K_t–K_f ratio for the component under normal stress as a function of *r*, that is the notch radius and $n_\sigma(d)$ is K_t–K_f ratio for the component under normal stress as a function of d, that in turn is the diameter or width of the net notch section. $n_\sigma(r)$ and $n_\sigma(d)$ are calculated as a function of the related stress gradient $\bar{G}_\sigma(r)$and$\bar{G}_\sigma(d)$ [6]. For $\bar{G}_\sigma \le 0$, $1\,\mathrm{mm}^{-1}$ The following equations are considered:

$$n_\sigma = 1 + \bar{G}_\sigma * 10^{-(a_G^{-0.5} + (R_m/b_G))} \tag{7}$$

For $0.1\,\mathrm{mm}^{-1} \le \bar{G}_\sigma \le 1\,\mathrm{mm}^{-1}$:

$$n_\sigma = 1 + \sqrt{\bar{G}_\sigma} * 10^{-(a_G + (R_m/b_G))} \tag{8}$$

And for $1\,\mathrm{mm}^{-1} \le \bar{G}_\sigma \le 100\,\mathrm{mm}^{-1}$:

$$n_\sigma = 1 + \sqrt[4]{\bar{G}_\sigma} * 10^{-(a_G + (R_m/b_G))} \tag{9}$$

in which the a_G and b_G are constants respectively equal to 0.5 and 2700 MPa for steels. $\bar{G}_\sigma(d)$ is also defined as following:

$$\bar{G}_\sigma(d) = \frac{2}{d} \tag{10}$$

For the components which have been subjected to surface hardening, such as components treated by SP, the ratio K_f–K_t is lower than untreated parts; this is due to the fact that the maximum stress and stress gradient normally are applied to the surface of the component, thus a work hardened surface will show higher resistance.

The dependence of $\bar{G}_\sigma(r)$ on the notch radius can instead be expressed as a function of the notch type. A table is provided by FKM that provides the corresponding formulation for $\bar{G}_\sigma(r)$ as a function of the most common notch effects based on parameter φ that is defined as Eq. (13). The $\bar{G}_\sigma(r)$ for RBT series is defined as:

$$\bar{G}_\sigma(r) = \frac{2.3}{r}(1+\varphi) \tag{11}$$

and for AT series:

$$\bar{G}_\sigma(r) = \frac{2}{r(1+\varphi)} \tag{12}$$

$$\begin{cases} \varphi = 0 & \text{per}\,\dfrac{t}{d} > 0.25 \\ \varphi = \dfrac{1}{4 * \sqrt{\dfrac{t}{r}} + 2} & \text{per}\,\dfrac{t}{d} \le 0.25 \end{cases} \tag{13}$$

where *d* and *t* are geometrical aspects of the component described in FKM guideline [6]. The roughness coefficient is defined to consider the effect of surface roughness in the fatigue limit of the component. For a polished surface the coefficient of roughness $K_{r,\sigma}$ would be equal to 1; in case the specimen is not polished, the roughness coefficient can be calculated from the following equation for case of normal stresses.

$$K_{R,\sigma} = 1 - \alpha_{R,\sigma} * \log(R_z) * \log\left(\frac{2R_m}{R_{m,N,\min}}\right) \tag{14}$$

where $a_{R,\sigma}$ is a constant equal to 0.22 for steels, R_z is the roughness parameter in μm according to DIN4768, R_m is the tensile strength and $R_{m,N,\min}$ is the minimum tensile strength, which for steels is considered equal to 400 MPa.

A surface treatment factor, K_V has been also defined to take into account the surface hardening induced by surface treatments such as SP and rolling [6]. K_V in case of as received specimen without surface treatment is equal to 1. The FKM guide defines a range for this coefficient and the definitive value is to be determined by the user. The defined range for SP is 1.1–1.2 for un-notched steel components, and 1.1–1.5 for notched steel components. The higher K_V value for notched components is attributed to the fact that the plastic deformation below the notch, caused by the surface treatment, decreases to a considerable extent the level of stresses and thus slows down the crack growth rate.

The fatigue limit for a ratio of $R = -1$, σ_{WK}, for tensile and bending stresses can be calculated, with reference to the estimated coefficients according to Eq. (3) as following:

$$S_{\mathrm{WK,zd}} = \frac{S_{W,\mathrm{zd}}}{K_{\mathrm{WK,zd}}} \tag{15}$$

$$S_{\mathrm{WK},b} = \frac{S_{W,\mathrm{zd}}}{K_{\mathrm{WK},b}} \tag{16}$$

where $\sigma_{\mathrm{W,zd}}$ is the material fatigue limit for completely reversed stress and K_{WK} is the corresponding design factor. $\sigma_{W,\mathrm{zd}}$ is supposed to be a fraction of tensile strength as described in Eq. (17) [6].

$$\sigma_{W,\mathrm{zd}} = f_{W,\sigma} * R_m \tag{17}$$

in which $f_{W,\sigma}$ is considered equal to 0.4 for steels under tensile stress.

The effect of mean stress on the fatigue limit is also considered in FKM guide. The influence of mean stress is calculated according to the fatigue limits (Eq. (15)), as follows [6]:

$$S_{\mathrm{AK,zd}} = K_{\mathrm{AK,zd}} * K_{E,\sigma} * S_{\mathrm{WK,zd}} \tag{18}$$

$$S_{\mathrm{AK},b} = K_{\mathrm{AK},b} * K_{E,\sigma} * S_{\mathrm{WK},b} \tag{19}$$

$K_{E,\sigma}$ is a factor that takes into account the residual stress induced by welding thus for not welded components it is equal to 1. The coefficient that takes the presence of an average stress into account is indicated as K_{AK}. This coefficient is dependent on the type of overloading. There are four cases that distinguish how the stresses may increase in the case of a possible overload in service [6]. The coefficient K_{AK} also depends on the extent of the value of the mean stress $S_{m,\mathrm{zd}}$ and mean stress sensitivity M_σ. Assuming that the mean stress $S_{m,\mathrm{zd}}$ (Eq. (20)) remains the same, under overloading, K_{AK} will be defined as following Eq. (21).

$$S_{m,\mathrm{zd}} = \frac{S_{m,\mathrm{zd}}}{K_{E,\sigma} * S_{\mathrm{WK,zd}}} \tag{20}$$

the following cases can be distinguished:

- for $S_{m,\mathrm{zd}} < \frac{-1}{1-M_\sigma}$

$$K_{\mathrm{AK,zd}} = \frac{1}{1-M_\sigma} \tag{21}$$

- for $\frac{-1}{1-M_\sigma} \le S_{m,\mathrm{zd}} \le \frac{1}{1+M_\sigma}$

$$K_{AK,zd} = 1 - M_\sigma * S_{m,zd} \tag{22}$$

- for $\frac{1}{1+M_\sigma} < S_{m,\mathrm{zd}} < \frac{3+M_\sigma}{(1+M_\sigma)^2}$

$$K_{AK,zd} = \frac{1+(M_\sigma/3)}{1+M_\sigma} - \frac{M_\sigma}{3} * S_{m,\mathrm{zd}} \tag{23}$$

- $s_{m,\mathrm{zd}} \ge \frac{3+M_\sigma}{(1+M_\sigma)^2}$

$$K_{\mathrm{AK,zd}} = \frac{3+M_\sigma}{3(1+M_\sigma)^2} \tag{24}$$

In the case of bending stress, the subscript zd would be substituted by the subscript *b*. The mean stress sensitivity M_σ in connection with mean stress factor describes to what extent the mean stress affects the amplitude of the component fatigue strength and is defined as following:

$$M_\sigma = a_M * 10^{-3} * \frac{R_m}{MP\alpha} + b_M \tag{25}$$

where for steel a_M is 0.35, b_M is −0.1 and R_m is the material tensile strength. For surface hardened components, the mean stress sensitivity is greater because of the tensile strength R_m of the hardened surface being higher than that of not surface hardened component.

2.2.2. Fatigue limit calculation through local stress approach

The difference of local stress approach with respect to that of the nominal stress lies in the fact that the stress gradient, $\bar{G}_\sigma(r)$ *and* $\bar{G}_\sigma(d)$, rather than being determined by assimilating the notch effect to a standard geometry provided in the tables of FKM, is determined through a finite element analysis. This approach is therefore suitable for components of complex geometry for which the nominal cross sections cannot be clearly defined.

Similar to local stress approach, a design factor is defined to consider the effect of surface roughness, notch effect and surface treatments. In case of tensile stresses, the design factor is described by Eq. (26).

$$K_{\mathrm{WK},\sigma} = \frac{1}{n_\sigma}\left[1+\frac{1}{\bar{K}_f}\left(\frac{1}{K_{R,\sigma}}-1\right)\right]\frac{1}{K_V * K_S * K_{\mathrm{NL},E}} \tag{26}$$

where $\bar{K}_f$ is a constant that for steels is considered equal to 2.0, K_R is the surface roughness factor, K_V is the surface treatment factor, K_S is the factor of coating and $K_{\mathrm{NL},E}$ is a factor of non-linearity introduced in the case in which the behaviour of the material is not linear elastic. The calculation of the coefficients is performed exactly as discussed in Section 2.2.1; the basic difference resides in the determination of the stress gradient.

The calculation of the coefficient $K_{R,\sigma}$ is performed according to Eq. (14). The coefficient of surface treatment, K_V, is defined in the same range of the previous approach and K_S and $K_{\mathrm{NL},E}$ are equal to 1 for steels. n_σ is also calculated using the previously mentioned Eqs. (7)–(9), in which for steels the dimensionless constant a_G is equal to 0.5 and b_G is equal to 2700 MPa.

The related stress gradient normal to the direction of the stress, $\bar{G}_\sigma$, necessary to compute the K_t–K_f ratios are to be determined from the stress amplitude σ_a for normal stresses at the reference point on the surface and a point below the reference point. This stress gradient is defined as:

$$\bar{G}_\sigma = \frac{1}{\sigma_{1a}}\frac{\Delta\sigma_a}{\Delta S} = \frac{1}{\Delta S}\left(1-\frac{\sigma_{2a}}{\sigma_{1a}}\right) \tag{27}$$

where σ_{1a} is the stress amplitude in the reference point and σ_{2a} is the stress amplitude at a neighbouring point below it at a distance of ΔS. The point below the surface is to be chosen such that the maximum value of the strain gradient is calculated.

The component fatigue limit for completely reversed normal stress is defined is:

$$\sigma_{\mathrm{WK}} = \frac{S_{W,\mathrm{zd}}}{K_{\mathrm{WK},\sigma}} \tag{28}$$

in which $\sigma_{W,\mathrm{zd}}$ is the material fatigue limit for $R = -1$ and $K_{\mathrm{WK},\sigma}$ is the design factor.

The effect of mean stresses is also considered exactly similar to the approach already explained in Section 2.2.1. This in the presence of a mean stress the fatigue limit can be calculated as following:

$$\sigma_{\mathrm{AK}} = K_{\mathrm{AK},\sigma} * K_{E,\sigma} * \sigma_{\mathrm{WK}} \tag{29}$$

where $K_{\mathrm{AK},\sigma}$ is the mean stress factor, $K_{E,\sigma}$ is the welding residual stress factor that for not welded components is equal to 1, and σ_{WK} is the component fatigue limit for completely reversed stress. Also in this case, the mentioned factor depends on the behaviour of the component under overload condition and the same assumptions and equations of the previous case are applicable.

3. Experimental tests

The mentioned fatigue assessment criteria were applied to two different fatigue test lots consisting of RBT and AT both performed on shot peened notched specimens. In both cases the tests were performed following the Staircase [7] procedure and the fatigue strength corresponding to a fatigue life of 3 million cycles was calculated through the Hodge–Rosenblatt approach [8]. The fatigue test data was elaborated based on the ASTM standard E739-10 [9]. Details of the material characteristics and the surface treatment applied to each series are presented as following. More information about residual stress distribution and surface roughness of these series are available in Part 1 of this paper [1].

3.1. Fatigue tests

3.1.1. Rotating bending test series

Low alloy steel (40NiCrMo7, UNI 7845) smooth and notched specimens were shot peened using three different SP set of parameters. The peening parameters are presented in Table 1.

The geometry of the smooth and notched specimens used for RBT tests, in accordance with ISO 1143 [10] are shown in Fig. 2. The stress concentration factor of the notch for all series is $K_t = 2$ that is common in many machine elements such as shafts and springs.

Table 1
Aspects of the SP treatment on RBT specimens.

Treatment	Shot type and diameter (mm)	Almen intensity (0.0001 in.)	Coverage%
RBT-SP1	Z100 (ceramic, ϕ = 0.1)	10–12 N	100
RBT-SP2	S110 (steel, ϕ = 0.3)	4–6 A	100
RBT-SP3	S170 (steel, ϕ = 0.43)	10–12 A	100

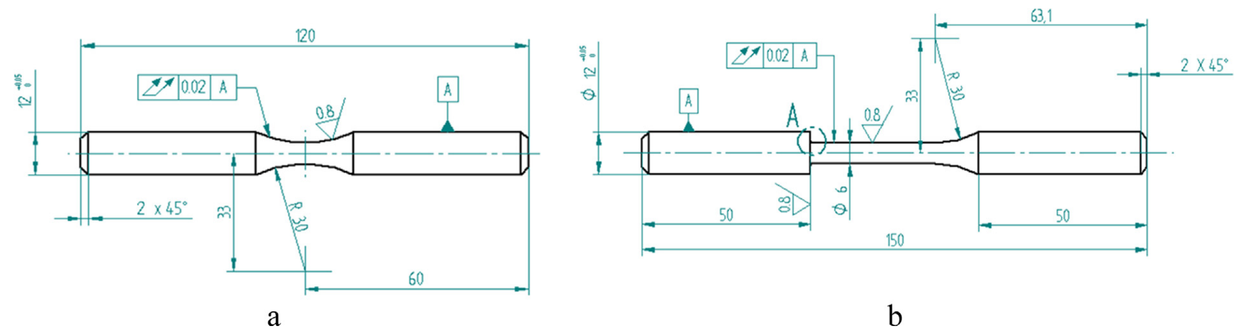

Fig. 2. RBT fatigue specimens' geometry (a) smooth specimen; (b) notched specimen.

Table 2
Aspects of the SP treatment on AT specimens.

Treatment	Shot type and diameter (mm)	Almen intensity (0.0001 in.)	Coverage%
AT-SP1	S70 (steel, ϕ = 0.18)	8–10 N	400
AT-SP2	S70 (steel, ϕ = 0.18)	12–14 N	100
AT-SP3	S70 (steel, ϕ = 0.18)	8–10 A	100

Table 3
Fatigue limit of RTB series (local stress concept vs. experimental data).

Treatment	Calculated fatigue limit (MPa)	Experimental data (MPa)	Error%
RBT-SP1	399	438	−9%
RBT-SP2	407	492	−17%
RBT-SP3	402	518	−22%

RBT tests (stress ratio $R = \sigma_{\min}/\sigma_{\max} = -1$) were carried out at room temperature.

3.1.2. Axial test series

AT were performed on different series of notched steel specimens, shot peened with unlike combinations of SP parameters. The material under investigation is steel normally used in pipeline applications named as A95. The choice of the specimen geometry stress concentration factor of $K_t = 5.9$ is based on the geometry of the threaded components used in pipelines. Specimen geometry is shown in Fig. 3 and the applied SP parameters are presented in Table 2. Pull-push AT were carried out in load control mode with stress ratio ($R = \sigma_{\min}/\sigma_{\max}$), $R = 0.1$.

4. Application of the criteria on axial fatigue and rotating bending fatigue tests

4.1. Local stress concept

The method suggested by Eichlseder [2] normalizes the stress gradient with respect to maximum applied stress (see Eq. (1)) to eliminate the effect of the external load on the results. Accordingly in this paper, the residual stresses are entered in to calculation just in the construction of Haigh diagram as mean stresses and the stress ratio is regarded to be dependent just on the external load. Thus the contribution made by SP in terms of increase of fatigue limit is considered as average residual stress.

4.1.1. RTB series

Axial fatigue limit of smooth specimens for $R = -1$, σ_{tf} was experimentally measured and the bending fatigue limit σ_{bf} of smooth specimen for $R = -1$ was calculated using it's relation with axial fatigue limit for a specimen with diameter of 6 mm [11].

As mentioned before, the local stress approach is originally developed for $R = -1$. For different stress ratios, the fatigue limit calculated by Eq. (2) was adjusted, considering the actual mean stress of the cycle that is the surface residual stress induced by SP, by constructing the Haigh diagram [11].

Eichlseder approach, not being developed for shot peened specimens, does not take account of surface roughness which is a well-recognized side effect of SP and normally leads to fatigue strength reduction [12,13]. Since relatively high surface roughness values were observed on all shot peened series, a roughness factor that is ratio of C_s coefficient for peened specimen to that of the NP specimen of the same material was introduced in to the calculations based on surface factor diagrams provided by Buch [14].

A further modification to improve the results of Eq. (2) is to apply a work hardening coefficient introduced by Fernandez-Pariente and Guagliano [15]. This modifying coefficient is calculated as the ratio of FWHM for peened specimen to that of the NP one. This modification takes into account the surface strain hardening index of FWHM obtained from XRD analysis. Thus Eq. (2) would be modified in the following form:

$$\sigma_f = \sigma_{tf}\left[1 + \left(\frac{\sigma_{bf}}{\sigma_{tf}} - 1\right)\left(\frac{\chi'}{2/b}\right)^{K_D}\right]\left(\frac{\mathrm{FWHM}_P}{\mathrm{FWHM}_{NP}}\right)\left(\frac{C_{sP}}{C_{sNP}}\right) \tag{30}$$

It is noted that the approximations of the Haigh diagram in the literature, such as that proposed by Marin [11], underestimate the actual fatigue limit in case of negative average stresses; thus in this case we have tried to reconstruct the Haigh diagram by interpolation of the experimental data available from the fatigue tests performed on shot peened smooth specimens. For the realization of this Haigh diagram, the effect of surface roughness and work hardening were deducted from the experimental data by dividing to C_s coefficient and FWHM, so as to consider only the increase in the fatigue limit due to the effect of the average residual stresses. In this way, the obtained results presented in Table 3 show a good correspondence with the experimental data.

4.1.2. AT series

The modified local stress concept was applied also the AT series. The obtained results after application of C_s and FWHM coefficients are presented in Table 4. The results indicate that the method provides a reasonable prediction for fatigue strength of AT series.

Table 4
Fatigue limit of AT series (local fatigue concept vs. experimental data).

Treatment	Calculated fatigue limit (MPa)	Experimental data (MPa)	Error%
AT-SP1	128	106	20%
AT-SP2	120	105	15%
AT-SP3	101	110	−8%

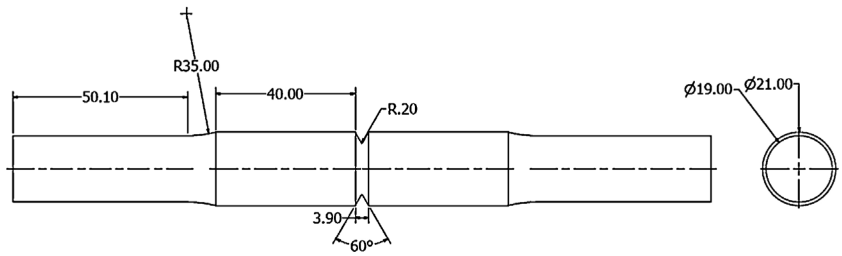

Fig. 3. Geometry of axial fatigue test specimen.

Table 5
Surface hardening coefficient K_V.

Treatment	RBT-NP	RBT-SP1	RBT-SP2	RBT-SP3
K_V for smooth specimen	1	1.1	1.14	1.16
K_V for notched specimen	1	1.1	1.2	1.25

Table 6
FKM fatigue limit, nominal stress approach, RBT series.

Treatment	Calculated fatigue limit (MPa)	Experimental data (MPa)	Error%
RBT-SP1	427	438	−2.51%
RBT-SP2	472	492	−4.06%
RBT-SP3	484	518	−6.56%

Table 7
FKM fatigue limit, local stress approach, RBT series.

Treatment	Calculated fatigue limit (MPa)	Experimental data (MPa)	Error%
RBT-SP1	426	438	−2.74%
RBT-SP2	471	492	−4.26%
RBT-SP3	485	518	6.37%

Table 8
Surface hardening coefficient K_V for AT series.

Treatment	AT-NP	AT-SP1	AT-SP2	AT-SP3
K_V for smooth specimen	1	1.2	1.2	1.25

Table 9
FKM fatigue limit, nominal stress approach, AT series.

Treatment	Calculated fatigue limit (MPa)	Experimental data (MPa)	Error %
AT-SP1	101	106	−4.71%
AT-SP2	100	106	−5.66%
AT-SP3	103	110	−6.36%

Table 10
FKM fatigue limit, local stress approach, AT series.

Treatment	Calculated fatigue limit (MPa)	Experimental data (MPa)	Error%
AT-SP1	97	106	−8.49%
AT-SP2	95	106	−10.37%
AT-SP3	97	110	−11.81%

4.2. FKM procedure

4.2.1. RBT series

4.2.1.1. Nominal stress approach. The approach described in detail in Section 2.2.1 is followed for calculation of fatigue limit based on the nominal stress approach. The range of the surface hardening coefficient K_V is indicted to be 1.1–1.2 for un-notched component and 1.1–1.5 for notched components. The corresponding value for each treatment was determined as presented in Table 5 assuming that this coefficient varies as a function of the peening intensity.

The residual stresses induced by SP on the surface were considered as mean stresses in the calculation of fatigue limit. The obtained results are presented in Table 6.

4.2.1.2. Local stress approach. The approach described in detail in Section 2.2.2 is followed for calculation of fatigue limit based on local stresses. A FE analysis was performed to obtain the distribution of stresses and calculation of stress gradient.

The obtained results are presented in Table 7. It is to be mentioned that the choice of the K_V coefficient is similar to what is presented in Table 5.

4.2.2. AT series

4.2.2.1. Nominal stress approach. The selected surface hardening factors, K_V, are presented in Table 8. The mean stress was also calculated by adding the surface residual stress induced by SP to the mean stress due to the external load ($R \neq 1$). The obtained results are presented in Table 9.

4.2.2.2. Local stress approach. A FE analysis was performed to obtain the distribution of stresses and calculation of stress gradient. The obtained results are presented in Table 10. The choice of the K_V coefficient is similar to what is presented in Table 8.

5. Summary and conclusions

The methods proposed in the literature for fatigue assessment of notched shot peened components were compared so as to determine which one is able to provide better results in terms of variation of the specimen geometry and the applied load.

- The local fatigue limit criterion proposed by Eichlseder was modified with corrective coefficients, which consider the effects of surface roughness and surface work hardening. With this modification satisfactory results are obtained for both series of specimens and the applied loads. This method requires the determination of the surface stress gradient induced by the external load through FE analysis with very precise and fine mesh definition.
- FKM approach requires the definition of a few parameters (ultimate strength, stress gradient, strain hardening and surface roughness coefficients) for the calculation of the fatigue limit; this method compared to a considerable simplicity of application, shows an excellent correlation with the experimental results both through nominal stress and local stress approaches. The approach of the nominal stresses categorizes and treats the notch effect as a general notch type available in the catalogue proposed

by FKM; while in the approach of local stresses, the stress gradient is determined through a FE analysis. FKM method considers the presence of residual stresses, the work hardening effect as well as surface roughness for the calculation of fatigue limit.

The obtained results indicate that among the examined approaches in Part 1 and Part 2 of this study, the FKM approach and TCD method approximate the experimental data more accurately. It is also to be considered that the method proposed by Eichlseder and the one proposed by Atzori et al., suitably adapt to the case of shot peened components, and are still able to provide results that approximate in a satisfactory manner to the experimental data.

By summarizing, the results indicate that FKM approach is the best compromise between accuracy and simplicity of application and provides reliable results for all the investigated series. The only limitation of this approach lies in the fact that it takes just the surface residual stresses into account; considering solely surface residual stresses does not provide an accurate estimation of effect of residual stress field, bearing in mind that for shot peening treatments with particularly high Almen intensity the surface residual stress decreases, while the layer affected by compressive residual stresses gets much deeper. This issue underestimates the effect of higher Almen intensity treatments and the induced deep stress field on fatigue behaviour of shot peened component.

Also the critical distance theory, described and evaluated in Part 1 [1], is able to provide a good correspondence with the experimental results: since it considers the critical conditions by integrating the stresses along a critical distance, it provides a robust solution to alterations of peening condition and to eventual local relaxation of residual stresses during the load cycles. Since partial relaxation of residual stresses induced via SP after fatigue loading is confirmed in previous studies [16].

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