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CORRELATION BETWEEN HARDNESS AND STRENGTH FOR REFINEMENT OF LIFETIME PREDICTION OF HEAVY GT CASING PARTS

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ABSTRACT

Despite current improvements in manufacturing and casting processes, casting defects are most of the times inevitable in the production of heavy gas turbine structural components. After the repair process has been carried out, inspections are performed to guarantee the quality of the produced gas turbine components and strength measurements are executed at room temperature on sample specimens to control material quality. In addition, hardness measurements can be performed in critical areas of possible crack initiations and over the casting surface of gas turbine structural parts, to check microstructure homogeneity.

In this paper the empirical proportionality between tensile stress and Brinell hardness has been obtained to estimate the local tensile properties due to post-weld heat treatment and are afterwards used to evaluate lifetime at critical locations.

Hardness at 175 locations has been measured and a mean value has been used to derive an updated global yield strength value of the material. The comparison of the updated yield strength against the nominal mean value has allowed a refinement of the lifetime prediction.

Finite Element assessments of two big casing parts are presented to show applicability of hardness-strength mapping on gas turbine components considering operational temperatures.

INTRODUCTION

Casting manufacturing process

Gas turbine casings have dimensions up to 5 m length and up to 6 m diameter. These structures are made of steel casting or nodular cast iron manufactured in a sand casting process and reaching a weight after casting of approximately 70 tons. Given the complexity of such components, casting and subsequent manufacturing steps have to be considered early in the design process, demanding a broad knowledge from the designer to combine the functional needs with the requirements on manufacturability of the component.

Figure 1 Casted Turbine housing

Material

The casings in the hot part of gas turbines are generally produced from steels that can be used up to the 400–500°C range. Stg10T is one of the most applicable steels for gas turbine components which operate at high temperatures to satisfy requirements on lifetime and deformation. Due to the composition, this material has advantages like high creep resistance, yield stress and LCF limit. In addition, it has low thermal expansion coefficient and good fracture mechanics properties and resistance against oxidation.

Table 1 Stg10T Chemical Composition (%, nominal)

G-X12CrMoWVNbN10-11								
C	Cr	Mo	W	Mn	Ni	V	Nb	N
0.12	10	1	1	0.8	0.6	0.2	0.06	0.05

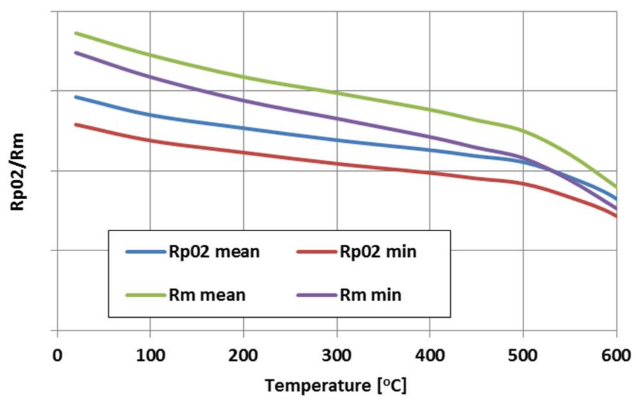

Figure 2 Strength properties against temperature for Stg10T

Defects on big scale components

Due to the complex shape and size of the component the casting process must be controlled using technology features like gating system, risers and chills to have a defined flow in the mold and a defined solidification. After demolding, the part gets cleaned, the technology features get removed and a quality heat treatment is performed. For steel castings it is common to find defects during inspection in the form of gas inclusions, hot and cold cracks or porosities. These defects are excavated and repaired using repair welding. After stress relive treatment (post-weld heat treatment) the part is ready for the final inspection, dimension control and handed over to the machining workshop.

Figure 3 Casting defects at a surface

HARDNESS AND STRENGTH MEASUREMENTS

Hardness of steels is the resistance to surface indentation under standard test conditions. Both hardness and tensile properties are indicators of steel resistance to plastic deformation and consequently they are roughly proportional. Several empirical correlations between hardness and ultimate strength for steels are normally available in handbooks and can be used for estimation of tensile strength of a given steel from its hardness.

Tensile proof stress, ultimate stress and hardness from 9 specimens out of two casing parts in Stg10T have been measured at room temperature.

The linear correlation between 0.2% tensile proof stress and hardness is expressed by the following equation:

$$R_{p02} = A \times HB + B \,. \qquad (1)$$

with:

Rp02: Yield strength
HB: Brinell Hardness
A,B: numerical coefficients

Similar equation is derived also for ultimate stress, as shown in Figure 4.

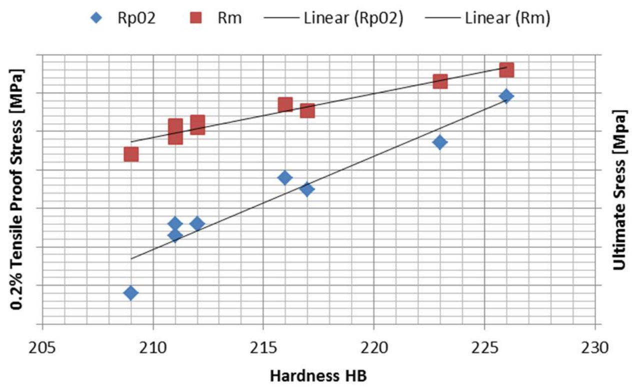

Figure 4 Linear dependency of tensile proof stress and ultimate stress on hardness

The square of the correlation between the response values and the predicted response values is 92%. Therefore, the correlation is generally good and can be used for the update of the strength properties based on hardness measurements.

Additional 120 hardness measurements at several locations of the two casing parts have been taken to check the repartition and homogeneity of the material after the heat treatment at 730°C for 8h related to repair process.

In fact reduction of strength properties is expected after prolonged permanence at high temperature, as anticipated by metallurgy theory and confirmed by practice. In Figure 5 this effect is shown for Stg10T and Stg9T.

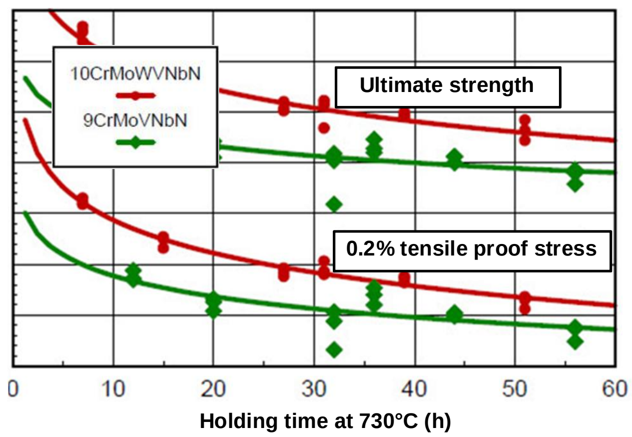

Figure 5 Strength properties reduction after heat treatment for two cast steels

Figure 6 presents all measured hardness values for both casings parts, using a set of standard and comparable locations. Hardness values range between 200HB and 250HB and this spread is related also to the fact that one part underwent more repair effort and consequent heat treatments than the other.

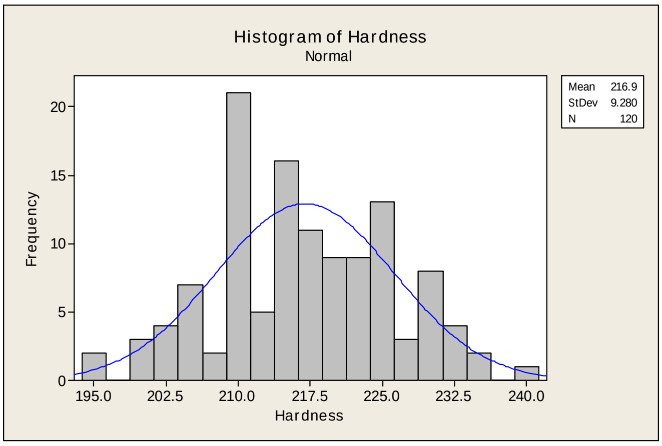

Figure 6 Hardness measurements results on two casing parts

The graph shown in **Figure 7** divides the 120 hardness values into categories according to measured part. The two halves of the part more heat treated exhibit an averaged hardness value which is lower compared to the other two halves.

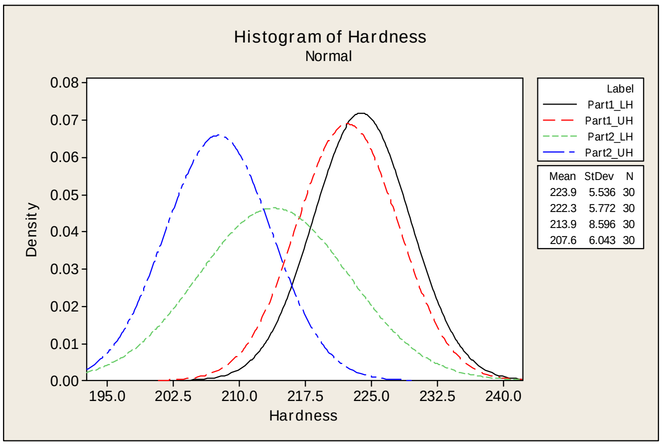

Figure 7 Normal distribution of the hardness values derived from on Minitab software

EFFECT OF HARDNESS ON STRESS-STRAIN CURVE

Ramberg-Osgood equation is normally used to model the elastic-plastic behaviour of ductile steels. The equation can be written for mono-axial applications in the form of (2):

$$\varepsilon_a = \frac{100 \cdot \sigma_a}{E_{stat}(T)} + 0.2 \cdot \left(\frac{\sigma_a}{r(T) \cdot R_{p02}(T)}\right)^{n(T)} \qquad (2)$$

with:

r: hardening factor [-]
n: stress exponent [-]
ε_a: strain amplitude [%]
σ_a: stress amplitude [MPa]
E_{stat}: static E-Modulus [MPa]
R_{p02}: yield strength [MPa]

Based on equation (2), the stress-strain curves at ambient temperature for minimum and mean data are shown in **Figure 8**, together with other curves derived using an interpolated value for yield stress.

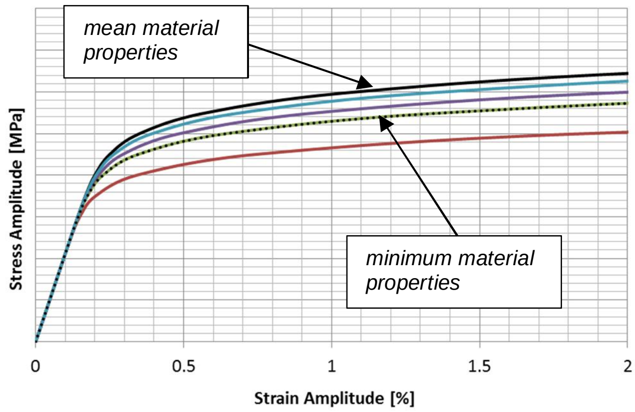

Figure 8 Stress-strain curves at ambient temperature

Considering the hardness-strength correlation shown in Figure 4, mean and minimum values of yield strength correspond to defined hardness values.
By changing $R_{p02}(T)$ in equation (2) degradation of the material due to PWHT can be transformed into different stress-strain curves which are between those derived from mean and minimum material values.

EFFECT OF HARDNESS ON LIFETIME

Large amount of LCF data for Stg10T is available, both from in house test results and from external public funded programs.

Since most of gas turbine components operate at high temperature, a damage temperature has to be defined based on thermal cycle experienced by the structural part at different locations, ranging typically between 400°C and 500°C. Such damage temperature is used to access corresponding Manson-Coffin curves and quantify the number of thermal cycles to crack initiation for a given level of elastic-plastic strain.

For the purpose of the task described in this paper, a backward application of Neuber hyperbola (3) to elastic-plastic strains from the Manson-Coffin curves allows generating σ-N curves for Stg10T in case of 400 and 500°C (see **Figure 9**):

$$\frac{2}{3}\times\frac{1+n(T)}{E(T)}\left(\sigma^{*}_{eq,a}\right)^{2}=\frac{2}{3}\times\frac{1+n(T)}{E(T)}\left(\sigma_{eq,a}\right)^{2}+\frac{\alpha(T)}{E(T)}\left(\frac{\sigma_{eq,a}}{\sigma_{0}(T)}\right)^{n(T)-1}\times\left(\sigma_{eq,a}\right)^{2} \qquad (3)$$

with:

$$\sigma_0(T) = r(T)\cdot R_{p02}$$

$$\alpha(T) = \frac{0.002\cdot E(T)}{r(T)\cdot R_{p02}}$$

and:

r: cyclic hardening factor [-]
n: stress exponent [-]
$\sigma^{*}_{eq,a}$: equivalent elastic stress amplitude [MPa]
$\sigma_{eq,a}$: equivalent elastic-plastic stress amplitude [MPa]
υ: Poisson ratio [-]
E: static E-Modulus [MPa]
R_{p02}: Yield strength [MPa]

In Figure 9, the continuous lines correspond to the mean and minimum LCF data. Assuming Coffin-Manson coefficients are not significantly affected by hardness variations, the dashed lines represent the resulting lifetime curve for an arbitrary measured value of hardness. It has to be mentioned that a reduction of hardness leads to a decrease in LCF lifetime only because of a bigger plastic deformation.

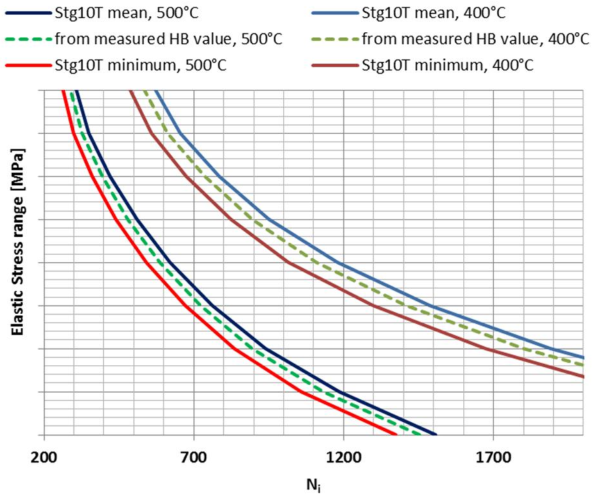

Figure 9 Effect of damage temperature and hardness on the lifetime

EFFECT OF HARDNESS ON LIFETIME OF CASING PART 1 (INNER CARRIER)

FEA calculations

Vane Carriers are critical components in gas turbine architecture, considering their cyclic operation under high temperature. Despite their design is optimized in such a way to satisfy the LCF requirements, the risk of fatigue failure at some locations is inevitable at highly cycling operational regimes, as shown in Figure 10.

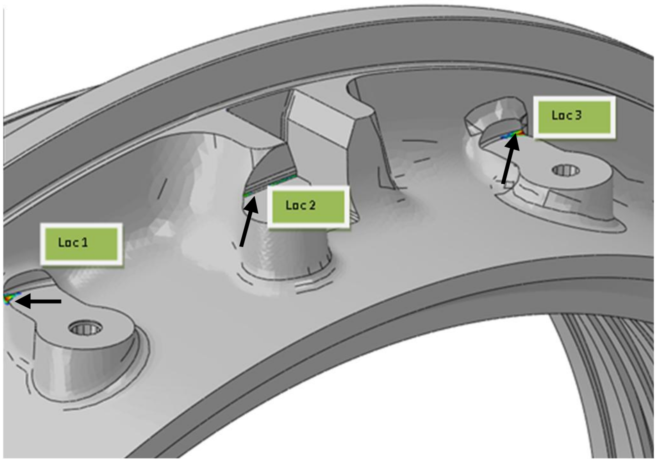

Figure 10 Simulated LCF lifetime, Casing Part 1

The corresponding damage temperature is globally approximately 450 C.

Hardness Measurements

Out of 60 standard hardness measurements, mean value corresponds to a yield value, which is slightly below the mean yield value available from material database. It matches the fact that this part underwent only one PWHT.

No locations have hardness values lower the value corresponding to the minimum yield available from material database.

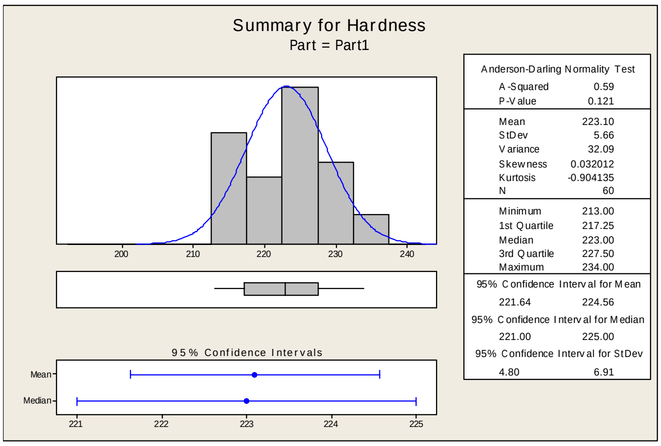

Figure 11 Normal distribution considering 60 measurements, Casing part 1

Scaling the empirical yield value available at room temperature for calculated damage temperature, Ramberg-Osgood and Neuber equations allow updating the max expected lifetime reduction, as described above. Maximum reduction of lifetime prediction is less than 20% for actual elastic stress range and damage temperature.

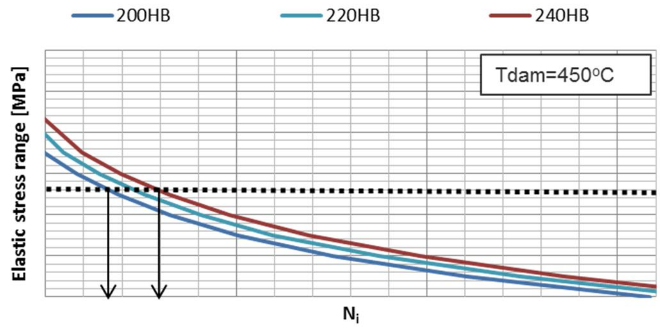

Figure 12 Fatigue curves σ-N for different hardness values

EFFECT OF HARDNESS ON LIFETIME OF CASING PART 2 (OUTER CASING)

FEA calculations

Hot outer casings are critical components in gas turbine architecture, considering their cyclic operation under high temperature, their complex shape, big size and the severe thermal gradients. Despite their design is optimized in such a way to satisfy the LCF requirements, the risk of fatigue failure at some locations is inevitable at highly cycling operational regimes, as shown in Figure 13.

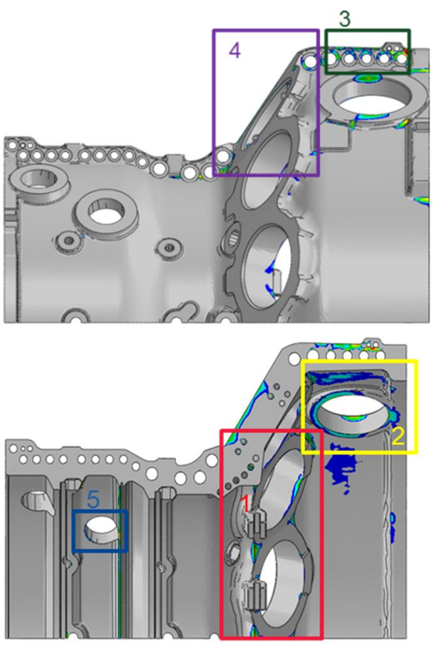

Figure 13 Simulated LCF lifetime, Casing Part 2

The corresponding damage temperature is visualized in Figure 14 and is almost equal to 500°C at the critical areas.

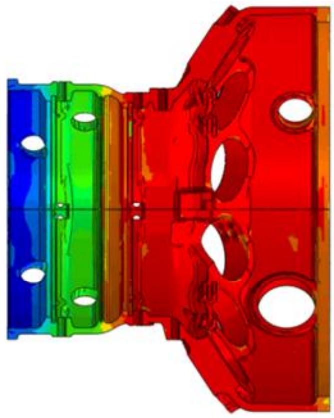

Figure 14 Simulated damage temperature, Casing Part 2

Hardness Measurements

Out of 60 standard hardness measurements, mean value is 211HB, corresponding to a yield value which is very close to the minimum yield value available from material database.

It can be concluded that the repeated repair cycles globally decreased material strength across the part, resulting in some single locations below strength specification/limits.

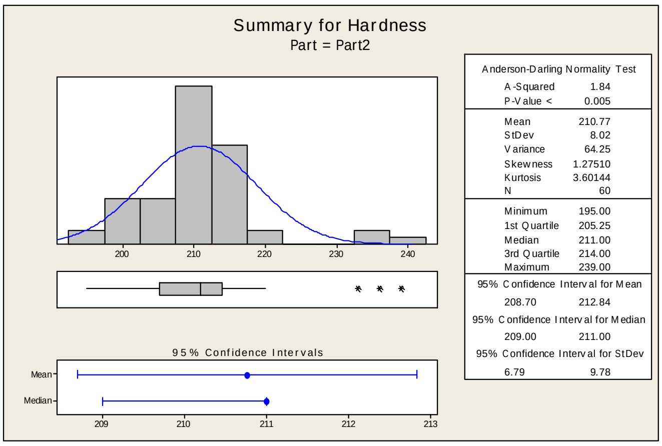

Figure 15 Normal distribution considering 60 measurements, casing part 2

In order to check that such locations do not coincide with critical ones, life limiting areas have been hardness-tested in detail, see Figure 16. Locations with hardness values between 200HB and 210HB are highlighted and most of these low hardness locations are around the can holes.

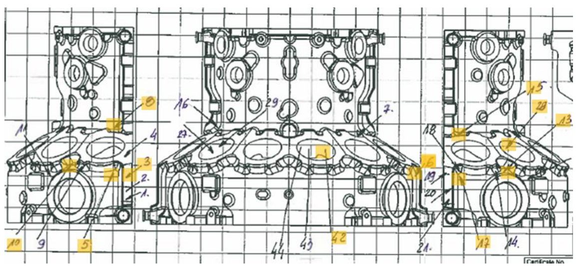

Figure 16 Hardness measurements for lifetime update

The hardness measurements have been used to estimate the tensile strength of the material and provide an update of the LCF lifetime burners holes area for this particular casting part, taking into account any irregularity of the material. The damage temperature of the outer casing at can-hole area has been assumed equal to 480°C as shown in Figure 14.

Using the procedure previously described, updated elastic-plastic strain amplitudes have been quantified and lifetime figures recalculated, to make sure that, despite global material degradation for this part, lifetime requirements are still met.

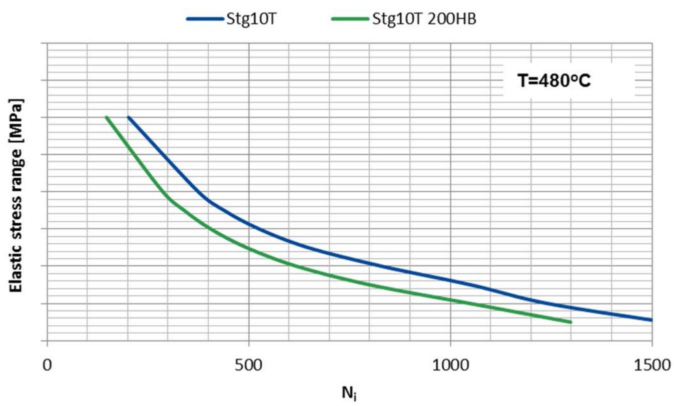

Figure 17 σ-N curves at 480°C

CONCLUSIONS

An empirical linear relationship between Rp02/Rm and hardness has been derived using dedicated specimens from specific casing parts in the form of Rp02/Rm=A*HB+B

Hardness-strength correlation has been used to estimate from a set of standard hardness measurements whether the PWHTs have caused significant global reduction of strength properties and lifetime figures.

For the case of a casing part which underwent several PWHTs, an additional set of hardness measurements has been performed and used to locally estimate the lifetime reduction.

NOMENCLATURE

HB – Hardness Brinell
Rp02 – Proof yield stress
Rm – Ultimate stress
PWHT – Post-weld Heat Treatment
LCF – Low Cycle Fatigue

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