ON THE IMPROVEMENT OF THE FATIGUE BEHAVIOUR OF AUSTENITIC STAINLESS STEELS DUE TO SURFACE RESIDUAL STRESSES PRODUCED BY LOW TEMPERATURE CARBURIZING

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ABSTRACT

Low temperature carburizing (LTC) treatment improves surface hardness and wear resistance of the austenitic stainless steels without reducing their corrosion resistance. Surface hardness over 1000 Vickers and compressive residual stresses whose modulus exceeds 1500 MPa are usually achieved in the carburized layer, thanks to the formation of the so-called “S-phase”, a carbon-supersaturated austenite phase.

A significant enhancement of the fatigue resistance due to different versions of this process is reported in literature.

The achievements obtained in recent years on the subject are summarized in this paper and the results of new rotating bending fatigue tests are illustrated. These tests showed that the low temperature carburizing treatment enhances the fatigue strength of the solution annealed 316 steel by 26.4% with respect to the non-treated material due to the high residual stresses present in the treated layer.

A much higher data spread than the one of the non-treated material was found and its causes have to be further investigated. Fatigue cracks in the surface-treated specimens always nucleated under the surface, near the boundary between the carburized case and the core.

A critical analysis of the recent literature on the modelling of fatigue behaviour of metals in the presence of surface compressive residual stresses was performed in order to verify the applicability of the models' hypotheses to the LTC case.

INTRODUCTION

Austenitic stainless steels such AISI 316 and AISI 316L are widely used in the nuclear, chemical, food and pharmaceutical industries and in biomedical applications mainly because of their excellent corrosion resistance.

The attempts made in recent years to engineer the surface of austenitic stainless steels to improve their hardness and tribological properties, without deteriorating their corrosion resistance, had the secondary effect of modifying the fatigue properties of those materials.

It is well know that austenitic stainless steels have good mechanical properties in terms of resistance and ductility, but a low hardness and consequently poor wear resistance.

Among others [1], a possibility of improving these properties is provided by different processes developed in the 1980's that consist in a low temperature carburizing, which involves the
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diffusion of large quantities of C atoms into the material at a diffusion temperature below 450 °C to prevent the formation of undesired chromium carbides and the degradation of the corrosion resistance.

In [2] the authors demonstrate that the phase produced by the nitriding, called the S-phase, has a highly distorted and disordered FCC austenitic structure, due to the formation of stacking faults and high compressive stresses. In the carbon S-phase, a high amount of carbon dissolved in the austenite causes the expansion and distortion of the FCC lattices of about 3% in the carburized layer, as in the nitrided layer. The carbon content [3, 4] reaches 10% on the surface and decreases gradually to zero in a few tens of microns towards the layer core interface, exhibiting a diffusion type carbon concentration profile.

Due to the low temperature, these treatments require long diffusion times from 35 to 100 h to achieve a carburized layer of a few tens of µm.

The value of the micro hardness is quite high if compared with values obtainable by other treatments, and in the literature it ranges from 950 to 1200 HV [3-8] (the variability depends also upon the different loads applied by the authors). Figure 1 shows a typical micro hardness profile obtained using a Vickers indenter with 10 g load (HV₀.₀₁) on metallurgical cross-sections of AISI 316 LTC treated specimens.

Such a hardness improvement, which is the primary goal of the LTC treatment, is mainly (not only as pointed out by [5]) due to the residual stresses induced by the Carbon supersaturation.

Many authors have used X-Ray diffraction to measure the biaxial residual stresses field in the LTC layer.

The values depend on the different carburizing process employed and ranges from a minimum of -1450 MPa, referenced in [1], to -1500 MPa found in [6,7], -2000 MPa in [4,5], up to -2400 MPa measured in [8]. The depth involved by the compressive residual stress depends mainly on the treatment time and is in the order of a few tens of microns.

The aim of the research was to find a phenomenological model of the fatigue behaviour of these materials after carburizing in order to predict the improvement of their fatigue life due to the presence of such high residual stresses. In this paper, on one hand the main findings on the fatigue behaviour of low temperature carburized austenitic steels will be reviewed and unpublished experimental results will be shown and on the other hand the latest approaches for fatigue life prediction in presence of residual compressive stresses will be analysed.
LITERATURE REVIEW THE FATIGUE RESULTS

To the author's knowledge the problem of the fatigue behaviour of LTC austenitic stainless steels has been studied in a limited number of very recent papers [1, 4-7]. The findings of the different authors are similar, and in particular they report a general improvement of the fatigue behaviour, but they also present important differences that have to be further investigated. There is no attempt to model the phenomenon quantitatively on the basis of the residual stresses. According to [6], which is the first contribution in this field, published in 2004, cantilever rotating bending fatigue life is dominated by small crack growth. The crack initiation phase is delayed due to the suppression of slip deformation at the surface and as a consequence the initial crack position is sub-superficial, just under the LTC layer. Crack propagation is discontinuous and proceeds simultaneously even with different velocities and different propagation directions in the base material and the hardened case. In fact, fracture has a fish-eye-like shape in the base material, while the front advances in a circumferential direction in the hardened layer that shows a brittle type final fracture. A significant temperature rise is observed and its negative effects on fatigue life are singled out. The same research group in [7] found no evidence of non-propagating cracks in the run-out specimens, concluding that the fatigue life is dominated by the initiation phase. They evaluated the fatigue notch sensitivity and observed a brittle fracture of the hardened case and a surface crack initiation for high stress concentration and high stress; otherwise the crack originated at the boundary of the LTC layer. A second research group [4,5] performed axial push-pull tests and did not find any evidence of embrittlement. They observed the mitigation of the surface stress raisers with the inhibition of the surface nucleation and activation of internal sources. Moreover the depth of the carburized layer (changed by multiple carburizing) seemed to have no effect on the fatigue life. Finally, Ceschini and Minak [1] found a remarkable improvement of the four point rotating bending fatigue behaviour in a cold worked austenitic steel. Fatigue testing was performed at 50Hz and a high, often unstable, temperature rise was found in LTC specimens. By cooling down the specimens by forced air a further improvement of the fatigue behaviour was obtained. The fracture mechanism observed was similar to the one reported in [6].

RESIDUAL STRESSES AND FATIGUE BEHAVIOR

The role of surface residual stresses in the modification of the fatigue behaviour of metals has been investigated in recent years by several authors [9-14] with different approaches. In [9] the effect of shot peening or surface rolling residual stresses, measured by XRD, on the fatigue crack initiation was studied by means of the classic Goodman criterion, provided that the sensitivity of the material to mean stress is known and independent from the treatment and that no stress relaxation occurs during the test. A literature survey of the residual stress stability during fatigue was performed in [10] for several materials and mechanical surface modification processes. The author accepted the hypothesis that the fatigue crack initiation is a function of the alternating stress amplitude only, while the crack growth rate is a function of both stress amplitude and mean stress. Different mechanisms of stress relaxation were singled out and in the case of shot peening (which is the most similar to the case under study in this work) it occurred due to high stress amplitudes and high temperatures.
The hypothesis that fatigue life improvement in shoot peened specimens is determined by the residual stresses ability of stopping crack propagation was accepted also in [11]. In fact, non propagating microcracks were observed at the SE microscope; these cracks originated from the surface. A FEM procedure to calculate the stress intensity factor resulting from applied and residual stress was developed. The effect of residual stresses on the threshold value of the stress intensity factor $\Delta K_{th}$, which determines the material resistance to the growth of a microscopic crack was singled out as the fundamental parameter. According to [12] the residual stress originated by shoot peening is a cyclically stable stress state that affects both the fatigue strength against crack initiation and the $\Delta K_{th}$. The approach used considers the stress gradient method for the crack initiation phase and the Linear Elastic Fracture Mechanics for the propagation phase. The authors concluded that only sub-surface cracks at a depth greater than the maximum residual stress depth are relevant for failure and that the sensitivity to mean and to residual stress is the same (in that particular case).

The relatively new theory of critical distance was used in [13] to determine the effect of shot peening and laser peening on some aluminium alloys with satisfactory results.

Finally, in [14] the residual stress field produced on a crankshaft by the rolling process was considered both in the initiation phase, using the SWT criterion, and in the propagation phase of fracture mechanics. Only surface cracks appeared for this particular situation.

The maximum value of the residual stress was in all cases significantly lower than the yield strength.

### EXPERIMENTAL TESTS

Rotating bending fatigue tests were performed according to ISO1143 [15]. A set of specimens was tested in the as-received (solution annealed) non-treated condition (NT) and a second set after the low temperature carburizing treatment (LTC). The load was applied in a four point bending scheme by means of calibrated weights. The value of the bending moment corresponding to each weight step was determined by means of a strain gage instrumented cylindrical specimen, before the start of the test campaign. The loading frequency was 50 Hz, the load ratio was $R=-1$ and the tests were stopped at $10^7$ cycles if the specimen did not break or bend before. The test campaign was planned according to ISO12107 [16] using a JSME scheme for the LTC material due to the limited number of specimens.
The LTC treatment in general can change the surface rugosity [1] which is a parameter that influences the fatigue behaviour.

In [1] the rugosity was intentionally kept at a value Ra=0.1 µm for both LTC treated and control specimens. Here, in order to evaluate the effect of this parameter on fatigue, the rugosity was Ra=0.8 µm.

Specimens for microstructural analyses were prepared using standard metallographic techniques and chemically etched with FeCl3. In figures 2 and 3 it is possible to see typical austenitic structure, with a considerable quantity of precipitates and the depth of the LTC layer, that was not etched by the acid.

The fatigue results are reported in figure 4 in terms of stress amplitudes and the logarithm of the number of cycles. It is worth noting a generally better behaviour of the LTC treated material with respect to the reference one. The fatigue endurance limit increased by 26.4 % (from 189 to 239 MPa) but a very high scatter was seen in the results, much higher than the one of the non treated material and also higher than what is reported in the literature [1, 4-7].
Differently from what is shown in [1] the specimens' temperature stabilized at values slightly higher than the room temperature for both series.

As usual in rotating bending fatigue tests, in the non-treated specimens the crack started from the surface, in some cases (for lower loads) from different points in the fracture section.

As is shown in figure 5, in the broken specimens fracture started at the border of the LTC zone and propagated from one side towards the centre of the specimen with an elliptical front and from the other, in the LCT layer in the circumferential direction, probably much more slowly due to the residual stress field [1,6].

Many of the failed specimens had several cracks visible on the surface (see figure 6), meaning that phase the crack propagation phase could not be ignored nevertheless on the surface of the survived specimens there was no evidence of non-propagating cracks.
DISCUSSION

Figure 7 shows the available data about fatigue endurance limits for LTC AISI 316/316L stainless steels. There is a general increase that ranges from 26.4% to 40%. In [1] a 70% increment is reported on forced air cooled specimens.

In trying to find the mechanism that provokes these increments, some firm points are available in the literature:
- hardness increases due to carbon supersaturation;
- hardness is mainly related to residual stresses and not to microstructural changes;
- the residual stresses main effect is to prevent the surface nucleation of crack.

One possible interpretation is that on one hand the high value of compressive residual stresses prevents the dislocation slips in the LTC layer, while on the other hand the hardened case forms a barrier to the propagation towards the surface. Once the internal crack reaches such a size that the stress intensity factor is higher than the hardened layer threshold one, the propagation proceeds in the LTC zone, but the residual stress field modifies the shape and the path of the crack as previously said.

The increase of the fatigue endurance limit in air cooled specimens [1] or the improvement of the fatigue behaviour in water cooled specimen [6] can probably be explained by considering the stability of carbon concentration, which causes the residual stresses, as a function of temperature [8]. In fact, as the temperature increases, the half life of the carbon depletion decreases exponentially.

The modest increment found in the present work is probably due to the high quantity of precipitates that act as preferential crack initiation points.

Another possibility is to consider the high value of the rugosity, that surely determines the crack path on the surface. Since the crack initiation was under the surface, the effect of surface roughness should influence the propagation phase only, which for most authors is negligible [5-7]. Moreover, [5] found that the treatment suppresses the effect of stress raisers (among them we can consider a high value of rugosity)

As regards the possibility to model the fatigue behaviour of LTC austenitic steels, a deeper understanding of the failure mechanism is needed.

First of all, most of the authors facing the problem of modelling the effect of surface residual stresses on fatigue considered either the propagation phase only or both phases, but in which the material properties are the same inside and outside the treated layer.

As already stated, there is a general agreement between the authors [1, 5-7] that the initiation phase is influenced by residual stresses; moreover, the macroscopic properties, first of all the yield strength, of the hardened case are surely different from those of the bulk material. The difference of this case with respect to those studied in literature [9-14] consists in the high value of residual stress that is at least three to six times the yield strength of the bulk material.

To correctly model this problem the stability of the residual stresses also has to be taken into account. As was observed by [1] and [4] (and in general by many author in austenitic stainless steels at high loading frequencies), the specimens heat up during fatigue testing, and if cooled they last more cycles. Probably, the loss of carbon due to temperature increase rapidly reduces the residual stress state and this could also explain the change of the fatigue crack location, from sub-surface to surface, observed by [5] in specimens with high stress concentration.
Finally, the effect of precipitates on the border of the hardened case must be investigated because in the case of defect-driven fatigue life, methods like the one proposed in [17] should be incorporated.

CONCLUSION

From the literature survey and the experimental tests performed, it is possible to conclude that the LTC treatment significantly increases the austenitic stainless steel specimens' life due to the high value of the residual stresses induced in the thin surface layer. There are different hypotheses on the mechanism that produces this improvement and more research is needed to clarify some points. The models available in the literature for analogous cases, due to their underlying hypotheses, are not directly applicable to the problem under study.

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