A test method for manufacturing effect assessment in HCF

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Abstract. Surface conditions produced by manufacturing processes are known to significantly affect the fatigue strength of metallic materials. However, fatigue tests on planar specimens usually present the onset of fatigue crack in a specimen edge, where the superposition of different machining techniques and subsequent machining operations can hide the effects of the studied process. This study deals with the design of a fatigue test able to reliably assess the effects on the high cycle fatigue strength of any machining process used to produce planar surfaces. It was devised a test configuration where the specimen geometry and the loading conditions are aimed to locate the crack nucleation in the middle of the surface machined by the investigated process. This condition is achieved by employing a notched specimen and a three-point bending test configuration, where the position and geometry of the notches are designed to relieve the specimen’s edges. Nevertheless, in the critical region, the stress state is quite uniaxial and uniform in the longitudinal direction. The specimen is manufactured by using the same parameters and processes adopted for full-scale components, thus producing a surface with the same properties as the real component. The designed test configuration was validated in a high cycle fatigue test aimed to compare the effects of broaching and wire electrical discharge machining on the Wöhler curve (S-N curve). The specimen geometry was tailored for a broaching process so that it has sufficient stiffness both in the directions parallel and perpendicular to the broaching direction. Fatigue tests were carried out on a resonant machine, that allowed to detect the crack nucleation by monitoring the test frequency.

1. Introduction

Manufacturing processes are known to reduce the fatigue life of metallic materials, especially in the region of the High Cycle Fatigue (HCF), [1,2]. The amount of the reduction depends both on the surface conditions produced by a process, [3,4], and on the susceptibility of the material to surface damages, which increasingly depends on the tensile strength and hardness of the material, [5]. High strength materials, used for critical applications, are the most affected by these phenomena.

Manufacturing processes intended to produce planar or not-round geometries, such as Wire Electrical Discharge Machining (WEDM), broaching, milling, and grinding, are widely used and studied. However, fatigue tests are carried out by using flat or hourglass specimens where the crack onset can occur near a specimen’s edge, [3,6–8].

The specimen’s edge is an anomalous crack initiation site because it is subject to the superposition of two different machining processes or of two passes of the same process when all the specimen surfaces are machined with the investigated process. Dealing with high cycle fatigue, the specimen edges represent also a weak point because on the sharp edges the grain slip is less limited by
neighboring grains than on planar or cylindrical surfaces, facilitating the slip bands mechanism at the basis of the fatigue crack onset, [9,10]. Finally, if the crack onset is near the edge, the fatigue life can be strongly influenced by the after-machining phase of edge deburring or sanding, which can eventually remove or worsen the damage produced by the studied process.

Manufacturing parameters significantly affect the surface conditions, namely in terms of roughness, scratches, residual stresses, grain distortions, [2,3,6]. In the case of broaching, the cutting parameters and the fixture that holds the specimen were demonstrated to affect the residual stresses in the machined surface and thus the fatigue strength, [11]. It is therefore important to have a specimen geometry designed to preserve, as far as possible, the machining parameters and holding fixture used in the production of industrial components. Broached specimens featuring a wide cross-sectional area were successfully tested in a bending loading configuration, [12].

A reliable assessment of the effects of the manufacturing processes on the fatigue life requires a specimen and a test configuration designed to produce the crack onset in the middle of the investigated surface, far from the edges with the other surfaces. In order to have data unaffected by further material properties, it is also important to produce a uniaxial stress state, at least in the critical area of the specimen.

The present study deals with the design of a fatigue test able to reliably assess the effects on the HCF strength of any machining process used to produce planar surfaces. It is presented the design of a test configuration where the specimen geometry and the loading conditions are aimed to locate the crack nucleation in the middle of the surface machined by the investigated process. It is also presented the experimental validation of this configuration in an HCF test aimed to compare the effects of broaching and WEDM on the Wöhler curve (S-N curve) of a high strength material.

2. Methods

A test configuration, aimed to reliably produce a crack onset in the middle of the investigated surface and to create a uniaxial tensile stress state in the region surrounding the critical point, was designed.

The test configuration is based on a prismatic specimen loaded in a three-point bending scheme. Only the surface on the tensile side of the specimen was machined with the manufacturing process whose effects on the HCF fatigue were investigated. The bending configuration was adopted in order to enhance the sensitivity of the test to the surface conditions, as the consequent stress gradient along with the specimen height reduces the likelihood of having a fatigue crack onset due to interior defects of the material.

The specimen was tailored for using a resonant testing machine. It involved that it was necessary to minimize the machine stroke and thus the specimen deflection in the region connected with the machine, while keeping the load within the machine limits and the contact pressure on the specimen within the bearing limit of the material. It resulted in the needing of maximizing, while preserving the above-mentioned limits, the ratio (ρ) of the maximum stress occurring in the tensile region of the specimen on its deflection of the region where the load is applied, yielding to:

\[ \rho = 6 \cdot \frac{E \cdot h}{L^2} \]  

where, as reported in Figure 1, \( h \) is the specimen height, \( L \) is the span between the supports, and \( E \) the Young modulus of the specimen material.

The specimen cross-section was designed to maximize the specimen width (\( w \)), compatibly with the available raw material and the testing machine limits, in order to have a wide area where the fatigue crack can occur and propagate until a detectable dimension without deeply propagating towards the interior of the specimen. Furthermore, as broaching was one of the studied machining processes, it was useful to have a specimen featuring a high stiffness both in the cutting direction of the broaching tool and in the direction orthogonal to it, allowing to reproduce the same manufacturing conditions as in the case of full-scale components, namely in terms of the type of the employed...
machine, cutting parameters, and holding fixture. Nevertheless, the applied test force was kept below 50 kN and thus within the limits of common testing machines present in laboratories.

To reliably locate the critical point in the middle of the investigated surface, it was chosen to decrease the stresses near the edges with the specimen’s side surfaces by introducing a group of symmetrically located lateral blunt notches, Figure 1. These full-height lateral notches were aimed to create a smooth stress concentration towards the central part of the investigated surface and thus to relieve the stresses on its edges.

The choice of a three-point bending loading configuration allowed to locate the notches in a less loaded region and thus to keep the critical point in the central part of the investigated region, despite of the stress concentration and the section reduction due to the notches.

The fundamental constraint was that the nominal stresses occurring in the middle longitudinal position (A) have to be greater than the ones occurring in any generic position (B), as expressed in equation (2), where $M_x$ and $W_x$ are the bending moment and the section modulus respectively and $k_t$ is the stress concentration factor caused by the presence of the notch. It follows that it was possible to formulate an analytical relation, equation (3), that provides a minimum constraint for the preliminary design of the notches’ longitudinal position ($s$) and severity, namely the amount of the section reduction. The notch longitudinal position ($s$) and the specimen height ($h$) and width ($w$), and the span between the supports ($L$) are defined in Figure 1. In absence of literature data for the specific notch geometry, it was assumed that the blunt lateral notches will not introduce any stress concentration and thus the stress concentration factor, $k_t$, was equal to 1. 

\[
\frac{M_{xA}}{W_{xA}} > \frac{M_{xB}}{W_{xB}} \cdot k_t \quad (2)
\]

\[
\frac{s_B}{h^2 w_B} \cdot k_t < \frac{L}{2 h^2 w_A} \quad (3)
\]

To increase the severity of the lateral notches and thus the gap among the stresses occurring in the middle of the investigated area and the ones occurring near the edges, the specimen height ($h$), in the middle longitudinal part of the specimen, can be decreased by machining a portion of the compressed side of the specimen.

The final specimen geometry was obtained by using a Finite Element Model (FEM). Because of the symmetry in the specimen geometry, loading, and supports, it was possible to model only one-quarter of the specimen and to apply symmetry constraints on the cut surfaces, Figure 2. The specimen was meshed by using three-dimensional 20-nodes hexahedral elements, featuring a minimum element size of 0.25 mm in the critical region. The material was modeled as a homogeneous and isotropic material, with a Young modulus and Poisson ratio of 210 GPa and 0.29 respectively. The applied load was modeled as a uniform pressure on the area facing the punch linked to the testing machine, and the supports were introduced as frictional contact between the specimen and a rigid surface, Figure 2.

The notches’ geometry and position were defined by carrying out a batch of numerical simulations aimed to maximize the gap between the peak values of Von Mises equivalent stress predicted near the edges and in the middle of the investigated surface while preserving a uniaxial stress state in the area of interest. The specimen length and consequently the span ($L$) between the supports were designed to reproduce the needed stress levels in the critical region while complying with the machine limits on the allowable force and displacement. The FEM optimization was also constrained by the geometry of the machining tools employed to manufacture the investigated region.
Figure 1. Scheme of the test configuration.

Figure 2. Boundary conditions (a), and mesh (b) of the FEM.
The designed test configuration was validated in an HCF test aimed to compare the effects of broaching and wire electrical discharge machining on the Wöhler curve (S-N curve). It was carried out an experimental campaign consisting of 10 tests per each manufacturing process, distributed at stress levels that produced fatigue endurances comprising between $10^5$ and $10^7$ cycles to crack nucleation.

The specimens were made in the nickel-based alloy Inconel 718, subjected to a heat treatment of solution annealing and aging, and were manufactured by using the same parameters and processes adopted for full-scale components.

The fatigue tests were carried out by using a resonant testing machine, Amsler HFP 1478 (RUMUL, Russenberger Prüfmaschinen AG, CH), equipped with a 50kN load cell and the specific fixture shown in Figure 3. The tests were run in force control, with a stress ratio (R) of 0.05.

![Figure 3. Three-point bending test fixture mounted on the resonant testing machine.](image)

The crack onset was monitored by acquiring the operating frequency of the resonant testing machine for each test. As the investigation was aimed to find out the cycles to crack nucleation, the failure condition was defined as a drop of 1 Hz of the frequency, Figure 4. The choice of the threshold is intrinsically a tradeoff between the error in the definition of the number of cycles to crack nucleation and the possibility to detect the crack after the test interruption, along with the necessity to avoid false interruptions of the test. The definition of the proper limit can depend on the mechanical properties of the tested material, in particular ductility and toughness. A preliminary commissioning phase is thus necessary to define the correct value.

The adopted threshold was defined after some preliminary tests aimed to monitor the trend of the test frequency and the velocity of the frequency drop during the crack propagation phase. For the
tested material, it can be seen in Figure 4 that the trend is almost constant for most of the test duration and shows an abrupt drop of about 1.5 Hz in less than 100,000 cycles, with an increasing drop velocity. The possible error is thus a negligible quantity compared to the ordinary HCF life and can be further reduced by adopting a stricter threshold.

After the test interruption, the fatigue crack was detected via dye Liquid Penetrant Inspection (LPI), carried out in conformity with the ASTM E1417-13 standard [13].

![Crack nucleation](image1)

Figure 4. Test frequency and crack detection.

3. Results and discussion

The final specimen geometry and dimensions, defined by using the FEM optimization procedure, are reported in Figure 5. The specimen is characterized by four symmetrical lateral blunt notches and a smooth height ($h$) reduction in the central region of the compressed side.

In the investigated area, the stress state resulted to be tensile and almost uniaxial, with the dominant component aligned with the specimen longitudinal direction ($z$). The longitudinal stress resulted to be almost uniform in the middle part of the investigated area, whose values were significantly greater than the ones occurring in the region nearest to the lateral surfaces, Figure 6. The maximum value turned out to occur in the center of the investigated area and 2/3 of the specimen width was subjected to a stress greater than 90% of the maximum stress.

In the critical point, the stress tensor ($S_{cp}$), expressed in the coordinate system represented in Figure 6, shows a uniaxial tensile stress state, with the prevailing component aligned with the specimen longitudinal direction, and the only other non-null component aligned with the specimen width ($x$) and equal to 3% of the former, (4).

$$S_{cp} = \begin{bmatrix} -0.03 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 \end{bmatrix}$$ (4)

The notched geometry resulted not to create any significant stress concentration in the area of interest, where the stress concentration factor, calculated as the ratio of the maximum predicted longitudinal stress and the nominal stress, resulted to be equal to 1.02.
Figure 5. Final specimen geometry and dimensions (dimensions in mm).

Figure 6. Longitudinal normal stress component (values normalized with respect to its maximum value), shown only one-quarter of the specimen due to symmetries in x and z directions.

The adopted configuration produced a 15% gap among the values of the longitudinal normal stress component occurring in the middle of the investigated region and near the specimen edges, as shown in Figure 7, reaching in this way the design goal of producing a significant drop in the prevailing stress that enhances the probability of having the fatigue crack onset in the middle of the analyzed surface.
It is worth analyzing the gradients of the prevailing stress, namely the longitudinal normal stress, occurring on the investigated surface along with the two lines parallel to the specimen longitudinal (z) and width (x) direction and passing through the specimen midpoint, Figure 7. While moving in the width direction, the stress gradient is smoother in the central region than in the outer one, providing a region of about 5 mm subjected to 97% of the maximum value. Also along with the longitudinal direction, the stress gradient is very smooth in the central region: a region that extends for about 4 mm from the specimen midpoint was subjected to a stress greater than 97% of the peak value, resulting in a test configuration that was sufficiently robust against possible specimen positioning errors.

The notches resulted not to be a critical region. The maximum value of the equivalent Von Mises stress occurring near the lateral notches is about 17% lower than the value occurring in the middle of the investigated surface.

Regardless of the manufacturing process and the applied load, all the tested specimens presented one or multiple crack onsets in the middle of the investigated area and no cracks were detected on the lateral surfaces or near the specimen edges, as shown in Figure 8 and Figure 9. The fatigue crack path was almost orthogonal to the direction of the principal stress and extended in the region predicted as the most stressed part of the investigated area by the proposed FEM, red hatched area in Figure 8.

Even if with a slight variability, probably due to the presence of the weakest a point on the surface, in all the tested specimens the fatigue crack was detected within the most loaded portion of the investigated surface, Figure 9, providing the evidence of the robustness of the presented methodology in producing the crack nucleation within the most stressed part of the investigated surface.

The crack propagation phase (N_p), detected as a 1 Hz drop in the test frequency, took a portion ranging between 3% and 10% of the total fatigue life (N_f), with higher durations at lower stresses.
Figure 8. Fatigue crack detected via LPI after a drop of 1 Hz in the test frequency, investigated surface (a), left lateral surface (b), right lateral surface (c) ($N_p/N_f = 3.3\%$, $N_f = 1.3 \cdot 10^6$).

Figure 9. Repeatability of the fatigue crack nucleation on the investigated surface for different manufacturing processes ($N_p/N_f = 6\%$ $N_f = 1.85 \cdot 10^6$ (a), $N_p/N_f = 5.1\%$, $N_f = 1.79 \cdot 10^6$ (b), $N_p/N_f = 4.7\%$ $N_f = 2.3 \cdot 10^6$ (c)).
A preliminary fractographic analysis showed how the nucleation of the crack, detected via LPI, was on the investigated surface and almost in the middle of the specimen width, white dotted circle in Figure 10 (a). The analyzed specimen, after the first drop of 1 Hz in the test frequency and the crack detection via LPI, was subjected to a further phase of crack propagation using the same test configuration. Starting from a Fine Granular Area (FGA), surrounded by a fish-eye area, that can be observed in proximity to the surface, the crack propagated with an almost semicircular front centered in the nucleation site, Figure 10 (b). Further investigations with a Scanning Electron Microscope (SEM) will be necessary to investigate the presence of microstructural defects or inclusions in the nucleation site.

Figure 10. Preliminary fractographic analysis showing the nucleation site (a), and a detail of the nucleation site (b).

4. Conclusions
The devised test configuration demonstrated to be suitable for a reliable assessment of the HCF strength of machining processes that create planar surfaces, such as broaching, grinding, milling, and WEDM.

The specimen geometry and the loading conditions were designed to locate the fatigue crack nucleation in the middle of the surface machined by the investigated process, far from anomalous sites as the edges with the specimen’s side surfaces. This condition was achieved by employing a three-point bending test configuration and a notched specimen, where the position and geometry of the notches are designed to decrease the stresses near the specimen’s edges. Nevertheless, in the critical region, the stress state is quite uniaxial and uniform in the longitudinal direction. The bending configuration also allows using high-stiffness specimens that can be machined using the same manufacturing conditions adopted for full-scale components, in particular for broaching, thus leading to an effective assessment of the machining effects on the fatigue life.

The test configuration was successfully validated by an HCF test campaign aimed to compare the effects of broaching and WEDM on the Wöhler curve (S-N curve). It resulted to be effective and reliable, producing the crack onset in the middle of the investigated surface in all the tested specimens. The crack onset and propagation were consistent with the prediction of the FEM employed to simulate the test and design the specimen geometry.

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