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Numerical integration of machining conditions to calculate the fatigue life of a mechanical part

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Abstract

This article deals with optimizing the fatigue life of machined surfaces. Since 2005, LTDS Laboratory has developed a scientific method for numerical prediction the residual stress state generated by cutting operations on surfaces. This so-called "hybrid" modelling principle is based on equivalent thermo-mechanical loads calibrated with experimental machining forces. This model has reached a high level of technological and scientific maturity. Starting from the turning process, this methodology is now available as a software called MISULAB®, which predicts the three-dimensional residual stress fields on any type of turned part. The aim of this article is to show how three-dimensional residual stress fields on machined surfaces can be predicted by a numerical model (MISULAB®) and then how the stress fields can be used in fatigue strength calculations of a shaft (NCODE DESIGNLIFE®).

Keywords: Turning; Surface integrity; Residual stresses; Fatigue

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1. Introduction

When industrialising a safety component, engineers must estimate its effective fatigue resistance by considering the fatigue strength of the material and the functional operating conditions that the part is expected to withstand. The fatigue performance of a material should be an intrinsic property characterised by standardised ISO tests. Fatigue specimens are usually produced by turning or grinding and then hand polishing (e.g. lapping with abrasive slurry) to remove machining scratches and achieve as close to a mirror-like surface as possible (Juvinall et al. (1991)). In Fig. 1, the effect of surface state is described with a multiplying factor m_s applied on fatigue limit. Surface roughness and residual stress imply a loss in fatigue properties, which is all the greater the higher the hardness and ultimate stress.

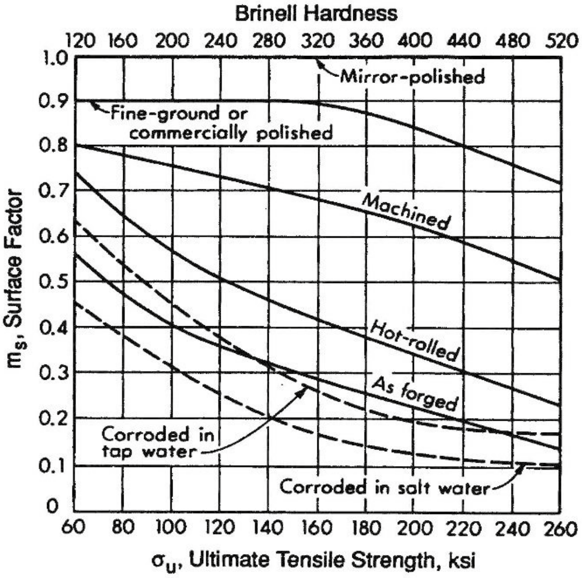

Fig. 1. Fatigue limit surface factor depending on surface finish and Ultimate Tensile Stress (since Juvinall et al. (1991)).)

However, companies are not as interested in characterising the fatigue strength of a mirror polished surface because their own components are machined using a variety of processes combined in a machining sequence. Each machining sequence results in a specific surface integrity, as defined by Fields et al. (1971), which is characterised by various features such as:

- The geometric parameters specified by two-dimensional roughness parameters (*Ra, Rz*, …) or by more complex three-dimensional ones (*Sa*, *Ssk*, …) that aim to reflect local stress concentration in the valleys, as proposed by Arola and Williams (2002).
- The mechanical parameters residual stress and microhardness. Jawahir et al. (2011) showed that machining processes typically affect residual stress within several hundred micrometres.
- The metallurgical parameters, such as microstructure (nature of phases and their corresponding grain sizes) and inclusions, as shown by Novovic et al. (2016). Several works have highlighted that common manufacturing processes, such as turning or grinding, induce systematic microstructural modifications (so-called 'white layers'), such as dynamic recrystallisation in the case of a martensitic 15-5 PH stainless steel since Mondelin et al. (2014) or transformation of martensite into untempered or overtempered martensite in case hardened steel since Tonshoff et al. (2000). These affected layers are 'white layers' several micrometres thick, as shown by Rech et al. (2023).

Several papers, such as that of Jawahir et al. (2011), argue that most standard ISO fatigue tests do not take into account these surface integrity features (mirror polished surface, no residual stresses, ideal microstructure). In fact, Griffiths (1971) emphasised that the majority of high cycle fatigue life is due to surface crack initiation. Surface initiation is directly controlled by the appropriate manufacturing sequence (from roughing to finishing). Therefore, after a roughing operation (i.e. turning) followed by lapping, it is questionable whether the surface of the fatigue specimen has been affected by the residual stress state induced by turning and/or whether the 'white layer' has been completely removed. It is also questionable whether the absence of residual stresses and the homogeneous microstructure have been verified. Between two sets of effective manufacturing conditions for each process in a sequence, it is easy to imagine that fatigue properties may vary even if all specimens have the same external surface integrity. This observation was clearly made by Hashimoto et al (2006) when comparing the influence on fatigue of a preliminary hard turning operation versus a grinding operation prior to the final honing operation. Even though the surface integrity in the outer surface layer is similar, they observed a doubled fatigue life for the probes produced by preliminary hard turning, which was attributed to a different crack propagation due to the different residual stress state under this honed surface layer, as shown by Hashimoto et al. This has been confirmed by Smith et al. (2007).

The companies are therefore interested in characterising the fatigue strength corresponding to their own machining sequences, which are used every day in the workshop, and not the fatigue strength corresponding to ideal surfaces produced by academic procedures (mirror-polished surfaces, free of residual stresses, ideal microstructure). It is therefore time to answer two questions:

- First : how would my machining process affect the three surface integrity features (surface roughness, residual stress gradient and microstructural state in the affected layer below the surface) ?
- Second : how these features will affect fatigue strength ?

Ideally, they would like to simulate the effect of the machining process onto the three surface integrity features and then simulate the corresponding fatigue strength. Then they would like to optimise their machining conditions to optimise the fatigue strength. This is clearly not the state of the art, either at an academic level or at an industrial level. However, recent advances in the numerical modelling of machining processes allow us to take a step towards this goal. Indeed, among a large number of scientific papers dealing with the numerical modelling of surface integrity induced by machining processes, the work of Dumas et al. (2021) has managed to reach a high level of maturity (TRL7). This modelling approach became an industrial software called MISULAB®, which simulates the residual stress state and surface roughness induced by turning. However, it does not yet predict the microstructural state.

Alongside this progress, software such as NCODE DESIGNLIFE®, which predicts the fatigue strength of a component, has been available for years. Such a model requires an SN or EN curve based model. They have the ability to include a uniform residual stress state in their simulation, or non-uniform, based on residual stress result simulated with FEA. The effect of residual stresses (Radaj et al. 2007) is taken into account with a mean stress correction, based on ultimate tensile stress (UTS) as Goodman, Gerber, on additional experimental parameters (Walker), from empirical rules (FKM), or by interpolating between experimental multiple curves (multi mean stress, multi R-Ratio or Haigh curves). In Morrow mean stress correction for EN approach (Morrow 1968), the effect is only applied on high cycle fatigue regime, as the low cycle fatigue regime tends to modify/override the residual stress state due to cyclic plasticity. In current paper concerning high cycle fatigue regime, we will use the simple Goodman mean stress correction approach to take into account residual stress, which only needs UTS as input. The aim of this paper is therefore to investigate the possibility of interfacing the two software packages to predict the influence of turning conditions on the fatigue strength of a shaft. The case study deals with the turning of fatigue specimens for a rotating bending test. The probes are made from 15-5PH martensitic stainless steels. This material has been chosen because Chomienne et al (2022) have shown that its fatigue strength in high cycle fatigue is mainly determined by the residual stress state.

The next sections describe the identification of the SN curve and the corresponding fatigue model. The principle of MISULAB® is then summarised. Finally, the interface between MISULAB® and NCODE DESIGNLIFE® is presented and applied to the case study.

2. Characterization of surface integrity features

The material considered is a martensitic stainless steel 15-5PH having a UTS of 1400 MPa. Rotating bending fatigue probes (Fig. 2) were turned using a carbide insert with the designation DNMG150612QM4215. The following cutting conditions were used: cutting speed Vc = 90 m/min, feed f = 0.18 mm/rev, depth of cut ap = 0.6 mm and cutting fluid: emulsion. The surface roughness produced is about Ra $\approx$ 0.9 μm. The residual stress state was characterised by X-ray diffraction using the $\sin^2\psi$ method. Fig. 3 shows a tensile state in both cutting (=circumferential) and feed (=axial) directions, with an affected layer around 150 µm.

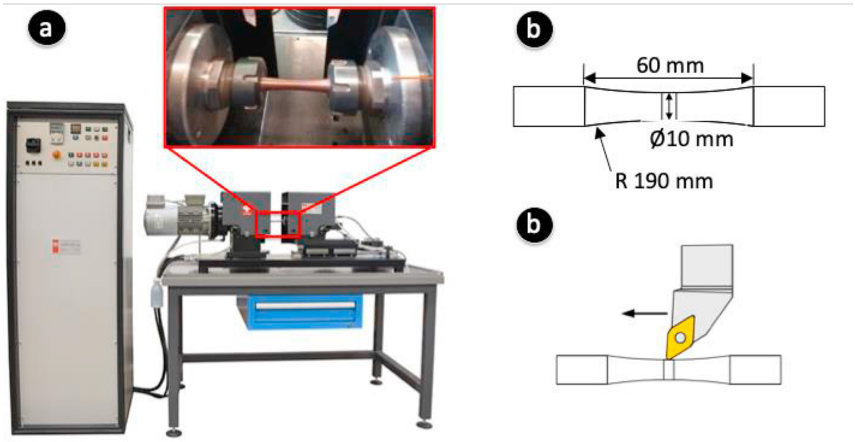

Fig. 2. (a) Rotating bending set-up, (b) fatigue probes, (c) turning conditions

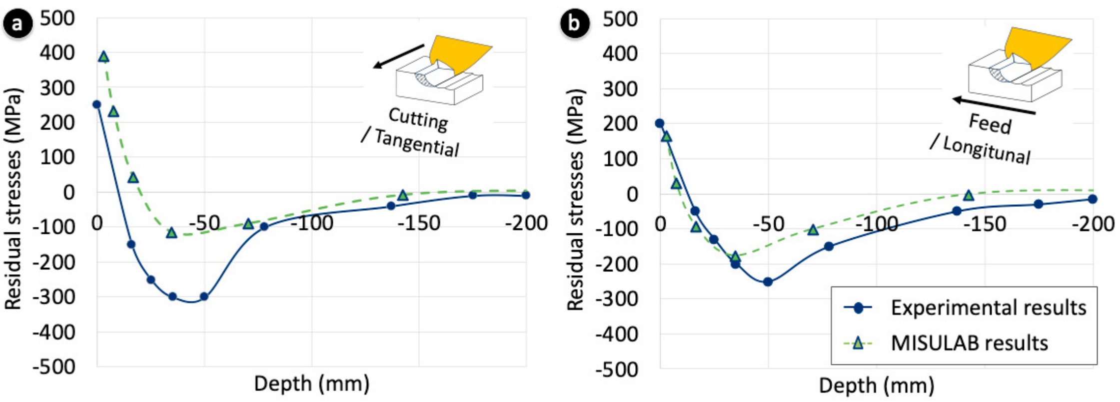

Fig. 3. Residual stress gradient induced by turning

Chomienne (2014) performed several rotating bending fatigue tests on a Walter+Bai setup as shown in Fig. 2a. The corresponding SN curve is shown in Fig. 4. The crosses correspond to the experimental results, while the black dashed line represents the fatigue model (bilinear model in logarithmic scale).

3. Numerical modeling of residual stresses

The aim of this section is to simulate the residual stresses generated using the MISULAB® software. The simulation is based on the "3D hybrid multi-pass model" developed by Dumas et al. (2021). A summary of the model is shown in Fig. 5. Residual stress prediction is achieved by applying equivalent thermo-mechanical loads to a finite element (FE) model of the machined surface. The 3D steady state stress distribution is calculated by three key steps: 1) decomposing the actual 3D problem (c) into elementary 2D sections (d), 2) calculating the thermomechanical loads (ABAQUS Explicit) generated by each 2D section on the machined surface along the extraction line (e+f), and 3) simulating the mechanical and temperature fields induced by the merged 3D equivalent loads over the final surface after several revolutions (g), finally extracting the residual stress profile at the centre of the model in two directions (circumferential and axial).

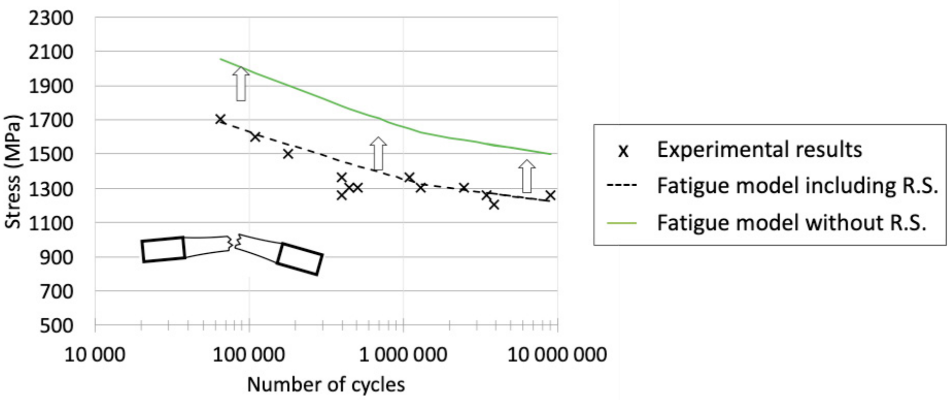

Fig. 4 S-N curve of the turned probes and corresponding fatigue model

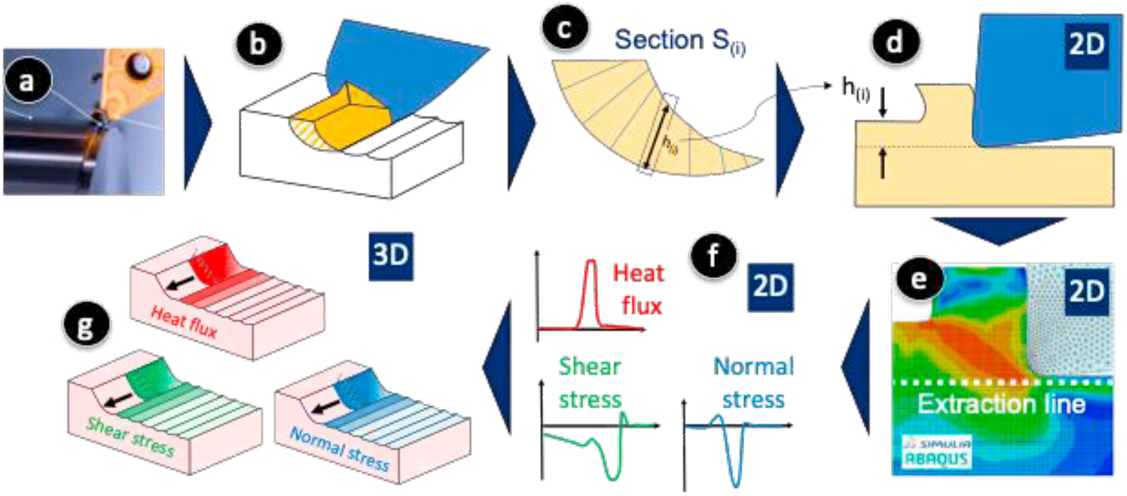

Fig. 5 Modeling strategy of residual stresses induced in turning

The MISULAB® software was applied to the case study. The thermal and physical properties of the 15-5PH and the cutting tool were taken from the work of Dumas et al. (2021). Fig. 3 shows the residual stress profiles predicted by the model (green dashed line). It appears that MISULAB® predicts the residual stress state in the outer layer with reasonable accuracy. The depth affected is also well predicted. On the contrary, the peak of compression in the subsurface is not well predicted for this case study. However, the most important for the present work is the residual stress state in the outer layer where cracks may occur. Considering that NCODE DESIGNLIFE® is able to predict the appearance of cracks on the outer surface, the accuracy of MISULAB® is satisfactory.

4. Prediction of fatigue strength

The purpose of this section is to use the NCODE DESIGNLIFE® software to predict the fatigue life of a probe under a defined load. The software has long been capable of integrating a residual stress with a uniform value in the part, or as input load case. However, the previous section has shown that turning induces a gradient below the surface. Furthermore, the residual stress state is different in the tangential and longitudinal directions (Fig. 3), from MISULAB® result format. One step in the present work was to develop an Application Programming Interface (API) that allows a complex 3D residual stress field to be transferred from MISULAB® to NCODE DESIGNLIFE® for integration into the fatigue life calculation. It is now possible to integrate a complex residual stress field from machining simulation into a fatigue life calculation.

However, one serious problem remains: the fatigue model. Section 2 presented the SN curve corresponding to the probes produced by turning. From this cloud of experimental values, a fatigue model (black dashed line) has been identified in Fig. 4 and integrated into the fatigue software. It is important to remember that the probes contain the residual stress field generated by its own sequence of machining. To validate the ability of the software to predict fatigue life, the fatigue probe geometry was modelled in the finite element software ABAQUS. A bending moment of 63 N.m was then applied, inducing a maximum von Mises stress state of 642 MPa in the outer layer, which results in an alternated stress of 1284 (=2x642) MPa. The result is shown in Fig. 6a. As expected, NCODE DESIGNLIFE® predicts a fatigue life of approximately 1.78 million cycles, which is in agreement with the experimental data shown in Fig. 4. This result is the consequence of the intrinsic properties of the 15-5PH material combined with the residual stress state generated by the turning operation. Now the question for an end user would be: How is it possible to distinguish the effect of the residual stress state? Is it possible to predict the fatigue life corresponding to a different residual stress state (= a different cutting tool or cutting condition)?

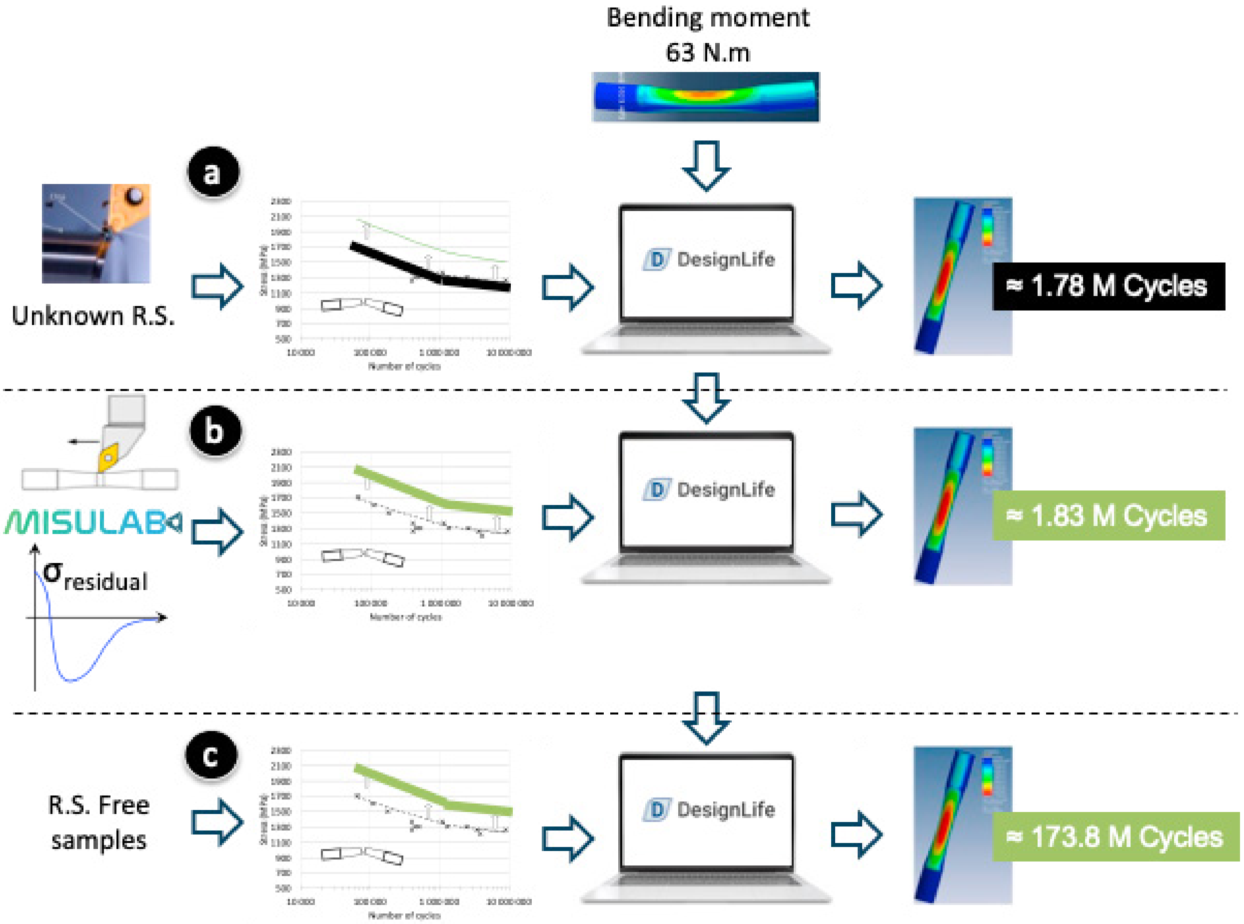

Fig. 6 Prediction of the fatigue life for various residual stress field and fatigue model

The first approach would be to heat-treat the specimen in order to relieve residual stresses without altering the microstructure or the mechanical properties, and then to perform additional fatigue tests to obtain a new experimental S–N curve (free of residual stresses). Unfortunately, despite extensive attempts, it was not possible to identify suitable treatment conditions for this alloy. It was therefore decided to adopt an analytical method to circumvent this issue. As shown in Fig. 7, the Haigh–Goodman diagram allows one to account for the initial state of the specimen (residual stresses being present before applying the alternating bending moment of 63 N·m) and to simulate a new S–N curve without residual stresses. This modification was made by considering the von Mises residual stress state in the outer layer, based on the measurements reported in Fig. 3. The new fatigue model (free of residual stresses) is plotted as a continuous green line in Fig. 4. The green curve was obtained by shifting the black dashed line by +2 × 200 MPa, corresponding to the von Mises residual stress state.

Based on this new fatigue model (assumed as free of residual stresses), the same fatigue calculation was simulated by applying a bending moment of 63 N.m using NCODE DESIGNLIFE®. Fig. 6c shows that the theoretical fatigue life would be approximately 173.8 millions of cycles. This value is very high and cannot be validated since stress relaxation is not possible for this steel. The uncertainty in this value is the combination of the uncertainty in the original fatigue model (black dashed line in Fig. 4 from the experimental points) and the uncertainty in the application of the Haigh-Goodman analysis method. Improving these two steps would improve the estimation of a theoretical fatigue life without residual stress. Moreover, the fatigue model, introduced in NCODE DESIGNLIFE®, only considers the stress state (mechanical loading + residual stresses) in the outer layer which determines the initiation of the crack. and does not consider the effect of the complex residual stress profile below the surface during the propagation phase.

However, if the new fatigue model (green continuous line - free of residual stress) (Fig. 4) and the residual stress field induced by turning (Fig. 3 - MISULAB®) are both introduced into the fatigue calculation with NCODE DESIGNLIFE®, then Fig. 6b shows that the predicted fatigue life is approximately 1.83 million cycles. Two consistent fatigue life can therefore be obtained either by using the fatigue model (black dashed line in Fig. 4) identified thanks to the experimental fatigue tests with the probes containing the residual stress state, or by combining the theoretical fatigue model (green continuous line in Fig. 4 – free of residual stresses) combined with a residual stress field predicted by MISULAB®. This statement gives hope to the interest in combining MISULAB® and NCODE DESIGNLIFE® to predict the influence of a turning operation on the fatigue resistance of a component. This approach is an efficient and flexible way as it becomes possible to predict the influence of various machining conditions (incl. new cost-efficient conditions) on the fatigue behaviour.

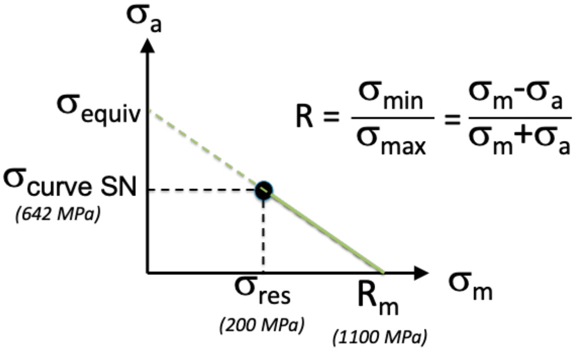

Fig. 7 Diagram of Haigh-Goodman

5. Discussion

The results highlight the value of a fully digital chain, from residual-stress prediction with MISULAB® to fatigue-life assessment with NCODE DESIGNLIFE®. For the 15-5 PH martensitic steel investigated, the average deviation between simulated life and rotating-bending Wöhler tests stays below 10 %, proving that the coupling can partly substitute expensive experimental campaigns.

Although the Goodman mean stress correction method is widely used for its simplicity, it has certain limitations. For example, it does not account for the effects of cyclic plasticity (relaxation) and may underestimate fatigue life in some cases. Alternative methods, such as the Morrow correction or the FKM approach, could be considered for more complex applications and would remove these shortcomings without altering the overall software architecture.

In addition to cutting conditions, post-machining heat treatments can also influence residual stresses and fatigue life. For example, an annealing treatment can reduce tensile residual stresses, thereby improving fatigue life. However, these treatments must be carefully optimized to avoid compromising the mechanical properties of the material.

6. Conclusions

This paper investigated the possibility of considering the residual stress state generated by a turning operation in a fatigue life calculation. It was shown that the MISULAB® software can predict the residual stress state generated by the turning of a martensitic 15-5PH stainless steel. This stress field has a complex spatial distribution that differs between directions and in depth. In the case studied, the surfaces are in tension and the depth affected is of the order of 150 micrometers.

Using an experimental SN curve in rotational bending identified on specimens manufactured by turning, it was possible to identify a fatigue model for predicting the fatigue life of turned specimens. Using the Haigh-Goodman diagram, it was possible to predict a theoretical fatigue model for this material in the absence of residual stresses.

An API has been developed between MISULAB® and NCODE DESIGNLIFE® to take account of these complex fields of residual stresses resulting from turning in the fatigue calculation. As a result, it has been possible to predict the same fatigue life as the experimental results. These results need to be studied in greater depth and applied to other materials. They are, however, encouraging for industry, which could have the possibility of simulating several machining strategies and determining their impact on fatigue life. This connection between MISULAB® and NCODE DESIGNLIFE® paves the way for optimizing the durability of mechanical components, while at the same time optimizing manufacturing productivity. This paper investigates the possibility of taking into account the residual stress state generated by a turning operation in a fatigue life calculation within a comprehensive numerical engineering chain.

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