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Residual life estimation of damaged structures exposed to high pressures and temperatures

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Abstract

This paper deals with the damage growth in High-Pressure Turbine (HPT) cooling holes of the case assembly made of Inconel 718. Several marks (cuts) were made on cooling holes into parent material during the service due to the non-skilled use of Electrical Discharge Machining (EDM) in the workshop. After a certain time, the case assembly returned to the workshop with all EDM marks cracked. Since HPT case assembly is not repairable and the only method for fixing this issue is its replacement with the new or used one (which might be pretty expensive), it was decided to use numerical analysis to estimate Paris coefficients for used Inconel 718, since the number of cycles and crack growth from the initial position were known, based on data obtained from the workshop. Firstly, finite element method (FEM) based numerical analysis was conducted in order to simulate crack propagation to match the one observed in the workshop, and then a multi-objective genetic algorithm – The standard response surface type - full second order polynomials – was used to obtain required Paris coefficients. The objectives of this optimization were the crack length and the corresponding number of cycles of crack growth. Obtained Paris coefficients were then used to estimate the residual life of HPT case assembly.

Keywords: high-pressure turbine; Inconel 718; Electrical Discharge Machining; Paris coefficients

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1. Introduction

It is well known that fatigue damage represents a growing issue, particularly in the aerospace industry (Tavares. M. and de Castro (2017)). Special problem in this area is the additional damage that occurs in the structure which is in service for longer period of time. This kind of damage alters the fatigue life of structure in question. The determination of this life represents a challenging task. In such cases numerical methods become necessary tools, as they represent a suitable alternative to the expensive and time-consuming experimental tests. These methods have been frequently used in recent years for fatigue life estimation which can be seen in Đurđević et al. (2015), Grbović et al. (2019), Sedmak et al. (2018), Aldarwish et al. (2017), Kraedegh et al. (2017), Sghayer et al. (2017), Eldweib et al. (2017).

The objective of this paper is to present advantages of numerical modelling of fatigue crack growth in aircraft component under complex thermo-mechanical loading conditions.

2. Problem description

The damage growth occurred in the High-Pressure Turbine (HPT) cooling holes of the case assembly made of Inconel 718 (Fig. 1.). Performing the EDM slice in the flange made of Inconel 718, the operator in maintenance, repair and overhaul (MRO) company eroded through the flange into the parent material at the opposite sides of the cooling holes. In total, 9 EDM marks (with depths between 0.11 and 2.46 mm) have been made.

Fig. 1. HTP case Assembly.

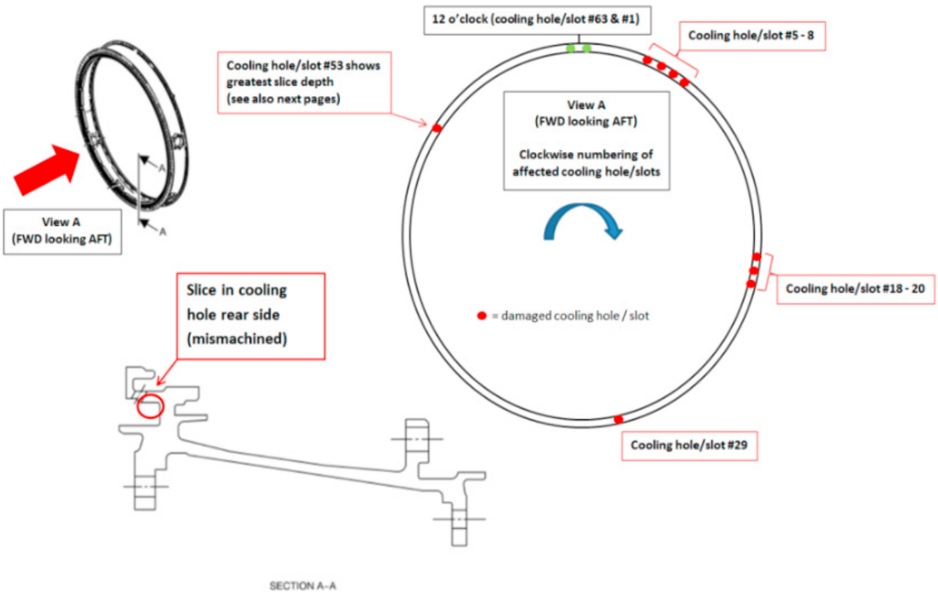

Fig. 2. Position of EDM marks.

After detailed examination and all the necessary steps that had to be taken in such cases, it was decided to re-install HPT case, and to re-examine it at the next scheduled workshop visit. After 2807 cycles (i.e., 8253 engine hours) the case returned to service. All error EDM marks were cracked.

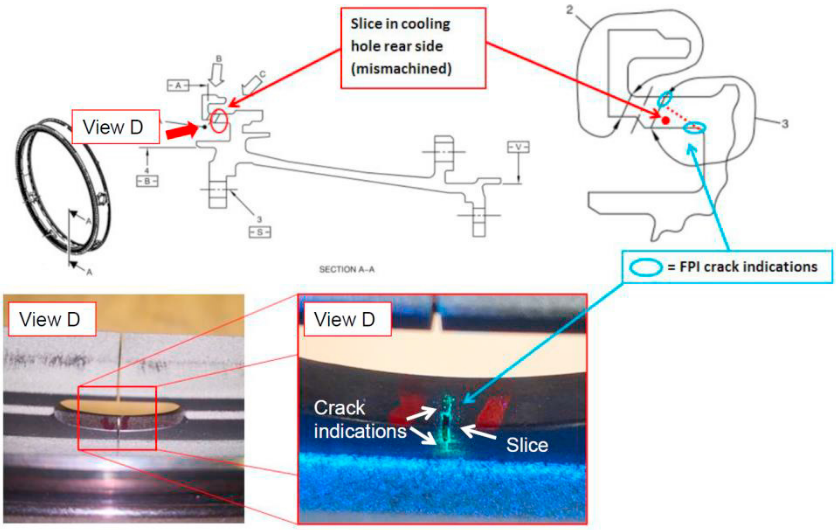

Fig. 3. Crack initiations.

This finding raised the question of the remaining fatigue life of the damaged part. It was necessary to estimate the residual life of the HPT case based on data obtained from the workshop. Numerical methods were applied for this purpose.

3. Numerical analysis

Computer aided design (CAD) model of the analyzed structure was created and used for finite element model generation.

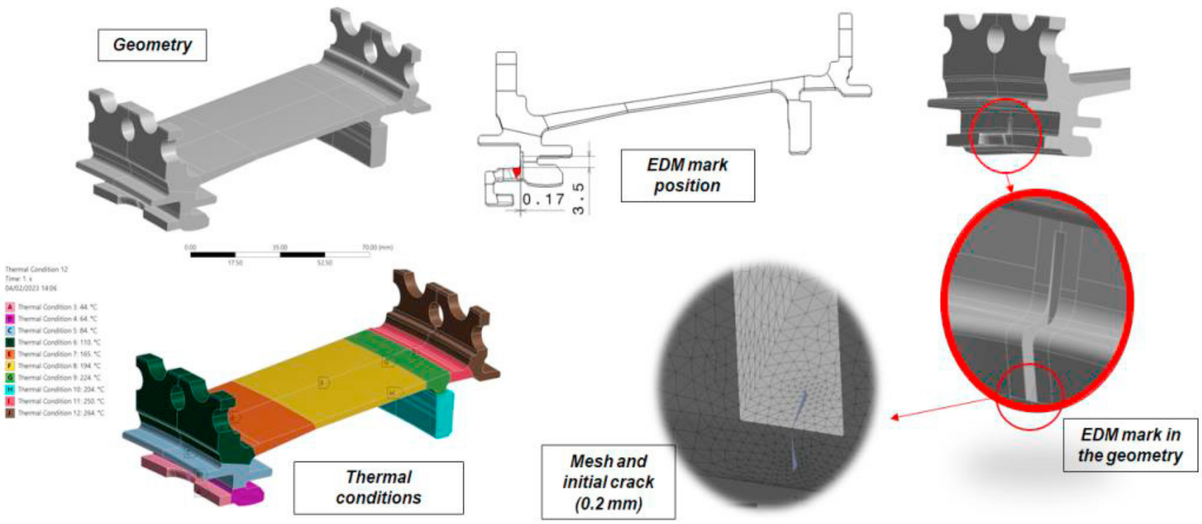

Fig. 4. CAD and FEM model of analyzed structure.

The finite element method, implemented in commercial ANSYS software was applied. Since HPT case is exposed to pressure and heat, special attention was paid to the applied load which involved thermal conditions. The approach involved evaluation of stress intensity factors (SIFs), paths of crack growth predictions and a fatigue life evaluation through an incremental crack extension analysis. The linear-elastic fracture mechanics assumptions were used. Separating Morphing and Adaptive Remeshing Technology (S.M.A.R.T.), which relies on the Unstructured Mesh Method (UMM) implemented in ANSYS has been used for the crack paths predictions (Đukić et al. (2020), Kastratović et al. (2020)). This numerical analysis was conducted in order to simulate crack propagation which had to match the one observed in the workshop (Fig. 5.). The Paris law model has been employed for the evaluation of the fatigue life which corresponds to the observed crack's length.

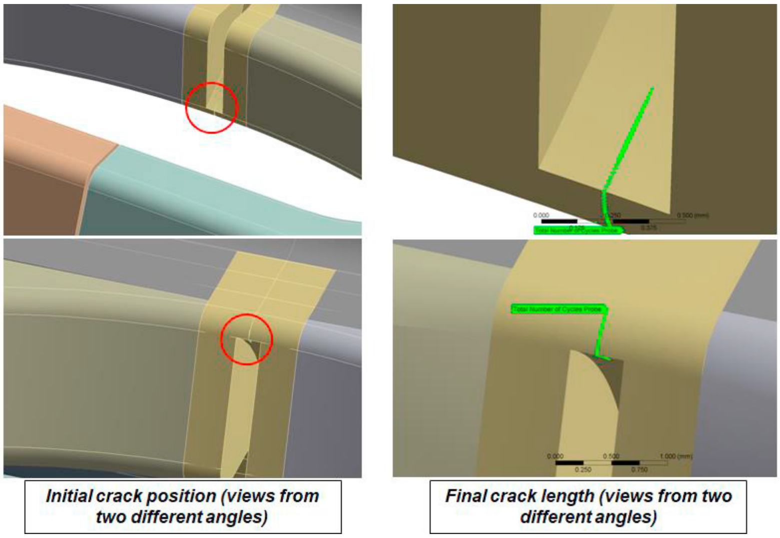

Fig. 5. Crack propagation.

To obtain required Paris coefficients a multi-objective genetic algorithm (MOGA), implemented through response surface optimization (RSO) – another module of ANSYS – was used. MOGA, as a global optimizer is more suitable for global optima searching, especially in the case of the multi-objective optimization, as it can be seen in Deb et al. (2002), Deb and Tiwari (2008), Shukla and Deb (2007). The sorting mechanism of the sample set (decision support process) represents weighted, aggregation-based and goal-based design ranking technique. Within the RSO, design of experiments (DOE) is applied to generate numerical experimental points. These points are used to build meta-model functions in which the output parameters are described in terms of the input parameters. The standard response surface type - full second order polynomials was used for meta-modelling. The objectives of this optimization i.e., output parameters, were the crack length and the corresponding number of cycles of crack growth, while input parameters, i.e., design variables, were Paris coefficients, C and m. For the purpose of establishing the suitable exploring domain, lower and upper boundaries of input parameters were being investigated. Several different domains were investigated until adequate range was established. The range of the design variables is presented in Table 1.

Table 1. Lower and upper boundaries of input parameters.

Design variables	Initial values	Lower and upper boundaries
Constant C	1e-13	5e-14 – 5e-13
Constant m	3.75	3 – 4.5

Based on the conducted computations, for required conditions, Paris coefficients of applied material are obtained as C= $1.5396e^{-13}$, and m= 3.305. These results had to be verified by the FEM analysis. The verification showed that determined Paris coefficients indeed gave number of cycles which corresponds to the observed crack's length (Fig. 6.).

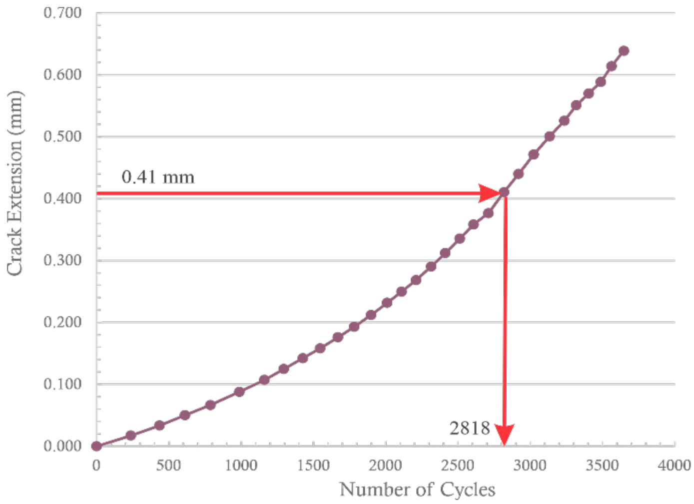

Fig. 6. Crack growth vs number of cycles-verification.

4. Conclusion

In this paper the combination of several numerical methods was applied in order to estimate the residual life of the damaged structure, based on data obtained from the workshop. First, improved FEM (S.M.A.R.T. technology) implemented in ANSYS was successfully used to simulate the crack growth in the Inconel structure exposed to complex thermo-mechanical loading conditions. The crack path observed in the MRO company was faithfully simulated based on calculated SIFs. Then, the multi-objective optimization procedure implemented thru RSO ANSYS module was used in order to determine required Paris coefficients which predicted the crack extension to a predefined length within a required number of cycles of service loading. The residual life of the component obtained in this manner is reliable and can be used for the estimation of the component's life.

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