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Study of Autofrettage Process Effect in Thick-walled Cylinder with Metal Matrix Composite by the method of Finite Element Cyclic Stress Analysis

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ABSTRACT: The goal of this study is to analyze the interplay of mechanical and thermal properties and the applied thermomechanical cyclic load combined with the fatigue crack numerical simulation of a thick cylinder. The applied boundary conditions are similar to the working gun barrel during continuous firing. Four stress conditions in 25-950°C and 100-400 MPa pressure has been investigated. Conditions include first, without autofrettage and cracking; second, with autofrettage and without cracking; third, without autofrettage and with cracking; and fourth with autofrettage and with cracking has been investigated. A comparison of the results obtained from simulated models of the autofrettaged and non-autofrettaged barrels has information about the evolution of strains and stresses in the barrel at different points under thermo-mechanical loading cycles in both cases. The materials in the barrel were ST50 steel and SiC/Ti-24Al-11Nb metal matrix composite in three different diameter ratios. The results showed that autofrettage softened the inner surface of the barrel. This phenomenon was seen as a decrease in the hardness of the inner surface of the barrel. The maximum stress of thermomechanical cyclic loading there was until 9 mm of depth. This depth is the active length of crack propagation.

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1- Introduction

Thick-walled cylinders are one of the most used parts in the industry. These cylinders are widely used in various industries. In order to save on materials and reduce production costs, many researchers and engineers intend to prioritize the optimal use of materials. One of the best methods in the production of thick-walled cylinders is a design based on elastic-plastic methods.

2- Methodology

For autofrettage modeling, the temperature is 25°C, and the internal pressure of 515, 525, and 535 MPa is applied according to the ratio of the inner and outer diameters of the barrel with ST52 steel. This causes hoop stress as large as the values mentioned on the inner surface of the barrel. At the end of this stage, the internal hoop stresses are spread on the surface and to a certain depth in the cylinder, and then the thermomechanical stage is defined to study the barrel under thermomechanical loading.

To further investigate the behavior of a thick cylinder in the thermomechanical cycle with cracking, a numerical simulation model with crack lengths of 3, 4, 5, 6, 7, 8, 10, 14, 12, 16, 18, 20, and 25 mm has been developed. Due to the limitations of the Abaqus software, it is not possible to model it in a single file. In all models, the tip of the crack is spider meshed. In the analysis used at the crack tip, the J-integral is calculated and a contact mode is defined on the internal faces of the crack so that they do not overlap during compressive loading. Also, a rigid interaction mode is defined between steel and composite in composite design.

A multi-physics numerical simulation model was used to analyze the effect of crack length on the fatigue life of autofrettaged and non-autofrettaged thick cylinders during operation. In this simulation, the barrel with two different types of ST52 steel and SiC/Ti-24Al-11Nb metallic matrix composite with diameters 25, 50, and 75% of the total diameter of the barrel as recommended [1] has been studied. The mechanical properties of the mentioned materials are listed in Table 1. Other properties, including thermal expansion coefficients, specific heat coefficients, density, and plastic properties at different temperatures, which amount to more than, are also used

The temperature on the inner surface of the cylinder is defined as heat flux. The heat flux value of 5400 W/m^2 is used for all simulations. An initial temperature of 25°C is defined for the entire model. The element type was CPE4T. The model was checked for mesh dependence and during meshing, the aspect ratio was maintained below 1.3.

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Table 1. Mechanical properties of the materials, used in this analysis

Properties	Unit	ST52	SiC	Ti-24Al-11Nb
Conductivity	$W(mK)^{-1}$	53.3	-	6.7
Young's modulus	GPa	212	399.9	110.3
Yield stress	MPa	452.5	-	371.6
Poisson's ratio	-	0.29	0.25	0.26

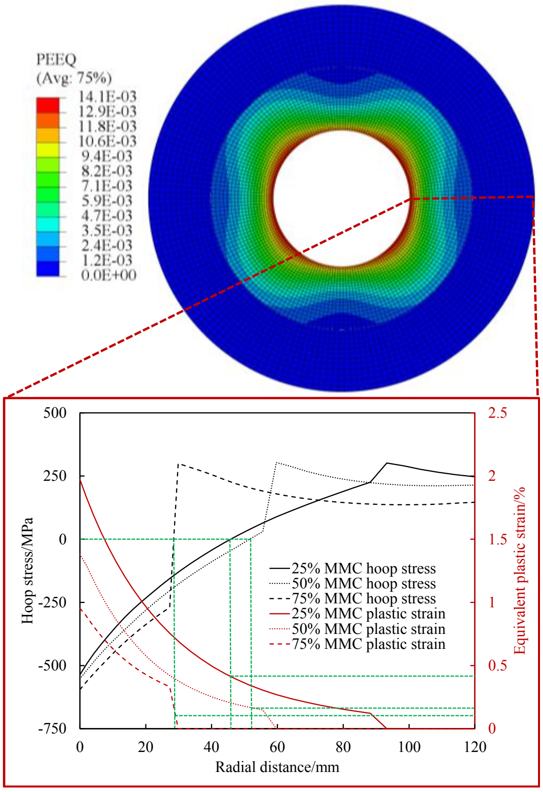

Fig. 1. The hoop stress and the equivalent plastic strain along the radius in the cylinder with ST52 steel and metal-matrix composite materials

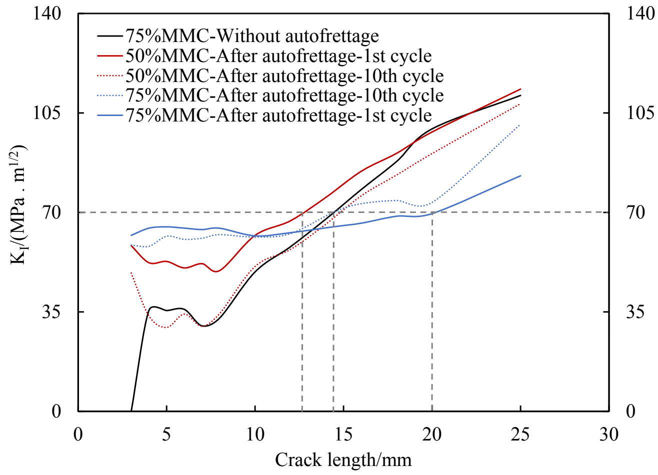

Fig. 2. The comparison of the stress intensity factor versus the length in autofrettaged and non-autofrettaged cylinders with the composite ratio of 75% and 50%

3- Results and Discussion

In general, autofrettage is used to create residual compressive hoop stresses inside thick-walled cylinders to improve their fatigue life during work. many researchers have worked on improving the integrity of thick-walled cylinders made of different materials [2, 3]. In addition, they developed models for the optimal estimation of loading and unloading pressures of autofrettage [4, 5] have created. The more important challenge is still in understanding the useful life of these autofrettaged thick-walled cylinders under complex thermal and mechanical loading cycles.

In this research, a study with numerical simulation of the cracked and uncracked barrel has been done for 20 thermomechanical cycles. The numerical model includes thermal, mechanical, and fatigue crack mechanics. The studied materials are ST52 steel and SiC/Ti-24Al-11Nb metal matrix composite. The applied boundary conditions are similar to the barrel during operation.

Four stress conditions have been investigated in this study at a temperature of 25-950°C and a pressure of 100-400 MPa during the loading cycle. Very high tensile stress is also observed after the first cycle. Through various studies, it has been determined that the first cycle is the most harmful cycle for thermal fatigue loading, such as Oudin et al. [6], who conducted an experiment on engine pistons to determine that the first cycle is the most damaging. Therefore, it is also common to preheat the barrel before operating.

Equivalent plastic strain and hoop stress after autofrettage are plotted in Fig. 1. It can be seen, the barrel is plastically deformed to the depth of the common diameters of the two materials, and after that, there is no plastic pressure in the composite. Also, with the increase of the composite ratio around the steel, the value of the maximum hoop stress is decreasing, but the amount of plastic before zero in the joint diameter is increasing.

In the cracked cylinder without autofrettage, due to the thermo-mechanical cycle and the softening of the material in front of the crack tip, the J-integral value decreases with the thermal cycle. The comparison of the calculated stress intensity factor (K_I) of autofrettaged and non-autofrettaged cylinders with different crack lengths is shown in Fig. 2.

However, it should be noted that for the value of K_I higher than K_{IC} (70 MPa.m$^{1/2}$ [7, 8]) in the cylinder design with 50% of the composite ratio if the crack length is 13 mm in the first cycle and 14 mm in the 10th cycle, as well as 14 mm for the composite design in the cylinder with 75% of the composite ratio for the first cycle without autofrettage and 20 mm for the first cycle with autofrettage, the barrel will probably explode.

4- Conclusions

A multi-physics numerical simulation model was used to analyze the effect of crack length on the fatigue life of autofrettaged and non-autofrettaged barrels during operation. The used material for the barrel was ST52 steel along with SiC/Ti-24Al-11Nb metal-matrix composite in the ratio of diameters .of 25, 50, and 75% to each other was studied

The numerical simulation model was carried out under plane strain conditions by applying thermo-mechanical loading. This study also contributed to the analysis of crack initiation and growth behavior under complex loading conditions .during the service life of the barrel

The following results were obtained from this study:

• Autofrettage practically does not make the inner surface of the cylinder resistant to the severe operating conditions it experiences. It was observed that the range of stress on the surface even increases. However, autofrettage causes residual compressive stress not only on the surface but also on the barrel.

• The barrel is only able to withstand the conditions in the case of a 75% composite ratio without cracks and without autofrettage. in addition to this ratio, the value of 50% for the ratio with autofrettage is also able to withstand the conditions. 25% of the composite ratio is only able to withstand the condition without cracks.

• This residual compression plays an important role in the crack tip and limits crack growth. It was observed that up to a depth of 9 mm for ST52 steel and metal matrix composite, autofrettage has a significant effect on increasing the life of the barrel.

• In the barrel, the crack growth at 75% of the composite ratio is reduced to half of the case without autofrettage in autofrettage. But at a 50% composite ratio in autofrettage, the growth rate is higher than 75% of the composite ratio without autofrettage.

• If cracks appear on the inner surface as a result of erosion, due to thermal softening and a very high amount of tension at the tip of the crack during conditions, the cracks can grow and only the amount compared to the state without autofrettage is reduced.

• After autofrettage, the radial stresses are not affected at the first. However, the plastic strain in the material is accelerated during operation. This affects the softening of the material, which is a negative effect of the autofrettage process.

• The developed model and method can be used to analyze complex phenomena and become useful.

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