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High temperature fatigue testing of gas turbine blades

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Abstract

With the increasing use of renewable energy sources, Gas Turbines (GTs) are currently required to accomplish more flexible operations for supplying the back-up energy. As a result, thermo-mechanical fatigue issues in the GTs components are emphasized. In this paper, the design of a novel rig for assessing the fatigue behavior in the trailing edge of full scale GTs blades is presented. Based on a detailed Finite Element (FE) analysis of the blade response under thermo-mechanical loads, it is demonstrated that the stress and strain cycles arising in this area during a start-up/shut-down transient can be accurately reproduced by clamping the blade in the shank zone and applying a transversal load to the trailing edge. It is also shown that the stress/strain states can be obtained using a Test Article (TA) extracted from the actual blade. In this configuration, the load magnitude and direction, and the distance of the application point from the blade platform are the test control parameters. A FE model simulating the TA test is developed to determine the test parameters. A tooling for clamping and loading the TA is finally proposed along with a rig apparatus consisting of standard equipment used in material testing.

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Keywords: high temperature fatigue, gas turbine blade, test rig, finite element analysis.

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1. Introduction

The use of renewable energy sources is nowadays growing in the perspective of sustainable and environmentally friendly solutions for energy production. Traditional fossil fuel power plants are facing new challenges to become more flexible and efficient back-up power providers. The European Project FLEXTURBINE is aimed at developing new technological solutions to guarantee a significant improvement in the flexibility of existing power plants and favoring the growth of renewable sources in the European power grid [Gonzalez-Salazar and Kirsten, 2016]. In this framework, one of the goals is to improve the components life cycle management of Gas Turbines (GTs) subjected to more frequent start-ups, shut-downs, and load changes, while keeping the life cycle costs at the current levels.

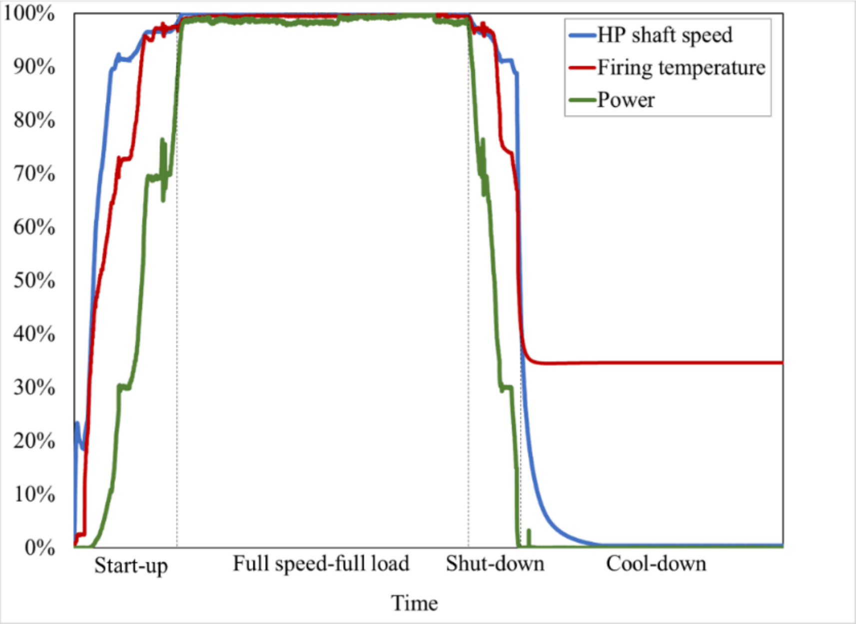


Fig. 1. Typical trends of the mission loading parameters for GTs.

Figure 1 represents the typical trends of the power, firing temperature, and High Pressure (HP) shaft speed in GTs. During a single mission, the GTs components withstand thermo-mechanical loads, which rise fast in the start-up to full speed-full load condition and then drop during the shut-down. Under these conditions, each GT component is subjected to stress and strain cycles pulsing from zero to maximum values given by the design full speed-full load condition. In the perspective of more flexible service conditions, it should be expected that fatigue becomes the most important damage process [Balevic et al. 2004, James et al. (2014), Kim et al. (2015), Wang et al. (2016), Vacchieri (2017)]. A deeper knowledge of the components fatigue behavior is needed to extend the service life of GTs, especially for those parts, which withstand the heaviest loading conditions such as the GTs high pressure first stage blades.

Extensive analyses of GTs blade mechanical response revealed that the disc-blade connection is usually the most critical part [Issler et al. (2003), Pineau et al (2009), Hu et al. (2013)]. However, the presence of the cooling system in cooled blades can determine critical stress and strain cycles in the airfoil too. It is reasonable to expect that these cycles are severe especially in the fillet region between the trailing edge and platform, because of the thin thickness of the trailing edge and the presence of cooling holes. The opportunity to study the behavior of the material in these regions through a rig testing full-scale blades allows to better estimate the service life of the components taking into account the actual geometry and manufacturing process [Bychkov et al. (2008), Hu et al. (2013), Wang et al. (2016)].

The aim of this paper is to design a novel test rig for studying the high temperature fatigue behavior in the above-mentioned fillet region. The identification of the test configuration and the component-like specimen definition are then reported for a typical high pressure first stage cooled blades. Finally, the rig apparatus and the required tooling for carrying out the tests are illustrated.

2. Thermo-mechanical response of the GT cooled blade

The determination of the stress and strain cycles in the region of interest during the start up/shut down transient is necessary for the identification of the test configuration and parameters. As mentioned in the previous section, the mission causes pulsed cycles with the amplitude defined by the Full Speed-Full Load (FSFL) condition. To identify the cycle, the stress/strain states in the blade under the FSFL condition have to be estimated.

To this purpose, a Finite Element (FE) model simulating a typical first stage cooled blade under the above mentioned operating condition was developed. The conceptual scheme along with the basic assumptions are summarized in Fig. 2. The model includes the blade only, while the disc is implemented as a boundary condition by constraining the surface of the fir tree in contact with the disc mortise. The loading conditions referring to the FSFL regime include the centrifugal forces generated by the shaft rotation and the thermo-mechanical loads determined by the gas flow. The centrifugal forces were implemented by applying the angular velocity ω to the all elements in the model. Thermo-mechanical loads were enforced by applying the gas pressure and temperature distributions derived by a dedicated Computational Fluid Dynamic (CFD) model.

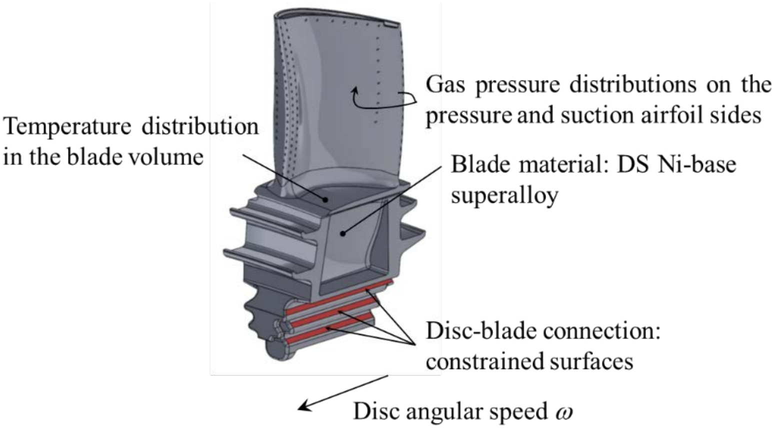


Fig. 2. Conceptual scheme of the FE model used for determining the investigated blade response in the FSFL condition.

The blade is made of a Directionally Solidified (DS) nickel-base superalloy. The blade material was modelled as a homogeneous and anisotropic medium with physical (linear expansion coefficient) and mechanical properties depending on the direction and temperature. A linear elastic stress-strain constitutive law was assumed. All the properties used in the model were determined by dedicated experimental campaigns. The blade solid model was meshed using 3D 10-nodes tetrahedral elements (Fig. 3a) resulting in a mesh containing 4.1 million DOFs. Due to the high level of the geometry complexity, special care has been taken during the meshing, in order to minimize the distortion of the elements especially in the region under investigation. However, although the high level of the mesh refinement, preliminary analyses of the results revealed that the sub-modelling technique is necessary to obtain mesh independent results in the region of interest. To this purpose, a sub-model of the trailing edge zone, where the most severe stress/strain states were observed, was developed. Since the most critical states were found in the volume surrounding the cooling hole nearest to the blade platform, the sub-model for this part was set-up. Fig. 3b shows the mesh used for the final computations. The volume was discretized using 20-node structural brick elements with characteristic size of 0.1 mm. The FE model was implemented and solved using the general software Ansys (ANSYS® Academic Research. Release 17.2).

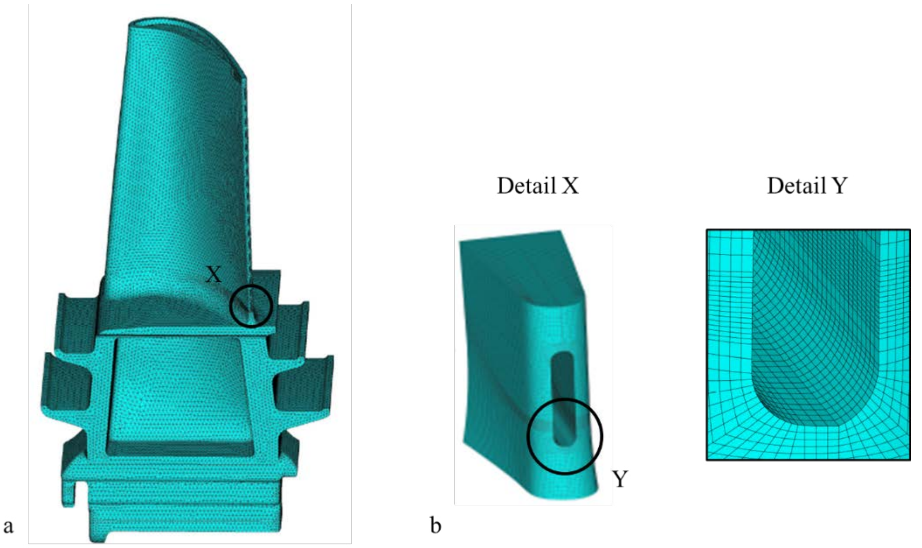


Fig. 3. Meshes used for the final evaluations of the blade response under the FSFL condition: (a) global model mesh, (b) sub-model mesh.

As expected, the examination of the global model results confirmed that the fillet region between the trailing edge and blade platform is one of the most critical areas. Severe stress/strain states were observed especially in the volume surrounding the cooling hole nearest to the blade platform. As shown by the map of the first principal stress in this zone (Fig. 4), peak values are located within a surface narrow band lying on the hole inner surface. Here, the stress states are mainly defined by the first principal component directed along the blade radial direction.

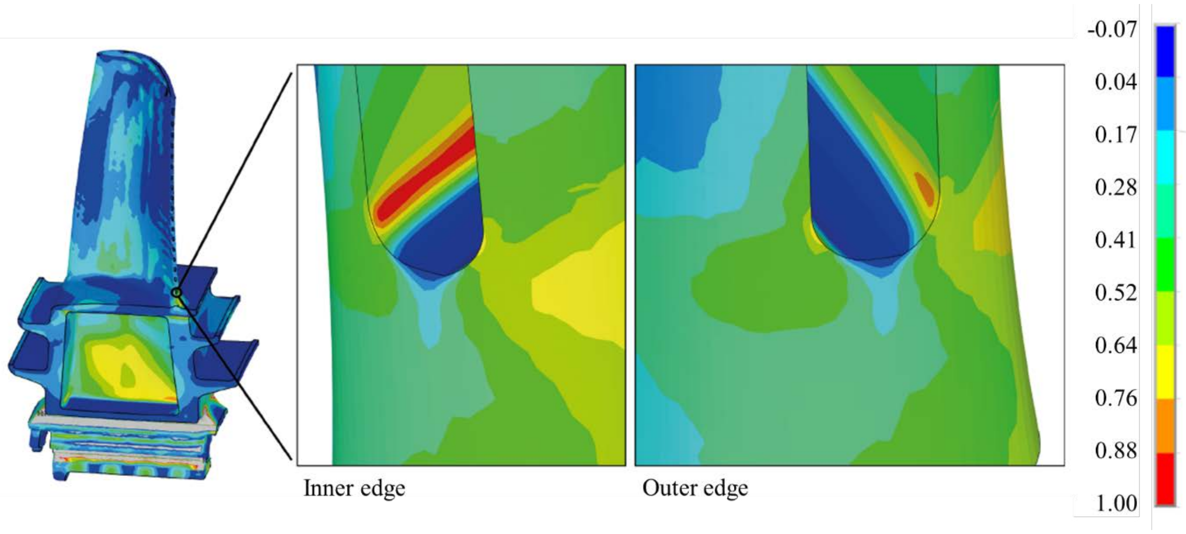


Fig. 4. First principal stress distribution in the studied blade and details of the inner and outer edge of the cooling hole nearest to the platform (values normalized with respect to the peak value).

3. Rig design

3.1. Test configuration identification

As highlighted in the previous section, the material volume in the region of interest is characterized by the first principal stress component directed along the blade radial direction. Similar stress states can be reproduced by constraining the fir tree and applying a radial or transversal load to the blade, as schematically sketched in Fig. 5. Moreover, since the stress state is mainly dominated by the presence of the cooling hole, it can be obtained by testing only on a portion of the blade containing the region of interest, hereafter defined as Test Article (TA). The use of component-like specimens enables the simplification of the clamping and loading solutions and its standardization, thus allowing the test of blades having different geometry and size.

In order to establish the best configuration, the previously presented FE model was modified to study the blade response under traction and bending loading conditions. For the traction configuration, a uniform normal pressure was applied to the blade tip, while for the bending configuration, a point transversal load was applied at the tip of the trailing edge.

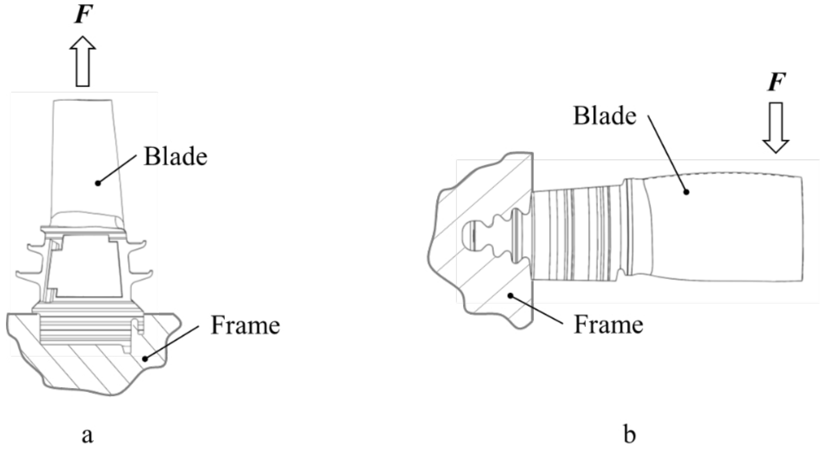


Fig. 5. Schematic views of the possible test configurations: (a) traction; (b) bending.

The analysis of the blade response under these two loading conditions revealed that the traction test configuration is characterized by two main drawbacks. First, due to the presence of the cooling channels, this loading configuration causes the blade failure in different locations of the blade. Then, the required load resulted very high, thus making hard the definition of a reliable solution for the blade clamping. On the contrary, bending test configuration was found to satisfy the test requirements even by applying much lower loads. For these reasons, the bending configuration was finally preferred to the traction one.

3.2. TA definition

To fully define the test configuration and the TA, the force *F* and its orientation have to be defined. Fig. 6 illustrates the strategy that can be adopted to get a possible TA. For an effective clamping, the fir tree is removed and the sides of the shank flattened by cutting the angel wings. A portion of the airfoil can be also removed to further reduce the TA radial dimension and the *F* value. Finally, the trailing edge should be machined to enable the load application in a defined point.

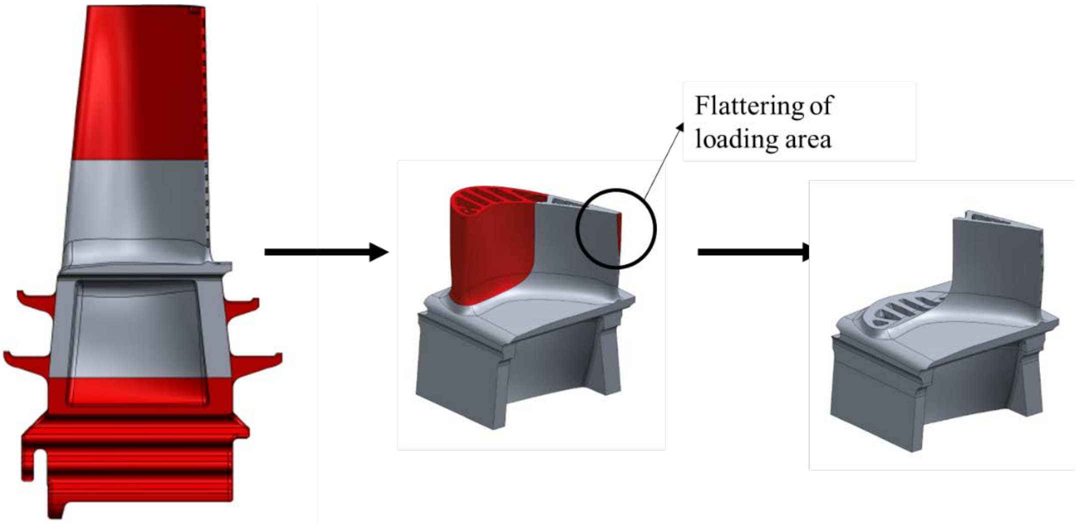
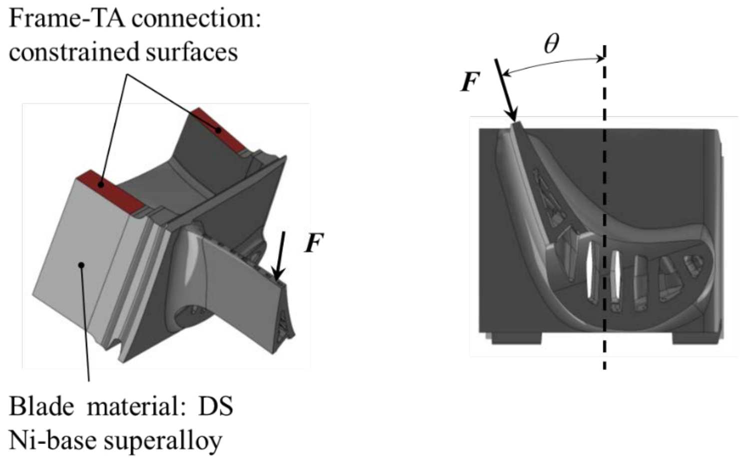


Fig. 6. Schematic representation of the blade machining for obtaining the final TA geometry.



a

b

Fig. 7. Schematic view of the bending test configuration: (a) conceptual scheme of the FE model used for the evaluation of the stress/strain field; (b) definition of the test parameters.

The test parameters were determined iteratively by analyzing the TA response, through an FE model simulating the test, with different TA geometries, force F and angle θ and selecting the conditions that provided the best agreement between the responses of the TA and the actual blade. Fig. 7a depicts the FE model conceptual scheme along with the definition of the boundary conditions for the final TA.

The results obtained with the final test configuration are shown in Fig. 8, where the plot of the first principal stress distribution in the TA is represented along with the details of the inner and outer edge of the cooling hole nearest the platform. The comparison between the results reported in Figs. 4 and 8 demonstrates that the stress field in the cooling hole can be accurately reproduced by loading the TA with a force F of approximately 5 kN applied with an angle θ of 20°. For the simulated testing conditions, the maximum relative difference between the stress components in the TA and the blade under the design loading condition resulted less than 5%.

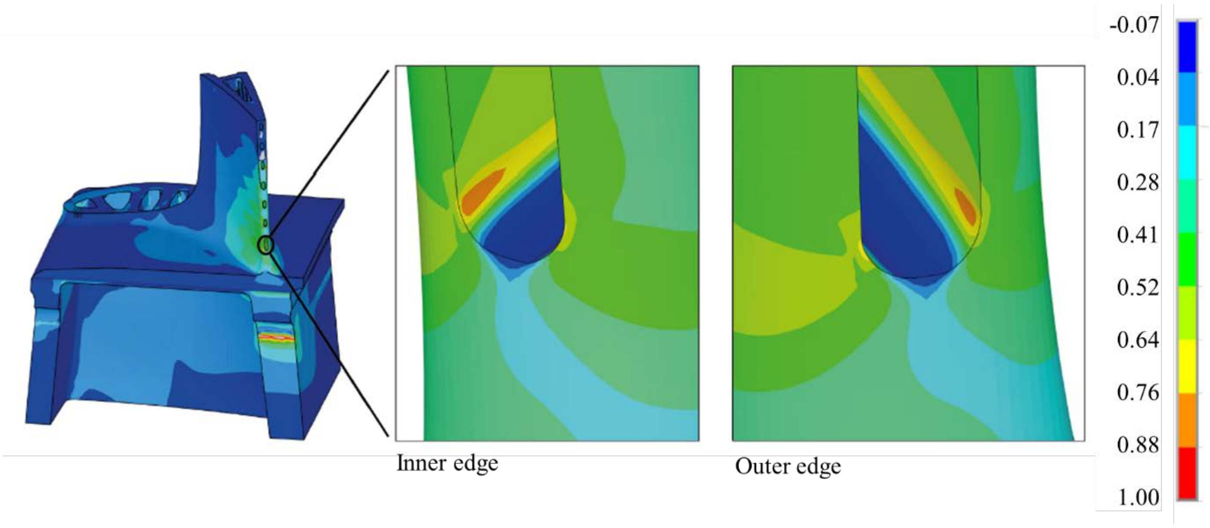


Fig. 8. First principal stress distribution in the TA and details of the inner and outer edge of the cooling hole nearest the platform (values normalized with respect to the peak value).

3.3. Rig apparatus

The proposed test rig is displayed in Fig. 9a with a detail of the gripping devices used for positioning and loading the component-like specimen (Fig. 9b). The rig consists of a standard uniaxial servo-hydraulic testing machine with a load capacity of 50 kN (MTS Systems Corporation, Eden Prairie, MN USA) and a temperature chamber able to reach temperatures up to 900°C (Thermotron 7201, RUMUL Russenberger Prüfmaschinen AG, Neuhausen am Rheinfall, CH). The control unit and data acquisition system of the servo-hydraulic machine (RT3, Trio Sistemi e Misure S.r.l., Dalmine (Bg), Italy) allow the test parameters definition and the control of the test. To prevent any damage of the load cell and hydraulic grips caused by the progressive heating, a closed loop water cooling system is inserted between the furnace and the hydraulic grips.

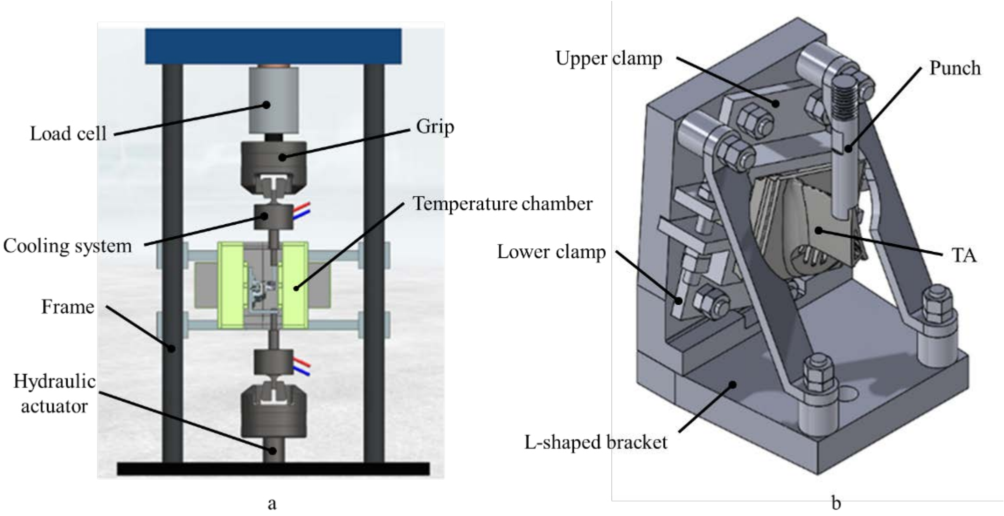


Fig. 9: The test rig concept: (a) general schematic view; (b) gripping fixture.

The load is applied to the TA, placed inside the temperature chamber, by the hydraulic actuator and a punch, which are connected to the hydraulic grips of the testing machine. The load is transferred to the TA by an L-shaped bracket. The TA is gripped using two bolted clamps having the surfaces in contact with the base of the TA shaped in order to maximize the contact area. The gripping is ensured by tilting two bolts joining the upper and the lower clamps. The angular alignment of the TA with respect to the loading direction of the testing machine is obtained by orienting the lower clamp through a prismatic rib and a linear guide machined in the vertical wall of the L-shaped bracket. All the tools used for positioning and loading the TA have been designed against creep and fatigue damage. To prevent unknown thermal stresses in the TA, the tooling has been made of using high temperature nickel-based super-allows having the same thermal expansion coefficient of the TA.

4. Conclusions

A methodology and a novel test rig for studying the high temperature fatigue behaviour of GT blades were developed. The test was designed to reproduce the stress and strain cycle occurring in the fillet region between the trailing edge and platform of GTs cooled blades. The test can be performed using the equipment typically adopted in high temperature material testing and easily extended to different GT blades by adapting the test configuration and the rig tooling. Moreover, the possibility of testing a full-scale blade or a component-like specimen allows to better understand the material behaviour in particular regions and study the actual geometry and manufacturing process of the real components. This leads to a better estimation of the service life, thus reducing the conservatism typical of blade life models.

Acknowledgements

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