Summary description of project context and objectives

Reduction of the fuel consumption and emission of NOX and CO_2 by jet engines is a priority of the EU ACARE SRA 2020 objectives. The development of an environmentally friendly aircraft engine (like open rotor SAGE1) considers using lightweight and efficient turbine components. It will have great impact on reduction of pollution and fuel consumption. Within the objectives of open rotor development in SAGE1, activities are underway to develop new technologies for rotating structures.

The rotating structure transmits the torque generated by the engine to the propellers and is subjected to the high temperature exhaust gas from the core engine. It is likely that the rotating frames will be made as a weld assembly consisting of some cast parts in a newly developed nickel based precipitation hardening superalloy. However, it is a great challenge to cast this alloy in the investment casting process because it was primarily developed in wrought form. In addition, its composition and properties are not optimized for casting processes, post cast operations and heat treatment. Currently, cast versions of this low content gamma-prime strengthened Ni-based superalloy are widely investigated, however failure analysis and damage mechanisms are not fully explored.

Thus the aim of this project is to perform complex failure analysis and damage mechanisms investigations of a newly developed, gamma-prime strengthened Ni - based superalloy, which is an enabler material for manufacture turbine engines components exposed at high temperature. In order to conduct a comprehensive failure analysis and investigation of damage mechanisms the following objectives have been defined:

1. Optimizing the casting process parameters and post casting heat treatment of a newly developed, gamma-prime strengthened Ni - based superalloy for a range of microstructures (grain sizes).
2. Experimental studies of mechanical behaviour of a newly developed, gamma-prime strengthened Ni - based superalloy with different grain size under different loading and temperature regimes during monotonous and fatigue tests.
3. Determination and characterisation of damage mechanisms/failure modes by advanced microstructural characterisation techniques.

The project was implemented over 29-month duration and was structured in 4 technical work packages and one addressing management and coordination activities, linked with the concept of project (fundamental research and experimental trials). The consortium consisted of technical university (Warsaw University of Technology, Poland) and two certified, modern research centres equipped with unique devices (Institute of Aviation, Poland and Swerea KIMAB, Sweden).

Description of work performed and main results

Important properties of the alloy in question were determined with the use of static tension test. Results of this test, performed in the anticipated range of temperatures (RT – 900oC), were used to determine elastic constants (Young's modulus and Poisson's ratio) and yield limit. Also additional information about ductility and ultimate tensile strength of the alloy were determined on the basis of the static test results. Range of service temperatures allowed from the point of view of static strength was determined.

Investigations of the alloy damage due to creep and fatigue were also performed in the above mentioned range of anticipated service temperatures. Analysis of the test results allowed determination of useful stress and temperature range for the engine components made of the alloy in question from the point of view of creep and fatigue damage to be avoided.

In the case of fatigue testing, changes of material characteristics in the form of hysteresis loop were observed during test. Analysis of the hysteresis loop evolution enabled definition of measurable damage parameter. Changes of that parameter have been correlated with results of macro and microstructural analysis to identify fatigue damage mechanisms for the alloy.

Moreover, the fracture mechanics properties of the new alloy were evaluated. To this end crack threshold (Kth), crack propagation (da/dN), fracture toughness (Kc) and crack growth under constant load and/or constant load with periodic unloading (Dwell) tests were performed. 39 out of 40 planned tests were successful; however, it took as much as 57 specimens to achieve this result. The alloy material was found to be prone to initiate fatigue cracks also without noticeable stress concentrations. The coarse and pronounced unequal grain size was the most probable cause.

Detailed microstructural investigations of the alloy after each type of mechanical tests has been performed. Light microscopy as well as scanning and transmission electron microscopy were used to characterise the fracture surfaces and the metallographic sections of the mechanically tested samples. X-ray diffraction and energy dispersive spectroscopy were used to analyse phase and chemical compositions of the specimens. Inter-dendritic areas and grain boundaries have been identified as weak points in the microstructure that facilitate the initiation and propagation of the cracks. The fracture surfaces of all investigated samples displayed an inter-dendritic character and depending of the test type also inter-crystalline and fatigue type of fractures were also observed. The fatigue fractures developing in fatigue sample tested in low and moderate temperatures predominantly followed the specific crystallographic plains whereas those tested at high temperatures propagated predominantly in plains perpendicular to the main loading axes. TEM investigations have shown that deformation mechanisms are controlled by stress-temperature relation. The stress level influences the type of defects nucleated, whereas the temperature determines their mobility. Three distinctive mechanisms of deformation have be identified: (1) Mild – when sample is loaded well below the yield stress measured in a tensile test at given temperature, where partial dislocations are nucleated and contribute predominantly to the sample deformation, (2) Severe – when samples are loaded above the yield strength at temperature up to 650oC where perfect dislocation nucleate and glide in slip bands and (3) Modest – when samples are loaded with stresses close to or above yield strength at temperatures above 650oC where highly mobile perfect dislocations glide that can easily change the slip planes.

Expected final results and potential impacts

The project was focused on complex mechanical characterisation, failure analysis and damage mechanisms investigations of a newly developed, gamma-prime strengthened Ni - based superalloy, which is an enabler material for manufacturing turbine engines components exposed at high temperature. The work performed in the project has provided the European aero-engine manufacturing industry, represented by the Topic Manager organisation, with new knowledge on the properties and deformation mechanisms of the investigated alloy. This should enable the industry to improve its capability to produce more environmentally friendly turbine engines through reduction of the engine components weight and increased service temperature. Lightweight and more efficient turbine components would result in reduction of fuel consumption and emission of nitrous oxide by jet engines, thus reduce the carbon footprint of the whole aircraft industry and the air transportation. This, in turn will have significant business impact increasing the companies' competitiveness by cost reduction of manufacturing and reduced fuel consumption.