

A TWO-STAGE MACRO BASED APPROACH FOR DEVELOPING AIRCRAFT ENGINE COMPONENTS CONCESSIONS BASED ON SURFACE MORPHING TECHNOLOGIES

**ROBERT RUSU¹, TUDOR-GEORGE ALEXANDRU²,
MONICA MANOLE³**

Abstract: Computer Aided Engineering tools are widespread in the aerospace industry, being used in all the life cycle stages of an aircraft in order to numerically capture the behavior of parts and sub-assemblies subject to ground and flight loads. In the case of turbofan engines, apart from the design stage, simulation tools are found in a close relationship with physical geometry measurement test procedures, being used to support manufacturing changes from the baseline virtual prototypes. While such approaches are found at the maturity stage, being used in various configurations by teams geographically delimited around the world, the high degree of manual work involved together with the high level of repetitive task required lead to high amounts of time being spent on such projects with a low degree of knowledge based engineering being captured and re-used. The present paper addresses such issues by extending conventional simulation approaches with surface morphing capabilities that are embedded within computer aided engineering pre-processing software, as tools that can fill the gap between physical geometry measurements data and numerical simulation models. The given concepts are proved by means of a conceptual case study regarding manufacturing non-conformities occurring for a variable stator vane turbofan engine component.

Key words: Jet engines, CAE, Non-Destructive testing, Morphing

1. INTRODUCTION

The ongoing trends in the aerospace industry call for new airliners that can operate with lower noise levels and higher fuel efficiency across extended flight ranges (Graham et al., 2014). Apart from the structural aspects of a jet airliner, the engines

¹ *Design Eng, Assystem Technologies, Bucharest*

² *Ph.D. Student, University Politehnica of Bucharest, tal Alexandru@assystem.com*

³ *Stress Eng., Assystem Technologies, Bucharest*

represent a main concern in this sense, R&D efforts being focused on components that are lighter and stiffer. A wide range of alternative materials are currently in use in the design of stator and rotor components. Examples include (but are not limited to) metal matrix composites, hybrid-metallic materials and titanium alloys, yielding enhanced aerodynamic performances and high structural durability (Srinvas et al., 2018). To support integration of such materials in the design of aircraft engine components, virtual prototyping technologies benefit from the use of computer aided software (Ryazonov, 2016). Surface modeling capabilities embedded within Computer Aided Design (CAD) software assisted design engineers with the necessary tools for achieving innovative shapes for blade structures while the applicability of such design scenarios can be validated thanks to the wide scale use of Computer Aided Engineering software (CAE), based on numerical modeling and simulation methods (Boldă and Pupăză, 2018). The resulting design stage prototypes are subject to several manufacturing processes in order to achieve a compromise between the baseline and the physical structure, such that the efficiency, natural frequencies, strength and toughness requirements are met with respect to economical and manufacturability criteria (Amoo, 2012). From this point of view, conventional and non-conventional manufacturing processes are deployed (i.e. investment casting of a turbine blade, electrochemical machining of blade shrouds and electro discharge machining of groove face surfaces in axial compressor blades). The wide scale implementation of industrial robots together with the ongoing improvement of fault detection and diagnosis expert systems has significantly lowered manufacturing issues (Ivan et. al., 2015; Alexandru, 2001) Even so, the ever increasing complexity of aircraft engines, results in components that are prone to non-conformities (NC). For example, shrinkage of thin walled structures during casting can result in non-uniform wall thickness that can lead to stress redistributions (Dong et. al, 2017) while generating features by electro discharge machining can result in rim zones in the case materials with characteristics altered by mechanical or thermal effects are used.

As a consequence, such non-conformities are susceptible crack initiation and propagation sites (Pramanik et. al., 2017). From an economical point of view, considering all out of tolerance components as scrapable parts, can result in low profit margins while from a technological point of view, performing rework (i.e. light machining and welding) does not guarantee on-time delivery of the final product. While some non-conformities cannot be acceptable without rework as they pose a threat to the structural integrity of the engines (i.e. internal cracks found in the proximity of stress concentration points), other non-conformities have no significant side effect as the impacted component can withstand damage throughout the life cycle of the engine (i.e. localized loss of thickness in low stress locations). Considering the high costs related to the manufacturing of aircraft engine components and the aerospace design philosophies, it is imperative to develop a concession approach, in order to prove that a component that is out of tolerance can be considered acceptable with or without further work performed. Physical geometry measurements supported by automated 3D scanning apparatus are well developed being used in wide scale for

identifying geometrical tolerance deviations (Burghardt et al., 2017). Non-destructive testing (NDT) approaches are common for the inspection of internal (x-ray scan) and external manufacturing NC (penetrating liquids) (Bernoud and Mourad, 2011). Results from both inspection types are used for performing manufacturing flaws concessions based on analytical and numerical calculations. The first part of the work discusses about the concessions process workflow, describing a generalized approach adopted in the aerospace industry. The second part of the work presents the significance of CAE simulations in the concession processes, together with the most common methods used for developing concessions calculations. In the third part of the work, limitations of the existing methodologies are discussed, highlighting the need to tackle such issues by developing new approaches. The original contribution is illustrated in the last part of the work, consisting of a macro-based tool that performs a two-stage process for test reports data conversion and update of the baseline models. Automation of FEM editing is achieved by expanding the simulation models with surface morphing based on parametric surface definition capabilities and by combining FEM transformation commands found in most commercial pre-processing software. To prove the given concepts, a conceptual case study regarding the update of a baseline Variable Stator Vane (VSV) model is illustrated by the end of the work. LMS Samtech SAMCEF Solver suite is used due to its embedded geometric, FEM modeling, solving and post-processing capabilities.

2. CONCESSIONS WORKFLOW

The concession process is characterized by the use of inspection data in other to prove by analytical, numerical or design means that an out of tolerance component can withstand damage throughout the life cycle of the assembly it is part of. The method requires an identification of the applicable criteria and their relationship with the NC. For example, loss of thickness of a stator blade causes the mass of the component to change, developing a different dynamic behavior than that of the baseline. To verify the criteria, the dynamic calculations are updated to consider the thickness loss and the analysis is re-run in order to process the changes of the natural frequency and vibration mode shapes.

Major jet engines manufacturers successfully implemented and use concession approaches for components having a certain non-conformity threshold value. While the choice of tools, methods and guidelines is specific to each company, a general approach workflow is depicted in Fig 1. Test reports based on geometrical measurements or NDT are studied to identify if the manufactured component exceeds the tolerance values prescribed in the shop drawing. A certain threshold value is defined; such that aerodynamic criteria remain unchanged (pressure and temperature gradients are not impacted by the NC).

If the manufactured parts exceed this value, either a different concession approach is used or the part is sent to scrap. The concession process represents a three-step approach:

- *Identification of applicable criteria:* based on the out of tolerance values, their location on the part and the type of NC, certain functional criteria are impacted. For example, a surface crack located on the trailing edge of an outlet guided vane significantly lowers the fatigue life of the impacted part;
- *Baseline concessions:* For each impacted criteria, an analysis is performed to determine if the NC can be acceptable as is (no rework is required), acceptable with further work performed or not acceptable (for parts that have NC or reworked NC that do not have the ability to maintain their structural reliability throughout the life cycle of the jet engine);
- *Concession report:* an overview of the calculations performed is presented in the concession report. This document serves as a basis for mounting the part as is or for performing further work.

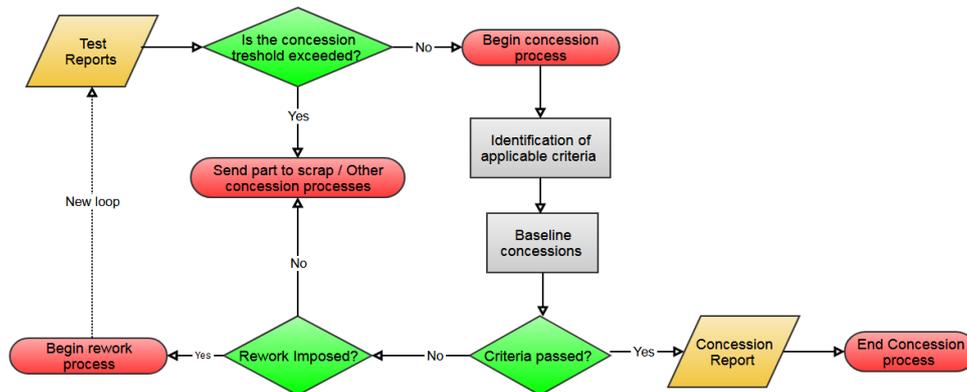


Fig. 1. A typical concession workflow structure applicable to aircraft engine components

2. SIMULATION MODELS

CAE simulation models are widely in use in the complete life-cycle of a product in order to numerically capture the behavior of parts or assemblies subject to ground and flight load cases. To perform most common analysis types (i.e. static stress, modal, frequency response, eigenvalue buckling), a CAD geometric model is subdivided in elements (meshed structure). Each element consists of set of nodes that are linked together to close the computational model, where each node typically represents an integration point. Both simulation metadata and results stand at the core of the concession processes, being used as baseline references for developing justification calculations. Several concession approaches are available:

- *Analytical calculations:* changes from the baseline section result in the increase of the mechanical stresses if the section loss occurs or decrease of the stresses and/or load redistribution if the out of tolerance value is positive. In this case, *results* are extracted from the baseline simulation models and are multiplied by specific

factors. Such factors are based on in-house knowledge (i.e. experimental assessment of mechanical stresses on out of tolerance parts) or on simplifying assumptions (i.e. stress increase factor are derived from the critical section area ratio) – see Fig 2. - a.

- *CAD/CAE based studies:* a reverse process can be performed to geometrically represent the area where the NC is localized. Various densities of mesh can be applied to refine the calculation model around the NC. Loading is applied under the form of displacements extracted from the baseline simulations that are applied to the boundaries of the model – see Fig 2 - b.

- *CAE simulations update:* each element consists of a set of nodes localized in the global model space by three coordinates (CX; CY and CZ). The free faces of an element (for 2D and 3D element types) define the boundaries of the outer skin for a solid body. To update the simulation models without performing a re-mesh of the structure, nodal coordinates should be updated to take in to account the NC. An example is illustrated in Fig 2 –c. The free faces of a 3 node 3D tetrahedron element are displaced such that the baseline mesh is translated to a modified mesh that captures a shape deviation.

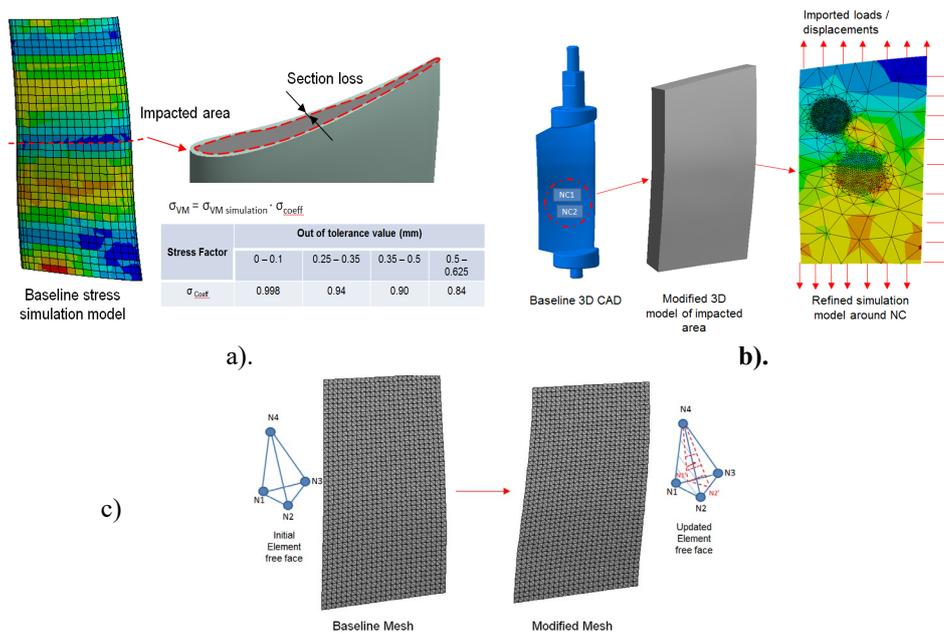


Fig. 2. The constructive solution for the support of the signal light APP AL 008 02 WH.

4. LIMITING ASPECTS OF CONCESSION APPROACHES

All concession approaches can be considered valid for supporting both manufacturing and R&D activities in the field of aircraft engines. Even so, specific issues arise that require a closer observation:

- *High level of repetitive tasks* – All types of concession processes involve a high degree of manual work to be performed. Most of the times, the selection of the impacted area, extraction of results from the baseline and / or generation of the mesh involve a high degree of repetitive tasks to be performed. This results in a high probability of errors to occur, requiring extra check to be performed;
- *Low traceability* – The choice of extractions, selection of the impacted area together with the mesh methods applied are a result of the engineer’s judgment. Being hard to define a standard approach, the same NC can be interpreted differently by different engineering teams, leading to different results and consequently, low traceability;
- *Low level of knowledge based engineering* – concession processes represent a rich source of knowledge modeling and sourcing. Even so, not much attention is paid to the development of knowledge based engineering approaches oriented for concession processes. As a consequence, small amounts of knowledge are re-used in such projects.

5. PROPOSED APPROACH

The proposed approach consists of a macro written in Microsoft Excel VBA application that performs a two stage process – see Fig 3.

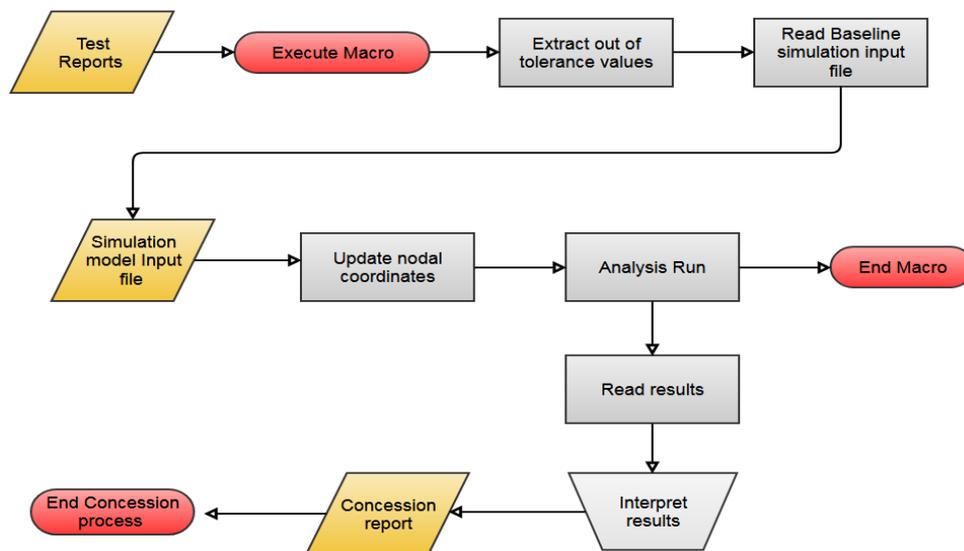


Fig. 3. Two-stage macro based approach

At first, test reports are read in .CSV file format. Considering that the test reports have a standard structure, data is read from specific lines. Each out of tolerance

point is used to update a baseline script written for SAMCEF Bacon module that has the aim of generating a parameterized surface that recreates the physical shape of the exterior solid faces. In the next step, a baseline CAE simulation model input file is read and stored in the memory. A graphical user interface was developed for simple control and preview of working files – see Fig 4.

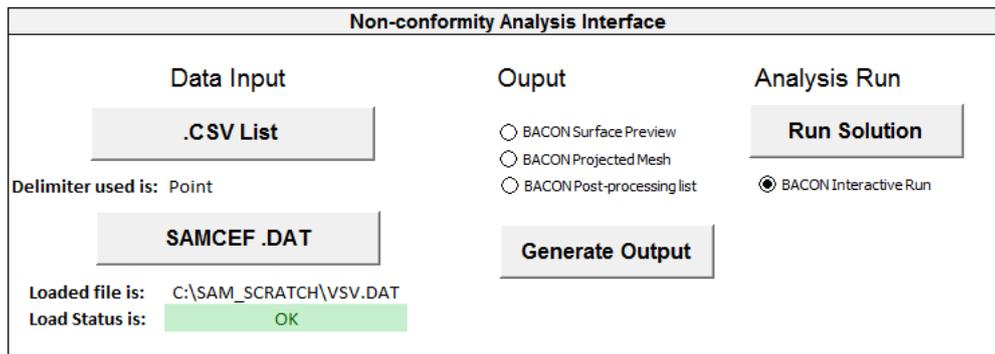


Fig. 4. Graphical user interface

In the next step, surface morphing is performed in order to map the exterior faces of the baseline mesh over the defined surface – see Fig 5. Note that exaggerated out of tolerance values were used for visualization purposes.

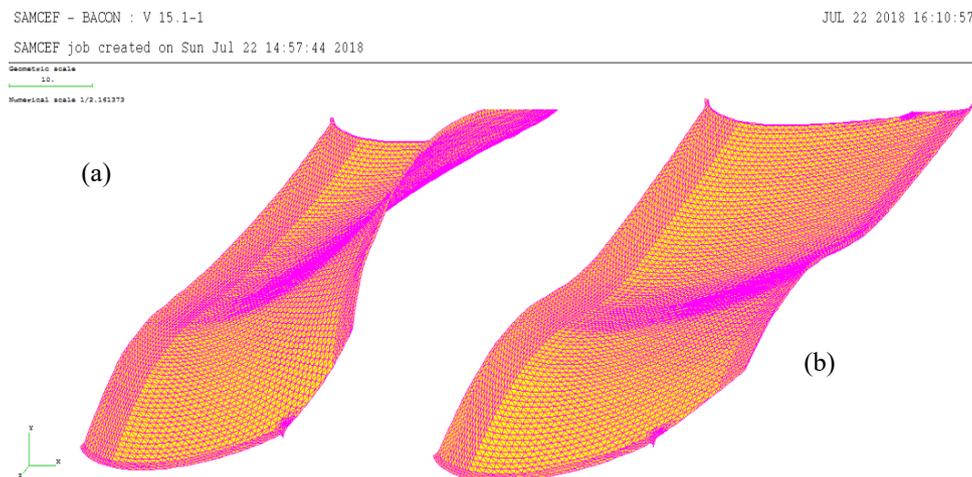


Fig. 5. Preview of Morphing operations performed for a VSV blade
(a) Mesh after performing morphing operations; **(b)** Baseline mesh

The modified nodal coordinates recreate the physical shape of the out of tolerance components allowing for high-accuracy studies to be performed. Furthermore, resulting script files can be stored in databases to be re-used for similar cases. In the last step, a batch process takes place for running the analysis considering the new nodal coordinates.

6. CONCEPTUAL CASE STUDY

A VSV component was subject to casting NC, resulting in a series of shape deviations occurring on the center section of the blade. Geometry inspection was carried out and results were saved to a standard .CSV extension file. The baseline mesh is presented in Fig 6. The workflow discussed in the previous chapter is applied. In this case, a static stress analysis is performed using SAMCEF ASEF module. High fidelity results are achieved by the end of the loop – see Fig 7. Compared to the baseline, the Von-Misses stress gradients and peak values have migrated, resulting in a new stress state that takes place due to the NC.

```
SAMCEF - BACON : V 15.1-1                                     JUL 22 2018 21:04:38
SAMCEF job created on Sun Jul 22 00:04:31 2018
-----
Geometric scale
  10.
Numerical scale 1/2.312708
```

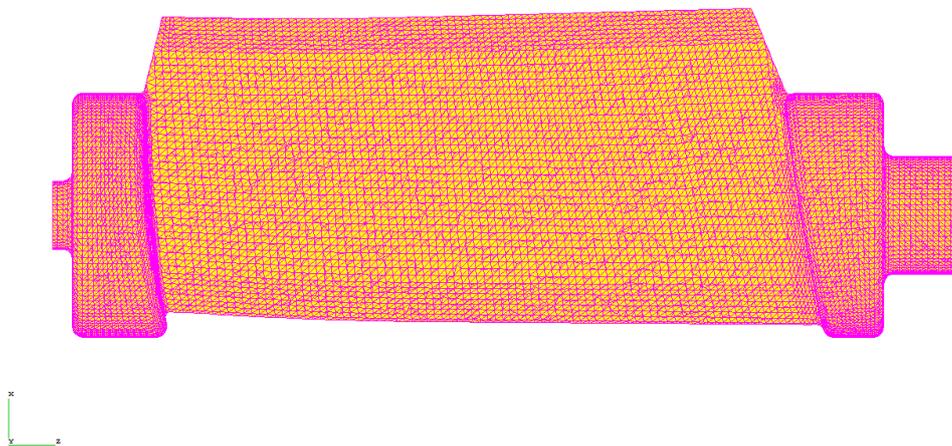


Fig. 6. Preview of the baseline 3D mesh

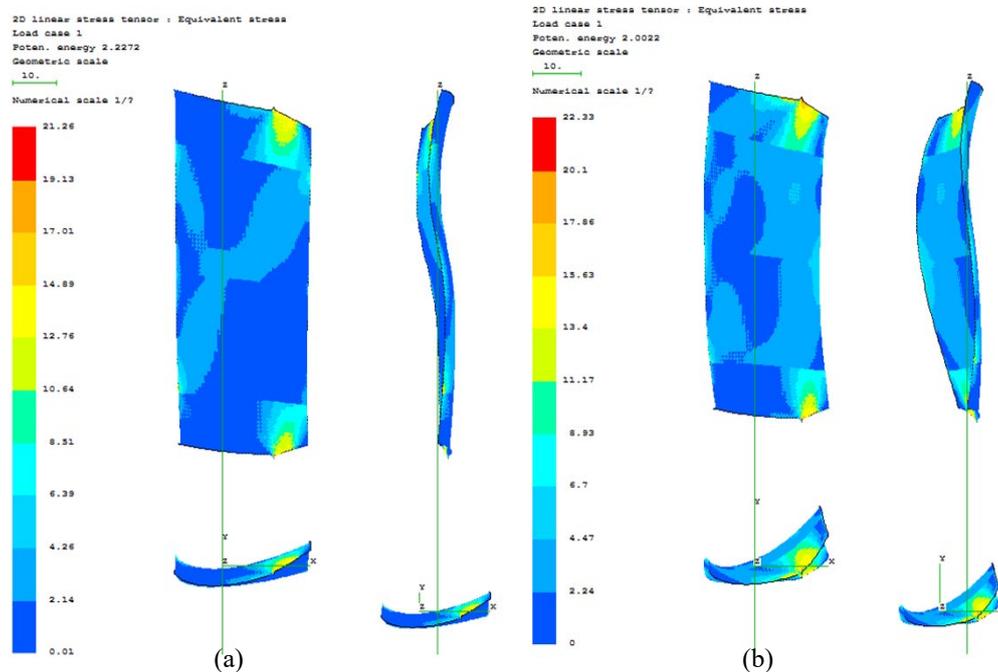


Fig. 7. Unaveraged Von-Mises stress criteria
(a) Baseline simulation; **(b)** Updated simulation model

The baseline mesh and results of the analysis are further used as input data for 3rd party tools used for verifying specific functional criteria.

7. CONCLUSIONS

The present paper presents the workflow and approaches available for aircraft engine components concession processes. The identified issues are tackled by deploying a two stage macro based approach that automates the CAE simulation update process by reading data form test reports and generating a geometric surface that captures the real shape of the non-conformal product. Morphing technologies are used to map the baseline mesh over the resulting surface. The approach lowers the amount of repetitive tasks, while enhancing traceability and knowledge based engineering capabilities.

REFERENCES

- [1]. **Alexandru, A.**, A real time knowledge-based approach for fault diagnosis and its applications. *International Journal of COMADEM*, Vol. 3, Iss. 2, pp. 32-38 (2001).
- [2]. **Amoo, L. M.**, On the design and structural analysis of jet engine fan blade structures. *Progress in Aerospace Sciences*, Vol. 60, pp. 1-11 (2012).

- [3]. **Bennoud, S., Mourad, Z.**, The non destructive testing methods applied to detect cracks in the hot section of a turbojet. *In Applied Mechanics and Materials*, Vol. 61, pp. 79-83 (2011).
- [4]. **Bolda, M., Pupăză, C.**, Dynamic simulation of industrial robots behaviour using integrated software procedures. *Proceedings in Manufacturing Systems*, Vol. 13, Iss. 1, pp. 39-46 (2018).
- [5]. **Burghardt, A., Kurc, K., Szybicki, D., Muszyńska, M., Szczęch, T.**, Robot-operated inspection of aircraft engine turbine rotor guide vane segment geometry. *Technical Gazette*, Vol. 24, Iss. 2, pp. 345-348 (2017).
- [6]. **Dong, Y. W., Li, X. L., Zhao, Q., Yang, J., Dao, M.**, Modeling of shrinkage during investment casting of thin-walled hollow turbine blades. *Journal of Materials Processing Technology*, Vol. 244, pp. 190-203 (2017).
- [7]. **Graham, W. R., Hall, C. A., Morales, M. V.**, The potential of future aircraft technology for noise and pollutant emissions reduction. *Transport Policy*, Vol. 34, pp. 36-51 (2014).
- [8]. **Ivan, A. M., Nicolescu, A. F., Avram, G. C., Stan, L.**, Robotic deburring cell virtual prototyping. *Proceedings in Manufacturing Systems*, Vol. 10, Iss. 4, pp. 183-188 (2015).
- [9]. **Pramanik, A., Dixit, A. R., Chattopadhyaya, S., Uddin, M. S., Dong, Y., Basak, A. K., Littlefair, G.**, Fatigue life of machined components. *Advances in Manufacturing*, Vol. 5, Iss. 1, pp. 59-76 (2017).
- [10]. **Ryazanov, A. I.**, Automated 3D modeling of working turbine blades. *Russian Engineering Research*, Vol. 36, Iss. 9, pp. 751-754 (2016).
- [11]. **Srinivas, G., Raghunandana, K., Shenoy, B. S.**, Recent developments in turbomachinery component materials and manufacturing challenges for aero engine applications. *In IOP Conference Series: Materials Science and Engineering*, Vol. 314, pp. 1-15 (2018).