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NUMERICAL SIMULATION OF DISSIMILAR FRICTION STIR WELDING OF ALUMINUM ALLOYS AA7075 AND AA2024: INFLUENCE OF TOOL GEOMETRY ON TEMPERATURE DISTRIBUTION

Alexandru-Ionuț TOMA, Younes DEMMOUCHE, Matthieu DHONDT, Claudiu BĂDULESCU, Eduard Laurențiu NIȚU, Daniela Monica IORDACHE

Abstract: Friction Stir Welding (FSW) is an innovative joining process widely applied for aluminum alloys, offering low-cost and efficient solutions for complex industrial applications. This study focuses on welding dissimilar aluminum alloys AA7075 and AA2024, emphasizing the importance of temperature control and the influence of tool geometry on the process. Numerical modeling was performed Abaqus software to simulate the thermal behavior during welding and analyze key parameters such as pin profile and coefficient of friction. The results reveal that the cylindrical threaded pin generates moderate temperatures, making it most suitable for welding these alloys, while the square pin produces higher temperatures, posing a risk of overheating, particularly for AA7075. In contrast, conical and cylindrical pins generate insufficient heat for effective joint formation. This research highlights the value of numerical simulations in optimizing FSW parameters for defect-free joints in dissimilar aluminum alloys.

Key words: Dissimilar friction stir welding, Coupled Eulerian–Lagrangian (CEL), Tool pin profile, Friction coefficient

1. INTRODUCTION

Aluminum and its alloys, particularly AA2024 and AA7075, are highly valued in industrial applications due to their unique mechanical strength and low-weight combination [1], [2], [3], [4], [5]. Friction Stir Welding (FSW) enables the joining of AA2024 and AA7075 alloys, effectively merging their distinct mechanical properties into a single component. AA2024 is renowned for its excellent fatigue resistance and tensile strength, while AA7075 offers superior hardness and mechanical strength [6], [3], [4], [7], [8], [9]. By employing FSW, joints can be created that leverage the advantages of both alloys, resulting in components with enhanced performance [10].

This welding method is particularly beneficial in the aerospace and automotive industries, where combining low weight and high strength is important [11]. FSW facilitates the production of high-quality joints between AA2024 and AA7075 without necessitating the

melting of materials, thereby minimizing defects common in conventional welding processes [12]. Consequently, components can be manufactured that combine the fatigue resistance of AA2024 with the hardness of AA7075, providing efficient solutions for demanding structural applications.

Numerical simulation of FSW is important, offering significant advantages over experiments. It has been used to analyze temperature distribution, material flow, and residual stresses, reducing costs and experimental time [1], [13], [14], [13], [4], [15]. Simulations have demonstrated high accuracy in predicting material behavior, enabling process optimization and defect minimization [16], [9], [17], [18], [19], [20], [21], [11], [22], [5], [23].

The geometry of the tool used in Friction Stir Welding (FSW) is important for achieving high-quality joints, directly influencing the temperature distribution, material flow, and mechanical properties of the weld. The tool shoulder is responsible for generating heat

through friction and applying pressure to the welded area. When joining aluminum alloys, the flat shoulder is frequently used. The flat shoulder ensures uniform distribution of pressure and heat, being effective in reducing surface defects [1], [6], [21], [23], [5], [11], [4], [24], [13]. The concave shoulder improves material mixing and reduces surface defects. [25]. The most commonly used types of pins for aluminum welding are: cylindrical threaded [1], [23], [24], used for homogenization, optimal material flow, and defect minimization, and conical threaded [11], [22], [23], used for optimizing material flow. Conical simple and cylindrical simple pins are used less frequently as their capability to mix material is lower [4]. The square pin improves the flow of the material, which leads to good mixing in the stir zone[10]. Typical tool sizes include shoulder diameters between 12 and 16 mm and pin diameters of 3 to 7 mm when welding aluminum alloys.

The temperature in the FSW process is an important parameter for the structure and mechanical properties of the joints. For AA2024 and AA7075, the optimal temperatures range between 400 and 500°C, ensuring material plasticization without melting. This temperature prevents major defects such as porosity or cracks and enables the production of durable and strong joints [6], [4], [24], [13], [1].

In the work by Guo et al. (2020) [1], the maximum temperature in the welded zone was 438°C on the AA7075 side, under conditions of tool rotation at 400 rpm and feed at 150 mm/min. The paper analyzes the influence of friction and pin shape on temperature distribution, using numerical simulation in Abaqus.

2. NUMERICAL MODEL DEVELOPMENT

Numerical simulation of friction stir welding (FSW) provides an efficient method to analyze and optimize the thermal and mechanical behavior of aluminum alloys, such as AA2024 and AA7075, used in high performance industrial applications.

The simulations allow the evaluation of temperature distribution from the process

without requiring a large number of physical experiments, so reducing time and costs.

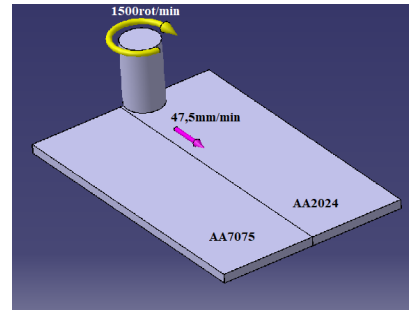


Fig. 1. Friction stir welding process

For the numerical modeling of the friction stir welding process, the software Abaqus was used, the approach being a Coupled Eulerian-Lagrangian one.

This approach was used because the primary aspect is the analysis of the temperatures in the process and the influence of the profile of the tool pin on the temperatures.

The numerical modeling of the friction stir welding process was performed using the Coupled Eulerian Lagrangian finite element. The numerical model that is the subject of the present research work is a particularized one that simulates the temperature distribution at the expense of material flow simulation.

The model is based on six steps:

1. establishing the part and the active element
2. establishing a material behavior law
3. establishing properties
4. establishing friction laws and contact type
5. process boundary conditions
6. discretization of each part.

The first of these steps is the step in which the elements of the friction stir welding process have been created.

The following dimensions were selected for these components: 100mmx40mmx4mm for each plate, AA2024-T3 and AA7075-T6 (Fig. 2).

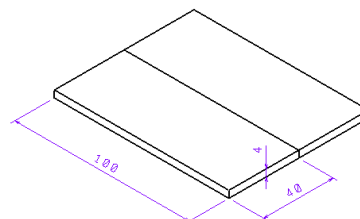


Fig. 2. Dimensions of the jointing plates

The tool features a Ø20 mm shoulder, and the pin length is 3.8 mm. In the next two steps, the materials are defined. AA2024-T3 and AA7075-T6 will be assigned to the welding plates, while H13, a material with superior properties, will be assigned to the tool. Additionally, in this stage, the constitutive behavior law is established to describe the material behavior during the friction stir welding process.

The Johnson-Cook law is a constitutive model widely used to describe the plastic behavior of materials under extreme mechanical and thermal stresses, such as those encountered in friction stir welding (FSW). This law allows the modeling of material behavior as a function of temperature, strain rate and deformation state. The use of the Johnson-Cook model, Equation 1, for the aluminum alloys AA2024, and AA7075 helps to better understand their response to specific FSW process conditions.

$$\sigma = [A + B(\varepsilon^n)] \left[1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \right] \left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right] \quad (1)$$

where: σ is the yield stress; ε - plastic strain; $\dot{\varepsilon}$ - strain rate; $\dot{\varepsilon}_0$ - reference strain rate; T - material temperature; T_{room} - ambient temperature; T_{melt} - material melting temperature; A , B , C , n , m - material constants. Material constants of the Johnson-Cook law for the two aluminum alloys are presented in Table 1, and Table 2.

Table 1

Parameters for AA2024-T3.

Parameter Name	Unit	Value
Yield Stress (A)	MPa	352
Hardening Modulus (B)	MPa	440
Hardening Exponent (n)	Dimensionless	0.42
Thermal Softening Exponent (m)	Dimensionless	1.7
Melting Temperature	°C	502
Reference Temperature	°C	20
Strain Rate Sensitivity (C)	Dimensionless	0.0083

Table 2

Parameters for AA7075-T6.

Parameter Name	Unit	Value
Yield Stress (A)	MPa	520
Hardening Modulus (B)	MPa	477
Hardening Exponent (n)	Dimensionless	0.52
Thermal Softening Exponent (m)	Dimensionless	1
Melting Temperature	°C	620
Reference Temperature	°C	20
Strain Rate Sensitivity (C)	Dimensionless	0.001

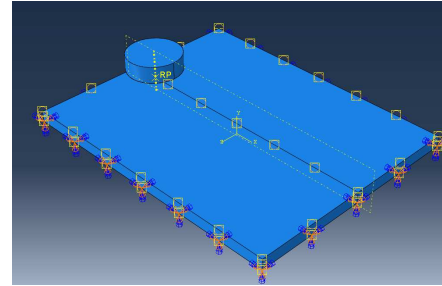


Fig 3. Boundary conditions

The boundary conditions, Figure 3, are set in the next step and consist of fixing the welding plates on the bottom and defining the parameters of the movements that the tool will perform: rotation around its own axis and translation along the joint line.

The plates were meshed into 8160 thermally coupled, reduced-integration, 8-node Eulerian hexahedral element (EC3D8RT), with 10675 nodes. The mesh was performed based on the reasoning that the finite element dimensions will gradually decrease towards the areas of increased interest and increase as we move towards the marginal areas, Figure 4.

The dimensions were chosen in such a way that the trade-off between computational accuracy and time required was correct.

The research started by studying the influence that certain parameters have on the process temperature:

The friction coefficient. Numerical models with values equal to 0.3/0.6 were implemented in order to try to understand how it influences the process temperature.

Pin profile. Numerical models were created for four profiles of the pin of the tool: cylindrical/ cylindrical threaded/ square/ conical.

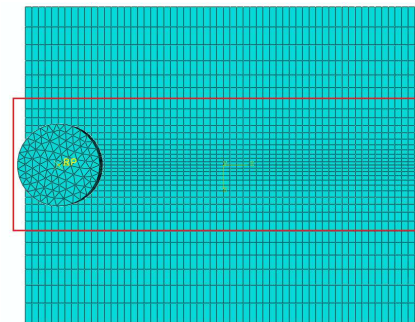


Fig. 4. The mesh of the Eulerian and tool

The friction coefficient. The coefficient of friction is the FSW process parameter, which has a determining role in the process temperatures, directly influencing the temperature and therefore the quality of the weld joint. The FSW process of aluminum alloys is based on the heat generated by the friction between the tool shoulder and the material, as well as the heat generated by the plastic deformation of the materials to be joined so this friction coefficient becomes extremely important.

The friction between the tool and the joining plates was defined as a Penalty type, and the values that were chosen to understand how this parameter influences the process temperature are 0.3 and 0.6. The process parameters used in the numerical modeling created to understand the influence of the coefficient of friction and the pin profile influence on the process temperature are shown in Table 3.

Table 3

Parameters for numerical simulation.		
Rotation speed [rpm]	Advance speed [mm/min]	Penetration [mm]
1500	47.5	3.8

Pin profile. The FSW welding process is a process that involves the generation of sufficient heat so that the materials to be joined change from a solid state to a thermoplastic state.

The tool, defined in the numerical model as a rigid element, has a role in the plastic deformation of materials as well as in the displacement of melted material from the front to the back of the tool.

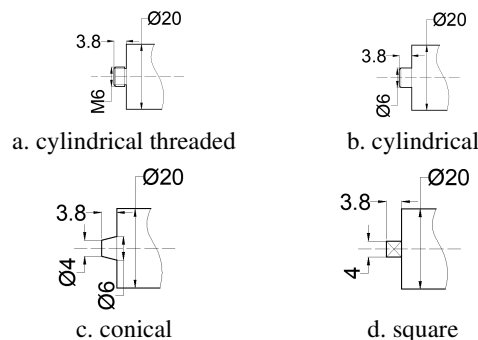


Fig. 5. FSW tool pin profiles

The constructive shapes of the tool can be extremely varied and have to provide friction with the shoulder plates as well as their plastic deformation. Identical numerical models with

identical parameter values, but different pin profiles, Figure 5, were proposed to understand how the tool shape influences the process temperature.

In the numerical model, the plates were constrained by restricting the displacements in each direction, Figure 3, and then the movements and their values were defined for each step.

The numerical model was validated based on the experimental results obtained under the same conditions (process parameters, tool shape) temperatures recorded with the thermal camera Optris The PI400i, Figure 7, have been compared with those obtained by numerical simulation under the same conditions, Figure 6, and the temperatures are similar, measured at the shoulder line, 232,5°C and 237°C.

3. RESULTS AND DISCUSSION

The friction coefficient. For each aspect, results were extracted from the areas of interest, which were further processed according to the following information.

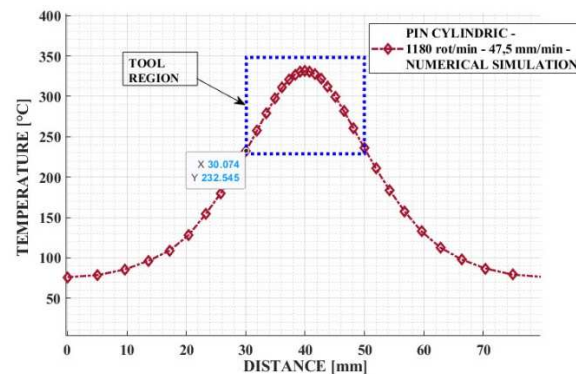


Fig. 6. FSW Numerical model temperature

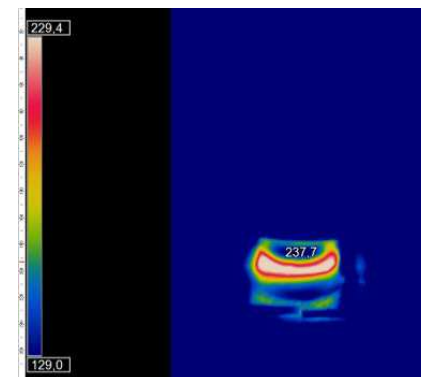


Fig. 7. FSW Experimental temperature

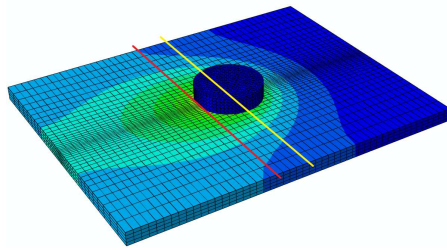


Fig. 8. Temperature extraction lines

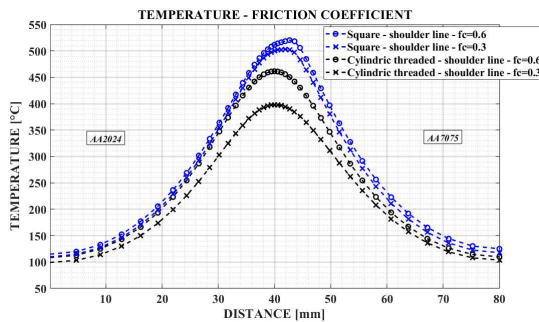


Fig. 9. Temperature at shoulder line - friction coefficient

For each coefficient of friction, 0.3 and 0.6, temperature data was extracted at the surface of the plates, at the shoulder-red line, and at the pin-yellow line, Figure 8. If the temperature at the pin is too low, the weld may be incomplete. In contrast, if the temperature at the shoulder is too high, defects such as material burning or excessive deformation may occur.

The results of the numerical simulation confirm that the temperature decreases with decreasing friction coefficient.

The percentage by which the temperature decreases, however, is different depending on the tool's shape, Figure 9, this aspect is more visible in the case of a cylindrical threaded tool than in the case of a square pin tool. A higher coefficient of friction ($f = 0.6$) leads to increased temperatures for both types of tools. Tools with a square pin generate more heat because material deformation becomes the primary heat generation mechanism. Consequently, the influence of the coefficient of friction on temperature is lower than in cylindrical tools, where friction plays an important role.

The cylindrical threaded pin is frequently used for joining materials with different thermal properties, due to its ability to better control temperature and prevent overheating.

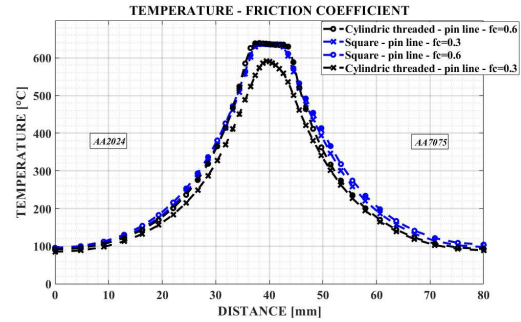


Fig. 10. Temperature at pin line - friction coefficient

If the extracted data are at the pin level, Figure 10 it can be observed that the influence of this friction coefficient decreases even more to the point that in the case of the square pin tool the influence is inconsiderable.

Pin profile. The pin profile influences the temperature in the FSW process. In order to have an overview, four numerical models have been created, the only difference between the four models being the profile of the pin.

The first set of results was extracted on the pin line (line yellow, Figure 9) have been processed and the results are plotted, Figure 11.

The temperatures resulting from numerical modeling confirm that there are minimal differences between the threaded, cylindrical and square shape of the tool when we talk about the temperatures extracted perpendicular to the weld bead at the pin, the temperatures being in the same area, around 600°C. The conical shaped tool, however, generates considerably lower temperatures around 420°C due to its reduced contact surface, less intense plastic deformation, and more efficient heat dissipation.

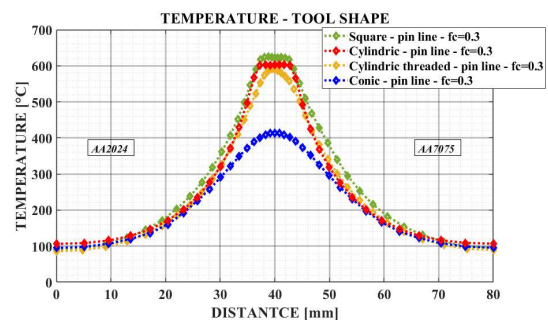


Fig. 11. Temperature at pin line – pin profile

The temperature distribution perpendicular to the weld line, at the tool shoulder is shown in Figure 12.

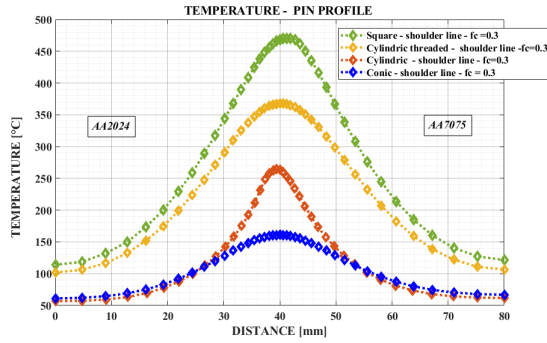


Fig. 12. Temperature at shoulder line – pin profile

The process temperatures obtained in this case are visibly lower compared to the initial case. The lower temperatures at the tool shoulder are the result of a more uniform distribution of friction, heat dissipation over a larger surface area, and less concentrated plastic deformation in this region. The pin, being responsible for material mixing and deformation, generates the highest temperatures. The temperatures obtained are around 475°C for the square tool, 370°C for the threaded cylindrical tool, 265°C for the cylindrical tool and 160°C for the conical tool.

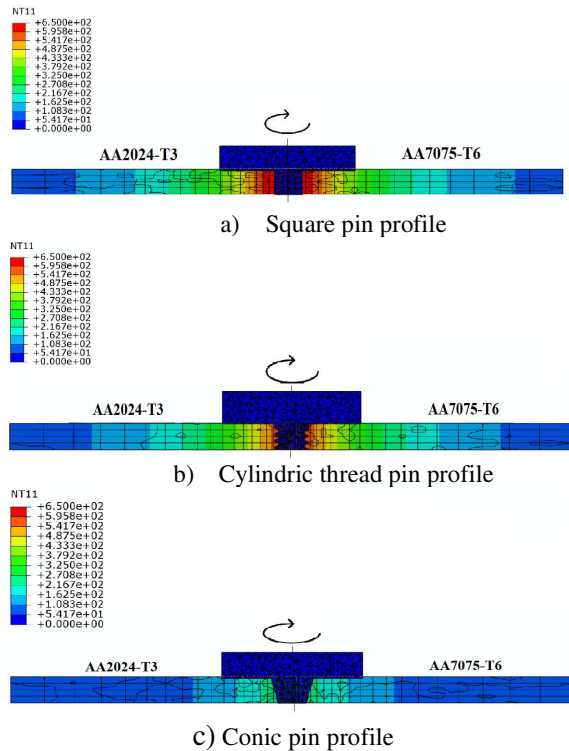


Fig. 13. Temperature [°C]

The temperature distribution, Figure 13, varies significantly during the FSW process, and

analyzing a single zone may not provide sufficient information to optimize the process. The Stir Zone (SZ) covers a uniform area around the pin, with the dimensions of this zone decreasing from the square pin to the conical pin. TMAZ and HAZ are narrower in the case of the conical pin due to the lower temperatures generated.

4. CONCLUSIONS

FSW welding is an innovative process that is increasingly finding applications across various industrial sectors.

Finite element numerical simulation is an important tool for understanding the thermal and mechanical phenomena involved in this low-cost, resource-efficient process.

Numerical modeling of the FSW process has provided critical insights into the process temperatures and the influence of factors such as the coefficient of friction and pin profile.

The study of the coefficient of friction confirms that the temperature significantly decreases when its value is 0.3 compared to 0.6, with reductions in some cases reaching approximately 70°C. The coefficient of friction directly influences heat generation during the FSW process because friction is a primary source of heat in this process. Additionally, temperatures are directly influenced by the pin profile, with the maximum temperature observed when using a square tool and the minimum temperature observed when using a conical tool.

Regarding the pin profile, analyzing the temperature at the shoulder area revealed that the most suitable tool for welding the AA7075 and AA2024 aluminum alloys is the Cylindrical Threaded pin, which leads to moderate temperatures (~370°C) and a uniform thermal distribution, suitable for the efficient joining of these materials. The Square pin, although it generates the highest temperatures (~475°C), poses a risk of overheating. The Conical pin (~160°C) and the Cylindrical pin (~265°C) may be insufficient to reach the required temperature for joining these alloys effectively.

The numerical element modeling correctly shows the temperature distribution and the need for further research on the temperature in the pin area, which is

caused either by the complexity of the process or by the behavior law used.

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Simularea numerică a sudării prin frecare cu element activ rotitor a aliajelor diferite de aluminiu AA7074 și AA2024: Influența geometriei sculei asupra distribuției temperaturii

Sudarea prin frecare cu element activ rotitor (FSW) este un proces inovator de îmbinare, utilizat pe scară largă pentru aliajele de aluminiu, deoarece soluții eficiente de îmbinare și costuri reduse pentru aplicații industriale complexe. Acest studiu se concentrează pe sudarea aliajelor diferite de aluminiu AA7075 și AA2024, arătând importanța controlului temperaturii și influența geometriei sculei asupra procesului. Modelarea numerică a fost realizată în Abaqus pentru a simula comportamentul termic pe parcursul sudării și pentru a analiza parametri cheie precum geometria pinului și coeficientul de frecare. Rezultatele arată că pinul cilindric filetat generează temperaturi moderate, fiind cel mai potrivit pentru sudarea acestor aliaje, în timp ce pinul pătrat produce temperaturi mai ridicate, prezentând un risc de supraîncălzire, în special pentru AA7075. În contrast, pinurile conice și cilindrice generează o cantitate insuficientă de căldură pentru formarea eficientă a îmbinării. Acest studiu evidențiază importanța simulării numerice în optimizarea parametrilor FSW pentru îmbinări fără defecte în aliaje diferite de aluminiu.

Alexandru Ionuț TOMA, PhD student, National University of Science and Technology POLITEHNICA Bucharest, Doctoral School of Industrial Engineering, Pitești University Center, ionut.toma@upit.ro.

RATEN Institute for Nuclear Research Mioveni, Romania.

Younes DEMMOUCHE, Associate Professor - Researcher, UBS – UBO - ENSTA Bretagne - ENIB, UMR CNRS 6027, Research Institute Dupuy de Lôme (IRDL), Brest Cedex 9, France, younes.demmouche@ensta.fr.

Matthieu DHONDT, Associate Professor - Researcher, UBS – UBO - ENSTA Bretagne - ENIB, UMR CNRS 6027, Research Institute Dupuy de Lôme (IRDL), Brest Cedex 9, France, matthieu.dhondt@ensta.fr.

Claudiu BĂDULESCU, Associate Professor - Researcher, UBS – UBO - ENSTA Bretagne - ENIB, UMR CNRS 6027, Research Institute Dupuy de Lôme (IRDL), Brest Cedex 9, France, claudiu.badulescu@ensta.fr.

Eduard Laurențiu NIȚU, PhD, Professor, National University of Science and Technology POLITEHNICA Bucharest, Pitesti University Center, Manufacturing and Industrial Management Department, eduard.l.nitu@upb.ro.

Daniela Monica IORDACHE, PhD, Professor, National University of Science and Technology POLITEHNICA Bucharest, Pitesti University Center, Manufacturing and Industrial Management Department, daniela.c.iordache@upb.ro.