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Analysis of Distribution of Temperature and Stresses during the Friction Metallisation of AlN Ceramics with Titanium

Abstract: The article presents the results of the numerical analysis of an AlN-Ti joint obtained during friction welding, where a titanium probe was rubbed frontally into the base of nitride ceramics. The process aimed to create a thin metallic (titanium) coating on the ceramic base enabling its further joining with metals. Until today, the metallisation of ceramics through friction has not been used for the metallisation of ceramics and, as initial tests have proven, this solution can constitute an advantageous alternative to currently used expensive processes of ceramics metallisation. The numerical modelling of the friction of AlN ceramics with titanium enabled the obtainment of information concerning the distribution of temperature fields and stresses on the contact surfaces of the AlN-Ti system during friction. The obtained results will be useful when analysing the mechanism related to the formation of the interpass of the joint connecting the AlN ceramics with z titanium.

Keywords: metallisation, friction welding, AlN-Ti joint, temperature field, distribution of stresses

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Introduction

The growing demand for ceramic-metallic joints has inspired the search for new efficient methods enabling the joining of various grades of ceramics with metals. Metallic-ceramic joints make it possible to combine various properties of components into a specific feature of a finished product [1]. Metallisation is one of the methods aimed to obtain ceramic-metallic joints; its purpose is to change the property of the surface layer of ceramics (usually by forming a thin metallic coating), making it possible to wet the surface using ceramic-inert metal. At the subsequent stage, the metallised coating enables the formation of a joint between a solid ceramic material and metal, e.g. through brazing or welding [2-4]. The metallisation of surfaces of ceramic materials is essentially related to their use and constitutes a vital stage of the technological formation of ceramic-metallic joints.

This article is concerned with a specific case of metallisation, constituting a stage in making ceramic-metallic joints and resulting from the search for a technologically new method enabling the metallisation of technically advanced

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ceramics. The obtainment of a joint connecting ceramic and metallic surfaces required the metallisation of the ceramic surface by the friction-based application of a titanium coating on an AlN ceramic base. During friction metallisation, the formation of a joint takes place in conditions, where the metallic component quickly reaches a temperature close to its melting point followed by cooling to ambient temperature. The presented method of the metallisation of ceramics using kinetic friction energy has a great application potential in the near future constituting a favourable alternative to presently used expensive and technologically complex methods of the metallisation of ceramics.

Regardless of joining methods, ceramic-metallic joints are exposed to the risk of high internal stress generation, primarily because of significantly different physical properties of materials being joined and high temperatures necessary for the formation of joints. Therefore, an issue of vital importance is the assessment of stresses in structures combining ceramics and metals [5].

The objective of the study was to determine and analyse the distribution of temperature and stresses during the friction-based metallisation of the AlN ceramics with titanium. The determination of the fields of temperature and those of stresses involved the use of the Finite Element Method (FEM) and two FEM-based software programmes, i.e. ADINA THERMAL and ADINA STRUCTURE (version 8.6.1), at the same time, as the problem was solved as unilaterally conjugated. The numerical simulation was performed in accordance with technological process conditions. The modelling of mechanical fields involved the contact of the butting faces of elements being welded. In turn, the modelling of the fields of temperature involved the assumption of the same temperature on the butting surfaces of both elements being joined. The physical and mechanical properties of the materials were linked to temperature. The problem, treated as non-linear, was solved for the axisymmetric model. The performed calculations enabled the tracking of thermomechanical phenomena taking place at the friction stage during the process of friction welding. The calculations provided information useful when analysing the mechanism related to the formation of the interpass of the AlN-titanium joint.

Test Specimens

Friction involved the butting faces of two elements, i.e. a titanium shape having an internal diameter of 3 mm, external diameter of 9 mm and a height of 60 mm as well as a 4 mm thick AlN ceramic plate having a diameter of 20 mm (Fig. 1a). The objective of the friction process was to obtain a uniform metallised titanium coating on the ceramic surface. The process of metallisation was presented in publications [6,7], whereas the effect of energy supply during the formation of dissimilar joints was extensively discussed in works [8-12]. The process of friction-based metallisation consisted of the friction-induced heating of the titanium shape under a load of 13.4 MPa; the titanium shape rotated in the probe at a rate of 2550 rev/min, rubbing against the ceramic surface at a constant (independent of temperature) friction coefficient of 0.42. The heating time amounted to 14 s, afterwards the tool started to move, rubbing its mass on the surface subjected to metallisation (not included in the presented modelling).

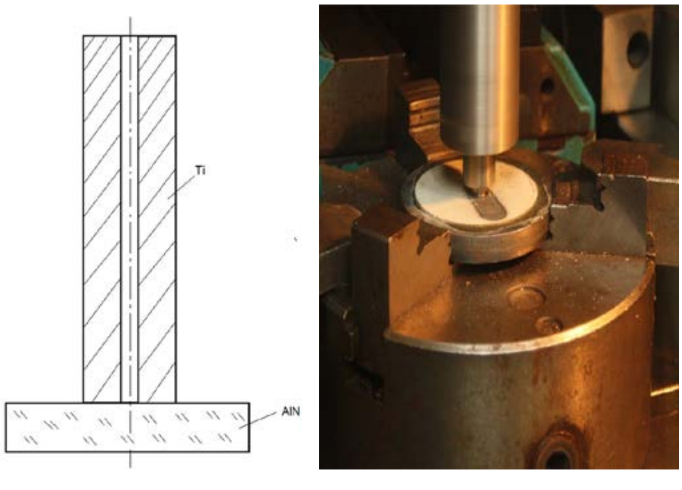

Fig. 1. System: titanium tool – ceramic base: a) scheme, b) in operation

Computational Model

The numerical simulation of the friction process was performed in the cylindrical coordinate system (r, θ, z). The adoption of symmetry in relation to the axes of elements being welded resulted in the disappearance of coordinate θ in the description of the phenomena taking place during the process of friction. The simulation involved the use of axisymmetric, quadrangular, quadrinodal conductive 2D elements and bimodal convective and radiation elements describing heat exchange at the edge of elements. The mesh of the model was composed of 1689 elements spread on 1787 nodes. The mesh was consolidated on the interface surface. Figure 2 presents the model geometry used for solving the thermal problem against the FEM mesh background with marked boundary conditions: the loading with the stream of heat q on the interface surface as well as convection and radiation-based exchange of heat with the environment on the lateral cylindrical surfaces of the ceramic and titanium shapes. It was assumed that the temperature on the surfaces being in contact was the same.

The stream of heat q on the interface surface changed in a linear manner in accordance with the following dependence:

$$q^{S^k} = \mu\, p_n V = \mu\, p_n \omega r$$

where:

μ – friction coefficient,

p_n – load affecting the friction surface,

ω – rate of rotation,

r – radius.

The value of the heat stream calculated on internal radius r_1=1.5 mm amounted to q_1=2,46 W/mm², whereas on titanium tool internal radius r_2=4.5 mm amounted to q_2=6.76 W/mm². The calculations involved the adoption of the coefficient of convection on rotating surfaces α_k=40 W/m², on remaining surfaces α_k=10 W/m² and surface emissivity ε =0.7.

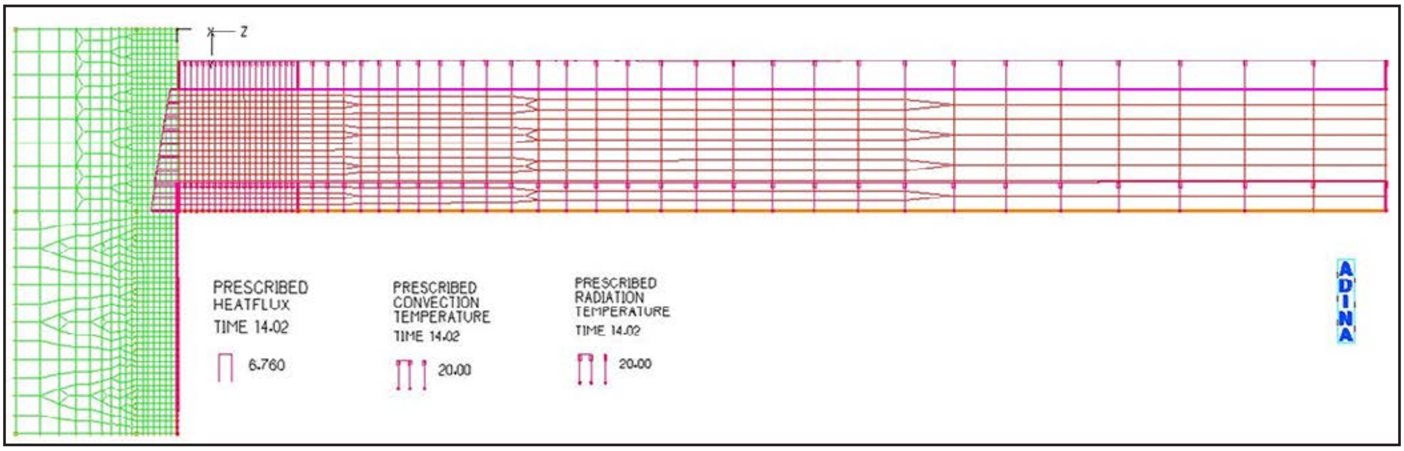

Fig. 2. FEM mesh of the AlN-Ti thermal model with boundary conditions

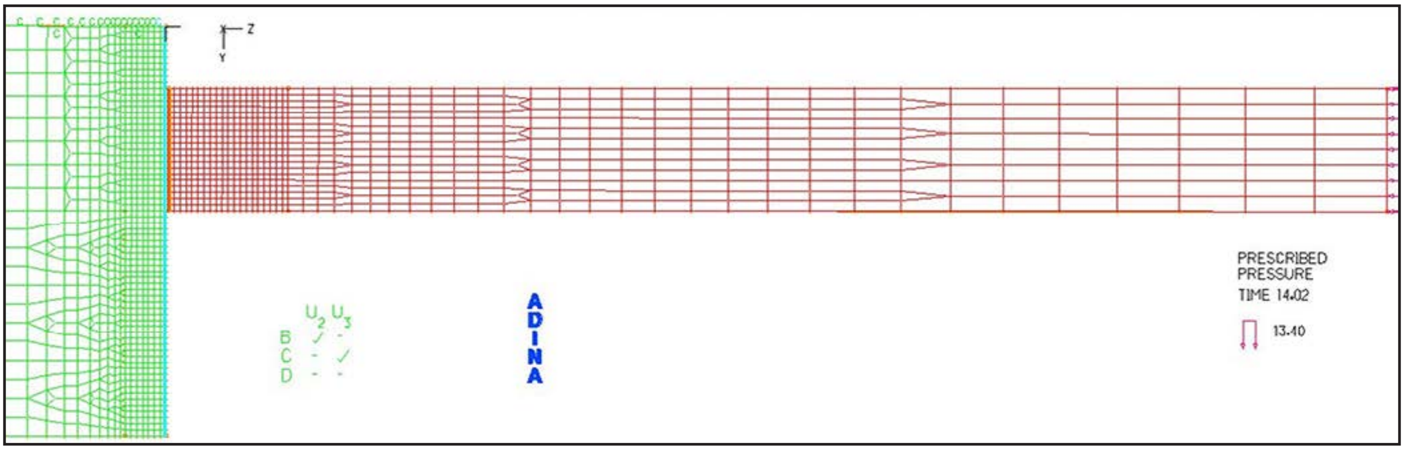

Fig. 3. FEM mesh of the AlN-Ti mechanical model with designated boundary conditions

For the purpose of simplifying the phenomena taking place during the process, the mathematical modelling of thermo-mechanical effects assumed that thermal and mechanical deformations considered for a given time increment would be treated as quasi-stationary. Figure 3 presents the geometry of the mechanical model with boundary conditions. The mechanical model geometry was composed of the FEM mesh arranged in the same manner as in the thermal model.

The modelling of the field of stresses during the process of welding involves the superimposing of a known field of temperature obtained by solving a thermal process in subsequent time increments onto a mechanical load (preset pressure p_i during the friction phase for the same iterative increments). The titanium material was described using the "plastic-bilinear" material model, whereas the ceramic model was described as an elastic material. The mechanical and thermal properties of both materials were linked to temperature.

Calculation Results

Distributions of Temperature

Figure 4 presents temperature field distributions during friction in subsequent times following the commencement of the welding of the AlN ceramics with titanium. It is possible to notice an increase in temperature in the boundary area, on the sides of both materials. The highest temperature reached approximately 1300°C after 14 s.

Figure 5 presents radial distributions of temperature on the AlN ceramics side and on the titanium side in relation to selected heating times. It is easy to notice an increase in temperature in the friction line is the ceramics and higher values of temperature in the area adjacent to the titanium sleeve opening.

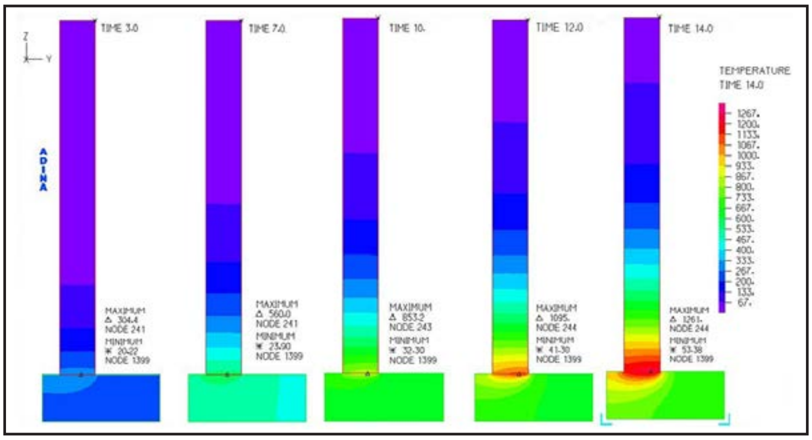

Fig. 4. Maps of temperature distribution for selected times of the friction-induced heating of the AlN ceramics with titanium

Distributions of Stresses

The mechanical analysis enabled the obtainment of distributions of all stress state constituents. The figures presented below contain maps of radial stresses σ_{yy} (Fig. 6, 7) at the final stage of friction as well as after releasing the load in the form of pressure affecting the specimens. As can be seen,

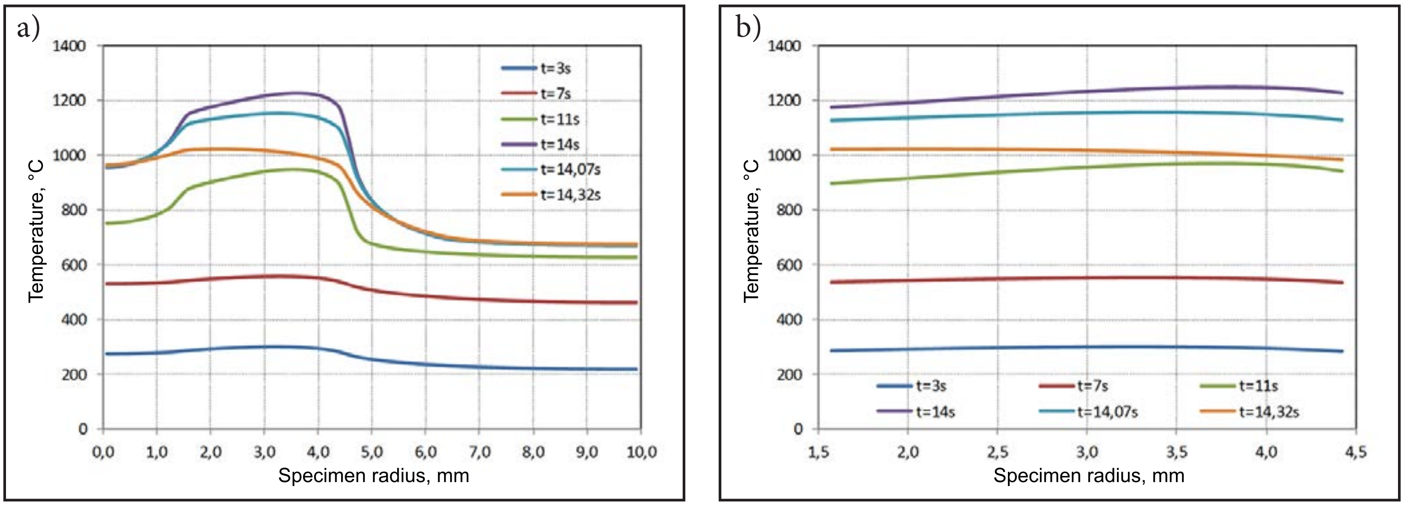

Fig. 5. Radial distributions of temperature on the AlN-Ti joint boundary: a) on the AlN ceramics side, b) on the titanium side

the friction zone of the AlN ceramics was affected by high compressive stresses (up to 800 MPa) and not excessively high tensile stresses in titanium (up to 60 MPa), partly limited by the plastic strain of the metal. After releasing the load, radial stresses in the ceramics decreased by approximately 150 MPa.

The distributions of axial stresses σ_{zz} are presented in Figure 8 and Figure 9, whereas that of circumferential stresses σ_{yz} in Figure 10 and Figure 11. Neither of these constituents reaches high values (up to -100 MPa) at the finals stage of friction or after releasing the load.

In the process of a ceramics–metal joint formation, an important role is played by the interpass. The time of friction-induced heating amounts to 14 s, whereas, at the final stage, the temperature on the interface surface reaches approximately 1300°c. In addition to temperature and time, the mechanism of joint formation is affected by stresses. Changes in volume depend on the stress axiator. Changes in volume triggered by octahedral (mean) stresses are expressed by the following dependence:

$\sigma_{śr}=1/3(\sigma_1+\sigma_2+\sigma_3)$,

where σ_1, σ_2, σ_3 – principal stresses.

Distributions of means stresses in the joint are presented in Figure 12 and in Figure 13 after releasing the load. In addition to the distribution of temperature,

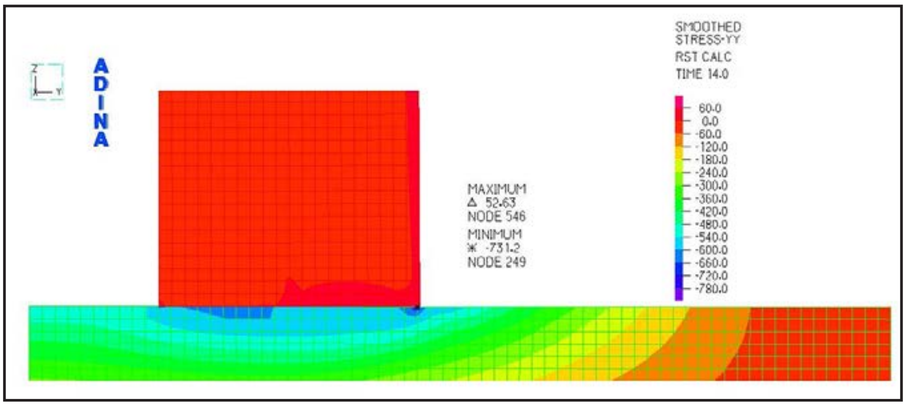

Fig. 6. Distribution of radial stresses σ_{yy} near the interface surface at the final stage of friction-induced heating

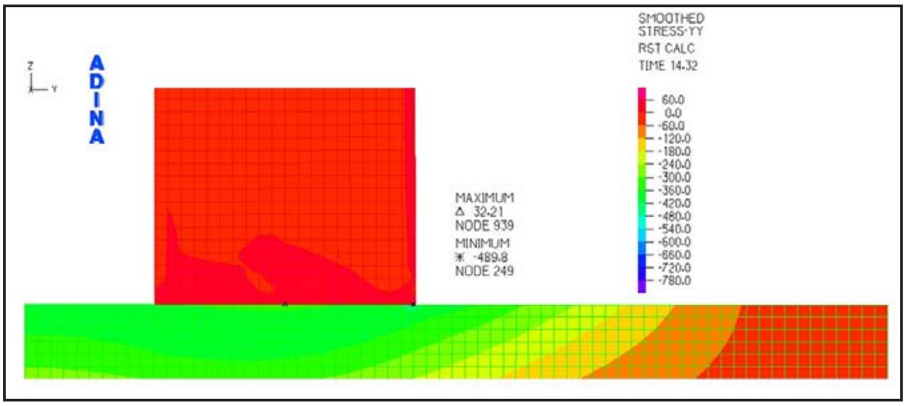

Fig. 7. Distribution of radial stresses σ_{yy} near the interface surface after releasing the load and heat stream from friction (0.32 s)

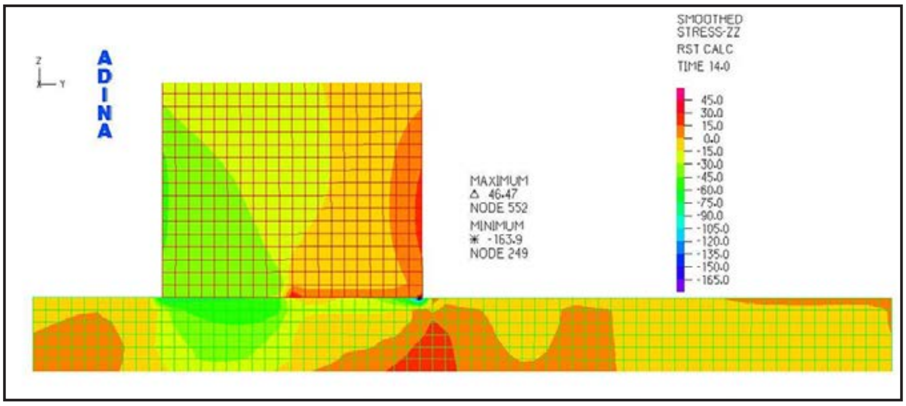

Fig. 8. Distribution of axial stresses σ_{zz} near the interface surface at the final stage of friction-induced heating

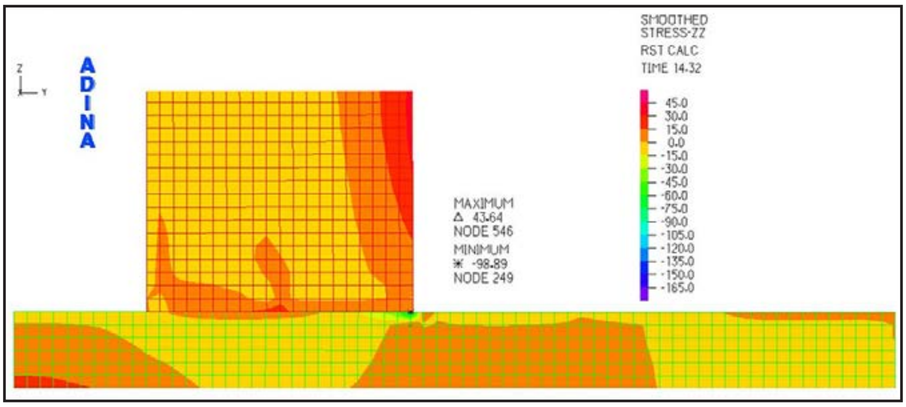

Fig. 9. Distribution of axial stresses σ_{zz} near the interface surface after releasing the load and heat stream from friction (0.32 s)

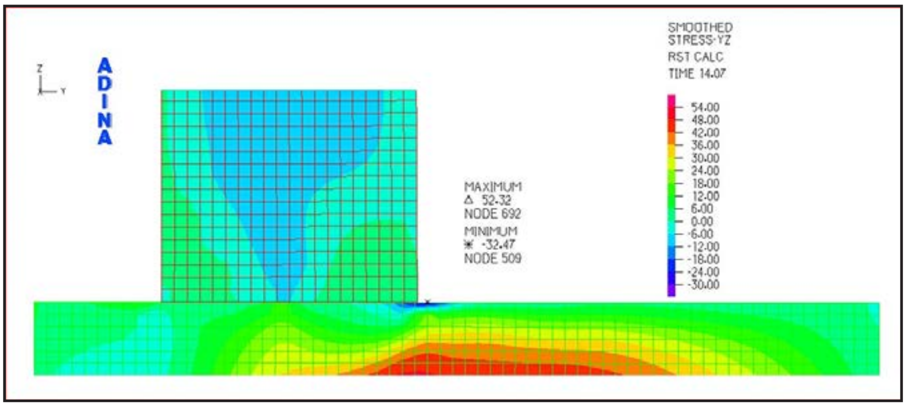

Fig.10. Distribution of circumferential stresses σ_{yz} near the interface surface at the final stage of friction-induced heating

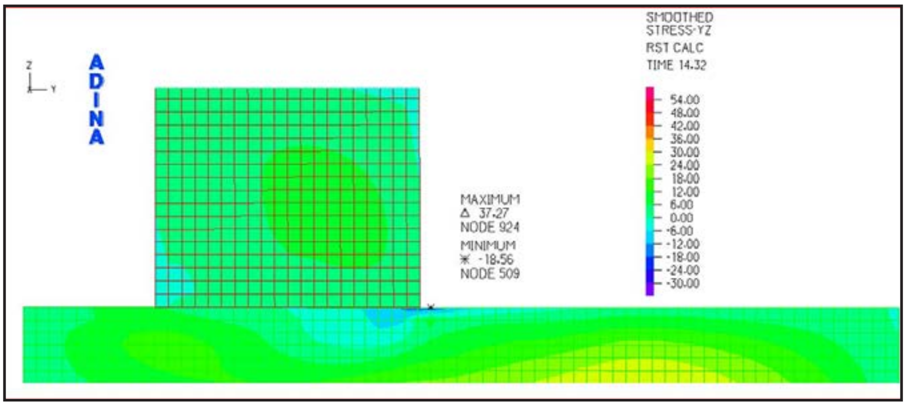

Fig. 11. Distribution of circumferential stresses σ_{yz} near the interface surface after releasing the load and heat stream from friction (0.32 s)

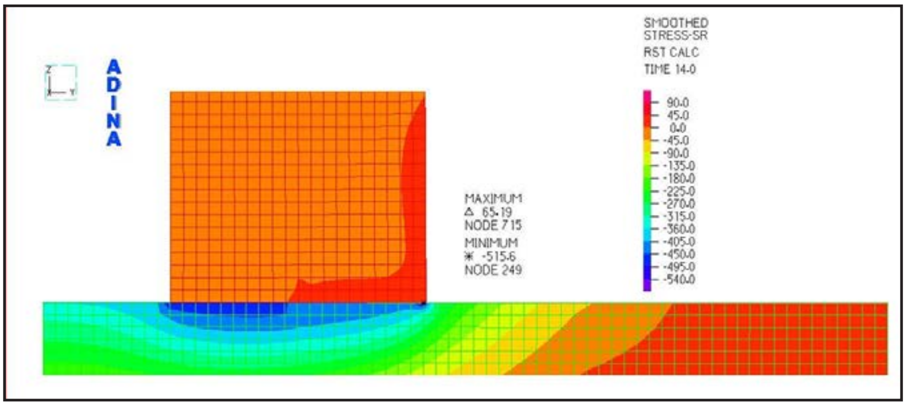

Fig.12. Distribution of mean stresses $\sigma_{śr}$ near the interface surface at the final stage of friction-induced heating

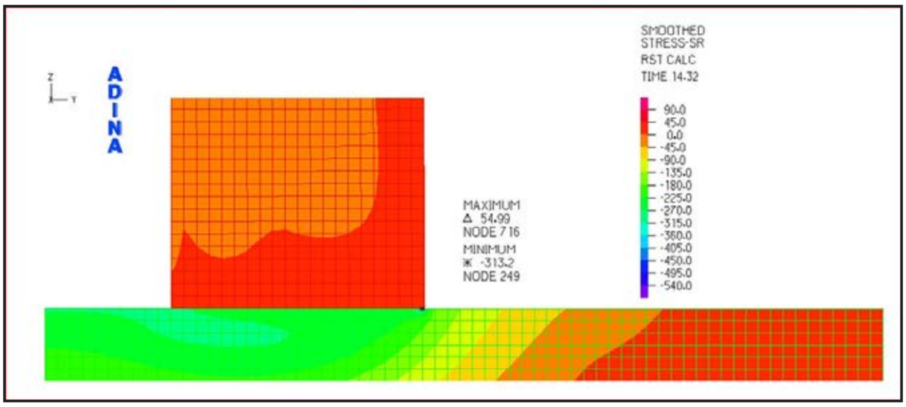

Fig. 13. Distribution of mean stresses $\sigma_{śr}$ near the interface surface after releasing the load and heat stream from friction (0.32 s)

the distribution of stresses significantly affects the mechanism of joint formation during the process of welding. The butting faces of elements being welded must be sufficiently close to each other so that the joint could be formed. Axial stresses near the ceramics-titanium interface surface should have the negative sign, thus allowing appropriate adherence. The distributions of axial stresses on the titanium side and on the AlN ceramics side are presented, for selected welding times, in Figure 14. As can be seen, the areas furthest from the axis, near the area designated *b* radius *r*=3 mm, are characterised by low compressive axial stresses of approximately -6 MPa. This results from the significant deformations of the titanium shape in these areas and could affect the quality of the joint in these areas. On the AlN ceramics side, the stresses are restricted within the range of -40 to -100 MPa in the finale phase of friction.

The distributions of stresses in the boundary area, separately on the AlN side and on the titanium side are presented in Figure 15 and 16. Attention should be paid to high compressive stresses in the ceramics and to the similar (in nature) distribution of mean stresses.

Summary

The numerical simulation of the friction metallisation of the AlN using titanium enabled the determination of temperature

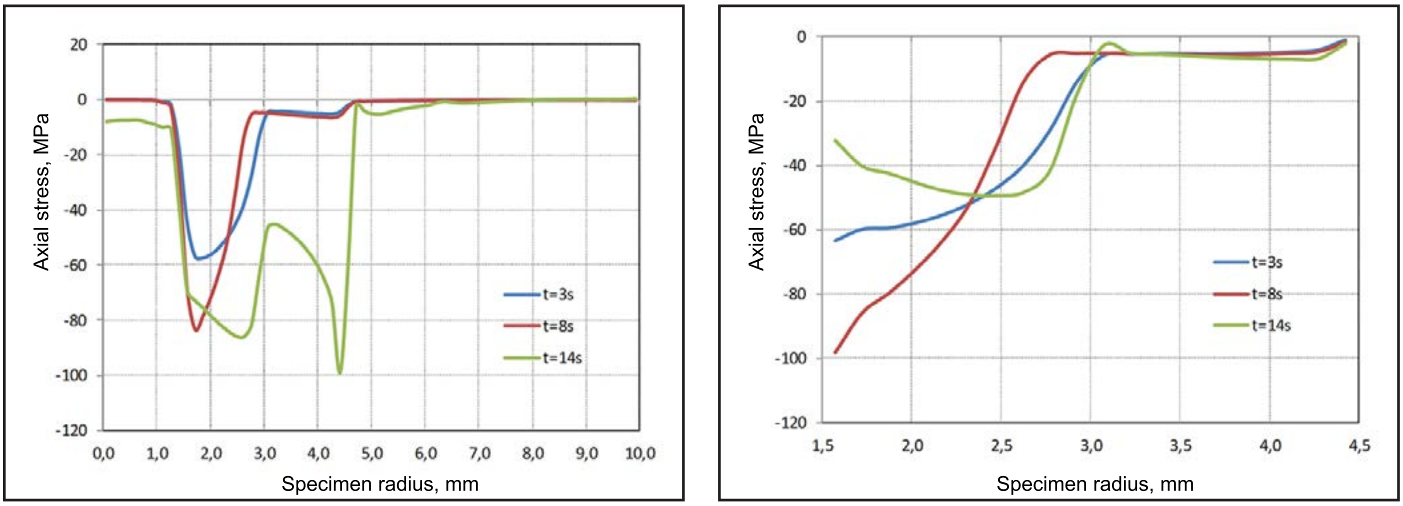

Fig. 14. Radial distributions of axial stresses in the joint: a) on the AlN ceramics side, b) on the titanium side

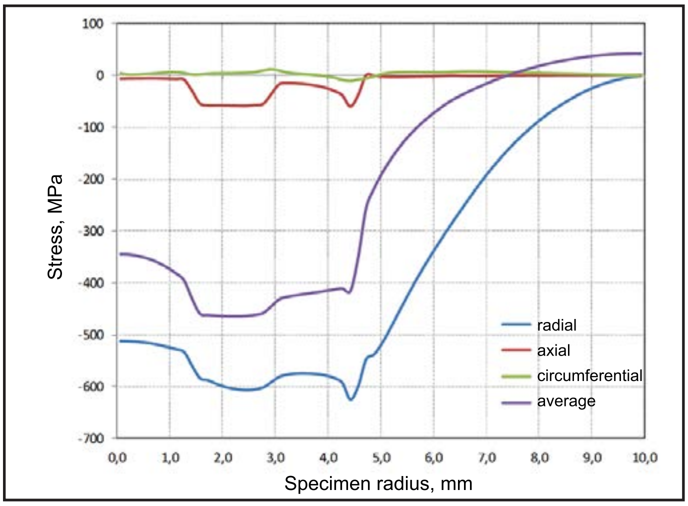

Fig. 15. Distributions of stress constituents (radial, axial and circumferential) and of mean stress along the radius of the AlN specimen

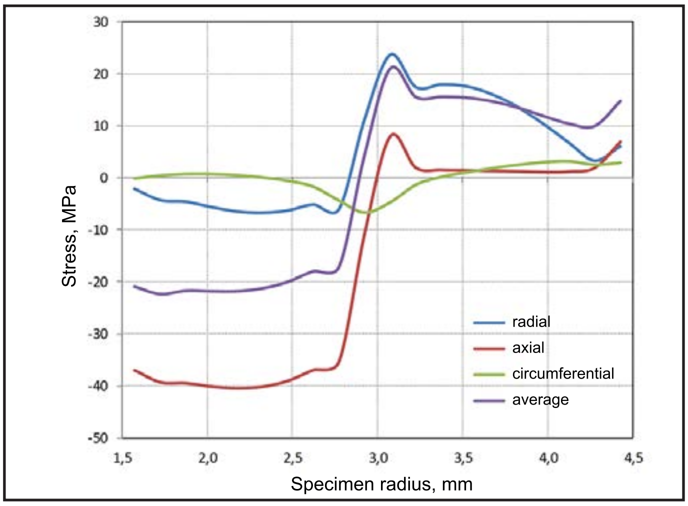

Fig. 16. Distributions of stress constituents (radial, axial and circumferential) and of mean stress along the radius of the titanium specimen

fields and distributions of stresses during the process of welding. The calculations were limited to the friction zone; the solidification zone was ignored as it affected the generation of internal stresses and not the mechanism of joint formation. The performed calculations justified the following concluding remarks:

– Distribution of temperature was non-uniform on the interface surface during the entire welding process; temperature in areas close to the axis was by approximately 200°C lower than the maximum temperature amounting to 1300°C.
– Highest temperature was present on the interface surface and near it, i.e. within a radius of approximately 4 mm of the titanium cylinder-AlN base system.
– Non-uniform distribution of axial compressive stresses near the interface surface, and increasing along with the time of friction, was caused by the significant deformation of the titanium tool material and could negatively affect the quality of coating.
– Mean stresses (decisive for changes in volume) near the boundary surface, both on the ceramic and titanium side had negative values throughout the process of friction.
– Releasing the load (0.05 s after the completion of welding) changed the value of mean stresses near the ceramics-titanium interface surface into positive.

It should be noted that the above-presented calculations were approximate in nature because of many simplifications adopted during the process of modelling, e.g. the lack of scientific references concerning the properties of titanium for the temperature range of 700-1400°C, or the adopted friction coefficient on the ceramic-titanium interface surface (constant and independent of temperature). In addition, the simulation was performed using the constant stream of heat generated from friction heat resulting from the assumed constant pressure on the interface surface. As a matter of fact, due to significant deformations of areas near the boundary surface, the pressure was variable in time. The performance of simulations with the stream of heat variable in time requires numerous restarts of calculations, which, taking into consideration the considerably long heating time (14 s) could translate to time-consuming calculations and technical difficulties.

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