Application of FEM simulation for the support of design and optimisation of forming processes

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Abstract

The development of unconventional technologies often requires attainment of narrow tolerances of several technological parameters in order to assure the maximal efficiency of the process. In many cases, it is impossible to observe all complex phenomena occurring during manufacturing process. Moreover, the possibility of direct measurement of some physical and technological parameters is also limited. In this reason, it is necessary to explore and apply new methods for analysis and quantification of interrelated phenomena. One of effective means in this area represents the application of FEM simulation accompanied by simplified experiments. Using such procedure, needed know-how for FEM simulation of more complex processes can be obtain. In the paper, some examples of FEM analyses used for design and development of new technology in the field of unconventional forming and thermomechanical treatment are introduced.

1. Introduction

During thermomechanical treatment (TMT) of materials, appropriate relations between deformation and temperature fields are essentially required for attainment of microstructures generally with better material properties than structures achieved by conventional treatment. Furthermore, thermomechanical treatment enables considerable energy saving for heating and heat treatment when suitable process arrangement is used. Additionally, total operation time can be reduced as well.

For example, in the technology of rotary spin extrusion, sequential and partial heating of semi-product can be exploited to influence the microstructure development during and after incremental deformation process. However, this requires to ensure not only desired temperature distribution in treated semi-product before forming but also to control the temperature fields in handled product over time during whole TMT. On the other hand, suggested methods of heating lead to more effective energy utilization and improving of surface quality of formed semi-product due to the reduction in scaling and decarburisation of undersurface layer. For the development of the process of rotary spin extrusion including technological equipment, a detail analysis of possibilities of temperature field generation and influencing in handled semi-product was performed using FEM simulation.

2. Technology of rotary spin extrusion

Technology of rotary spin extrusion developed at the Chemnitz University of Technology is dedicated to the manufacturing of hollow shafts for vehicle gear boxes [1-5]. This technology takes advantage of a very efficient incremental forming process. Applying unique incremental-deformation method with roll-off tools enables production of hollow and internally profiled parts directly from cylindrical rod semi-products with minimal material losses usually connected with conventional machining such as drilling or turning.
The principle of rotary spin extrusion is based on the deformation effect of three rollers located on the diameter of the forming zone that form the outer shaft contour (Fig. 1). At the same time, the spike is pressed in the axial direction into the rod to form the inner shaft contour. Thus, the material displaced by rollers and the forming spike runs off axially forming a cup wall. The rotational movements of the spike and rollers are not generated by separate driving mechanisms but they result from the friction. Because the spike is rotating with the same angular velocity as the formed rod semi-product, it is possible to produce even incircular or profiled inner shapes such as polygons, internal toothing, multiple-spline profiles using accordingly designed forming spikes (Fig. 2). In only one forming step, the semi-finished hollow shafts with a length–diameter ratio up to 20 can be produced [6].

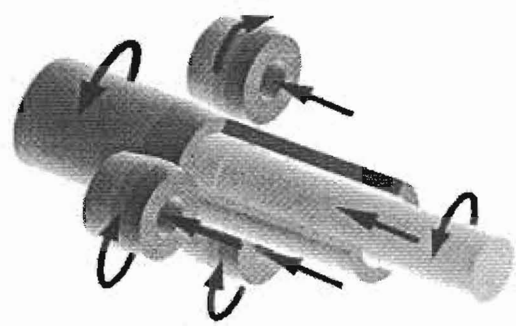


Fig. 1: Scheme of the technology of rotary spin extrusion [1, 7].

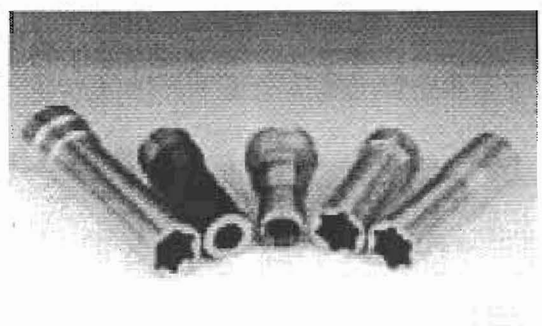


Fig. 2: Hollow and internally profiled shafts manufactured by rotary spin extrusion [7].

Depending on the material of the formed semi-product and required accuracy of internal and external shapes, the rotary spin extrusion can be used as a cold-, warm- or hot- forming technique. The high-strength steels are supposed to be treated by increased temperatures in order to improve conditions for plastic material flow what results in considerable reduction of the punch power [2, 5]. Moreover, the exploitation of incremental deformations at higher temperatures exhibits positive consequences on the microstructure and the material properties, particularly on the ductility, ultimate and impact strength. In this reason, wide range of strategies of thermo-mechanical treatment of steels has been examined and verified experimentally for the technology of spin extrusion [8-13].
In this work, the possibilities of the use of FEM simulation to study, analyse and optimise the process chain of hollow shaft production are illustrated through chosen examples. In all cases, the formed material is the low-alloyed relatively cheep 20MoCrS4 steel which is at present widely exploited in the automotive industry for rotary parts.

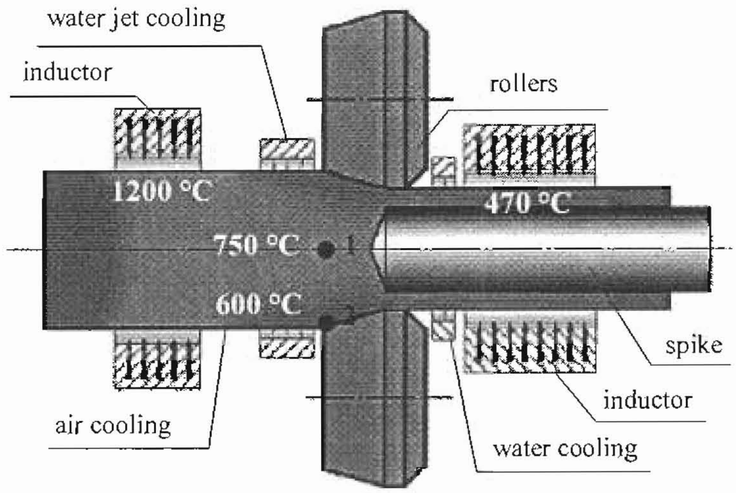


Fig. 3: Required temperature distribution during manufacturing process.

In order to obtain suitable plastic properties during the incremental deformation process and desired material properties of final semi-products, very exact temperature distribution in the handled semi-product before the forming process and during the tempering process is required (Fig. 3). The influence of parameters of heating and cooling were analysed and design using FEM simulation by the program code ANSYS. However, material treatment at increased temperatures influences the spike life in a negative way. From this point of view, the alternative of the exploitation of internally cooled spike was analysed.

3. Optimisation of heating and cooling processes before incremental forming

In the moment when the deformation process starts, the temperatures from 700 °C to 750 °C are required in the axis of a solid rod semi-product from the 20MoCrS4 steel while the surface temperatures under rollers shall be not higher than 600 °C (Fig. 3). To reach this temperature distribution, induction heating followed by surface cooling of a rod semi-product was proposed.

For induction heating of the rod semi-product with the diameter of 53 mm moving with the feed rate of 3 $mm.s^{-1}$, three-turn water cooled copper induction coil was designed. The current densities from 1.3×10^8 $A.m^{-2}$ to 1.4×10^8 $A.m^{-2}$ and relatively low frequencies from 2 kHz to 4 kHz were chosen according to the requirement to heat particularly the central parts of a billet. Using these parameters, static and dynamic induction heating processes were experimentally tested (Fig. 4a). Performed experiments served not only for the validation of the physical possibility to heat the billet sufficiently fast but also for the verification of developed FEM simulation model of induction heating [14, 15]. Comparison of measured and computed temperatures (Fig. 4b) proved very good coincidence of experimental and numerical results.

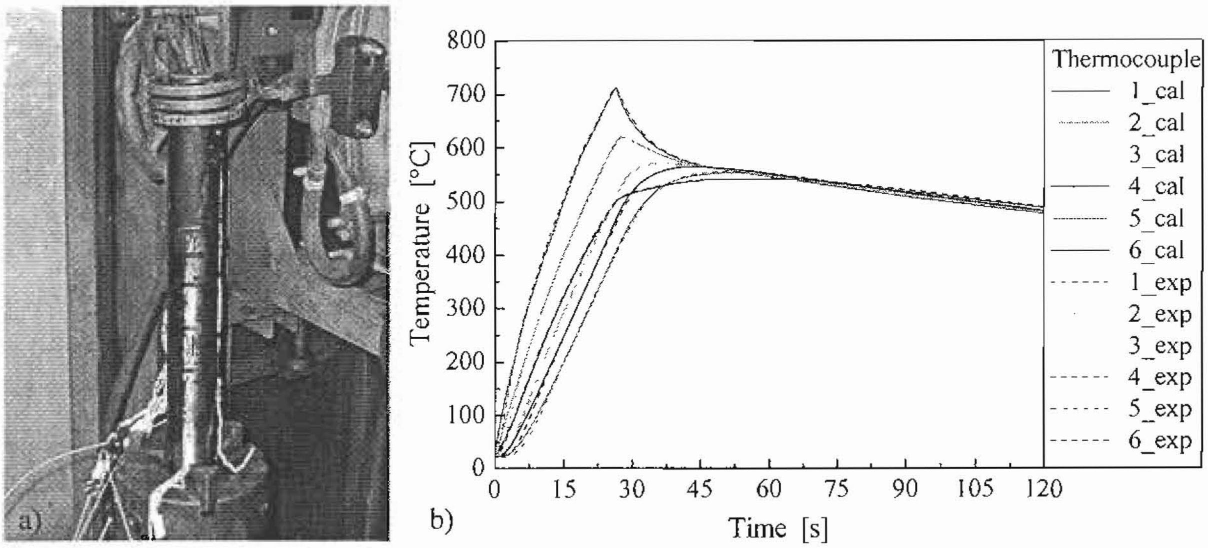


Fig. 4: Experimental temperature measurement by induction heating (a) and comparison of measured temperatures (dashed lines) and computed temperatures (solid lines) using the coupled electro-magnetic and thermal FEM analysis (b).

3.1. Analysis and optimisation of cooling process

The surface cooling was initially computer tested using pressure air. It was found that the application of technically the most simple air cooling is not intensive enough for quenching the rod surface to the required temperature under rollers [16, 17].

In the next step, it was supposed that the rod semi-product is cooled after the induction heating at first by water spraying and then subcooled by air free convection and radiation. This combination of cooling media in a described sequence resulted in rapid fall of surface temperatures during water spray cooling and to their following slight increase during air cooling [16, 17]. Moreover, the heat generated in a billet due to the induction heating was not used effectively. According to the basic principles of induction heating, approximately 87 % of generated Joule heat is concentrated owing to the skin effect in the surface area of a heated billet. The heat transfer to the central parts of the billet is realised by the mechanisms of conduction for which some time is needed. In case of water jet cooling location immediately behind the inductor, the surface layers are quenched before the heat has „chance" of being transferred to the rod center.

In above mentioned reasons, the exchange of cooling zones was finally suggested. The lengths of cooling zones and intensity of water spray cooling were optimised in order to attain required temperature field in a heated billet before the forming process. For the considered feed rate of 3 $mm.s^{-1}$, the length of air cooling zone (Fig. 3) was changed from 10 mm to 30 mm supposing the water spray cooling with the mass flow from 460 $kg.m^{-2}min^{-1}$ to 1000 $kg.m^{-2}min^{-1}$. According to Jeshar [18], corresponding average heat transfer coefficients are approximately from 1000 $W.m^{-2}K^{-1}$ to 2000 $W.m^{-2}K^{-1}$. The current density in inductor coil was set to the constant value of 1.35×10^{8} $A.m^{-2}$ by the frequency of 2 kHz.

As it follows from the time histories in the node 1 in the billet axis and in the node 2 at the billet surface (Fig. 5), the shorter air cooling zones are not advantageous as the water cooling starts before attainment of the maximum temperature in the node 2 at the billet surface. The elongation of air cooling zone results in the temperature increase in the billet axis due to the heat conduction from the billet surface to its central parts. Temperatures in the node 1 at the beginning of the forming process attain the values from 700 °C to 750 °C except the case with air cooling zone length of 10 mm when the axial temperature is lower than required. However, the length of water cooling zone reduced by extension of air cooling zone may not be sufficient to assure the quenching of a billet surface in the area of the node 2 under 600 °C.

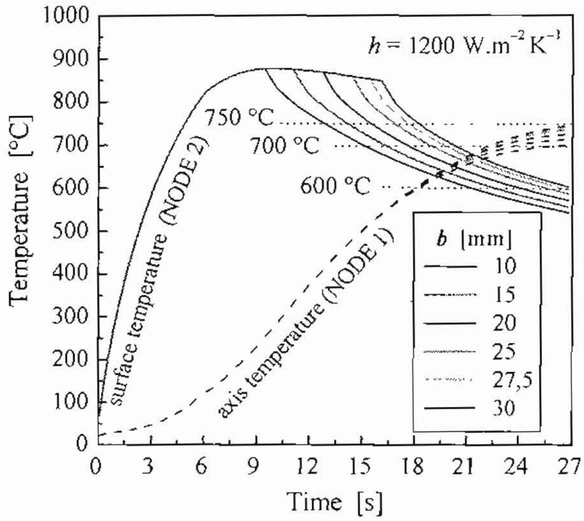


Fig. 5: Temperature histories in the node 1 (dashed lines) and in the node 2 (solid lines) for different lengths of air cooling zones b and water mass flow of 570 kg.m^{-2}min^{-1}.

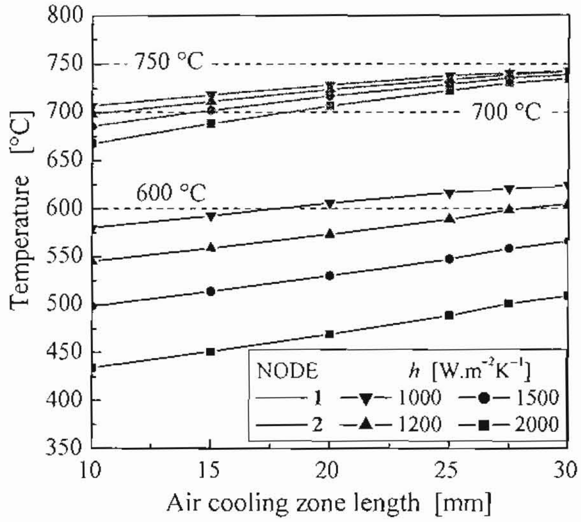
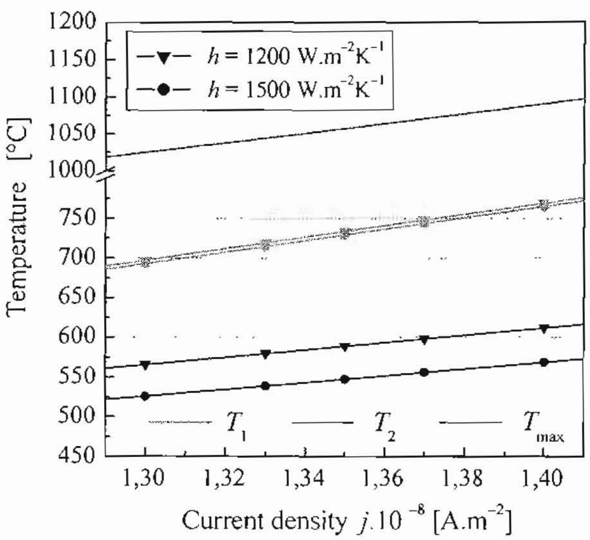


Fig. 6: Dependence of temperatures in the nodes 1 (red) and 2 (black) at the end of cooling process illustrating the influence of intensity of water spray cooling.

Intensity of water spray cooling given by varied heat transfer coefficient for different water mass flow influences more surface temperatures than axis temperatures (Fig. 6). To reach the minimal required axial temperature of 700 °C, the air cooling length should be about 18 mm at minimum. The influence of intensity of water jet cooling on the axis temperature at the end of cooling is not relevant for the air cooling zones with the length more than 25 mm. In this reason, the air cooling zone with the length from 25 mm to 27 mm and corresponding water spray cooling zone length from 35 mm to 33 mm can be considered as optimal. For these lengths of cooling zones, the water mass flow from 570 kg.m^{-2}min^{-1} (h = 1200 W.m^{-2}K^{-1}) to 730 kg.m^{-2}min^{-1} (h = 1500 W.m^{-2}K^{-1}) can be recommended according to the surface temperatures at the end of cooling. The lower water mass flows are not sufficient for required surface quenching. On the other hand, surface temperatures are too low when more intensive water cooling is applied.

3.2. Optimisation of induction heating process

The next task concerned the optimising of inductor power and necessary current density in induction coil, respectively. Using the frequency of 2 kHz and optimised parameters of cooling (air cooling zone with the length of 25 mm, the water cooling zone length of 35 mm with the water jet mass flow from 570 kg.m^{-2}min^{-1} to 730 kg.m^{-2}min^{-1}), the influence of current density in induction coil on the axis and surface temperatures in the nodes 1 and 2 was analysed (Figs. 7 - 8). The increase in intensity of water cooling affects particularly billet surface temperatures. The needed current density to reach the axis temperatures from 700 °C to 750 °C attains values from approximately 1,31×10^{8} A.m^{-2} to 1,37×10^{8} A.m^{-2}. For these current densities in induction coil and considered cooling conditions, the surface temperatures in the node 2 are as required below 600 °C. Moreover, the maximum temperatures during the heating process are lower than allowed temperature of 1200 °C. The computed temperature distribution in the rod semi-product just before the starting of incremental forming process (Fig. 9) satisfies required conditions for thermomechanical treatment.



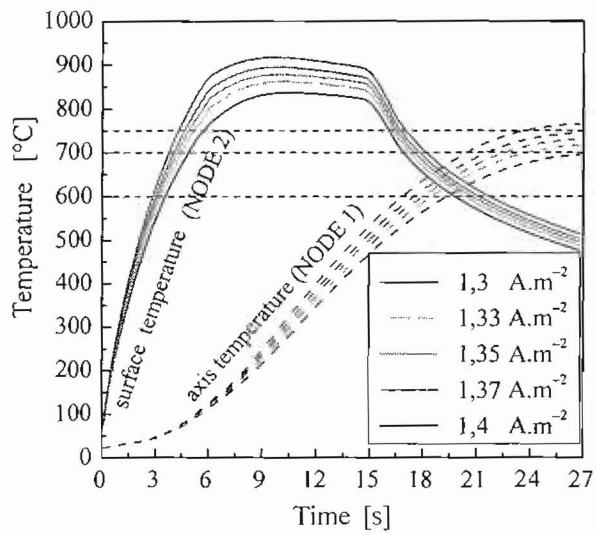


Fig. 7: Dependence of the axial temperature and surface temperature at the end of cooling and the maximum temperature during heating process on the current density in inductor coil.

Fig. 8: Time history of the axial temperature (NODE 1) and surface temperature (NODE 1) at the billet head for chosen current densities in inductor coil.

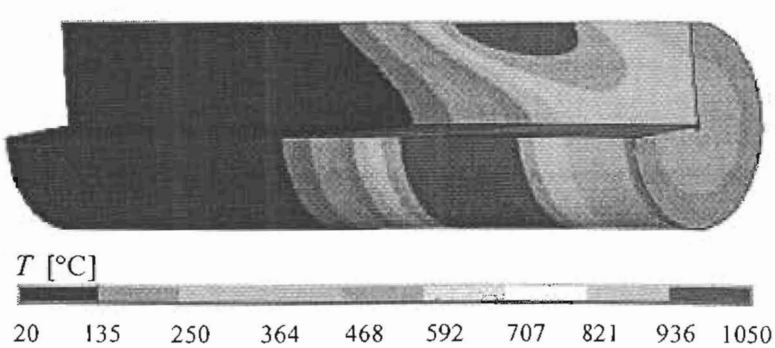


Fig. 9: Temperature distribution in a rod semi-product (a detail) before the forming process computed using the designed parameters of induction heating and cooling.

4. Analysis of induction tempering process

In order to achieve required mechanical and utility properties of hollow shafts produced by the technology of rotary spin extrusion, the tempering procedure is supposed to be integrated to the process chain during thermomechanical treatment of material [12]. This procedure involves material cooling from the temperature of 750 °C reached in the zone of intensive deformations in the front of spike (Fig. 3) to the temperature approximately 470 °C in the zone after the forming rollers followed by the holding time at this temperature using induction heating. The main aim of the performed numerical analysis was to design parameters of water cooling and induction heating including the intensity of water spray cooling, geometry of induction coil, frequency and needful inductor power. The influence of induction heating on the spike temperatures was evaluated as well.

Based on the obtained results of numerical simulation of cooling and induction heat treatment, the following parameters are recommended for the uniform shaft heating to the required holding temperature (Fig. 10):

- spray cooling with the water mass flow of 450 $kg.m^{-2}min^{-1}$ in the zone with the length of 60 mm followed by air cooling before induction heating,
- inductor shape: 12-turn copper water cooled induction coil with the total length of 164 mm,
- frequency: 4000 Hz,
- current density in the induction coil: given by the time dependent function with the maximum of $j = 3\times10^7\ A.m^{-2}$ at the beginning of induction heating.

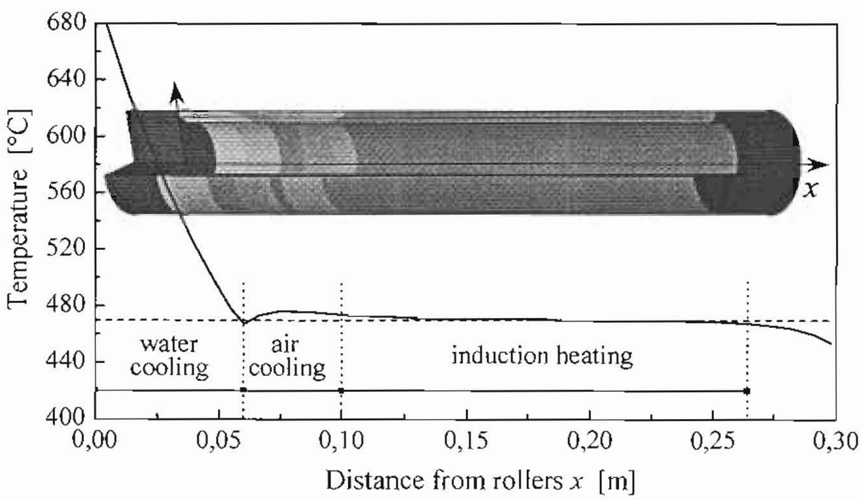


Fig. 10: Temperature distribution along the outer shaft surface in the time of 30 sec.

5. Analysis of temperature distribution in the internally cooled spike

At present, a solid spike is used for hollow shaft manufacturing by rotary spin extrusion. During the process of thermomechanical treatment and particularly during the holding time, the spike is exposed to increased temperatures what can finally result in loss of spike life. In this reason, the possibility of the use of internally cooled spike was analysed. Several variants of geometrically different cooling systems were considered. The diameter of a hole in the spike, D, for the cooling water supply was supposed to be from 6 mm to 20 mm (Fig. 11a).

Based on performed static and buckling analyses, the spike with a hole of 16 mm in diameter was recommended for placement of cooling system. Hence, the internal diameter of the cooling pipe, d, was supposed to be from 5 mm to 9 mm whereas the pipe wall thickness, δ, was modeled from 1,5 mm to 2 mm.

The dependence of the maximum temperature of cooling water on the internal diameter of water feed pipe (Fig. 11b) revealed that the pipe with internal diameter of 7 mm and the wall thickness of 2 mm is optimal from the point of view of water cooling temperature. This geometry of cooling system is also suitable considering the maximum spike temperature.

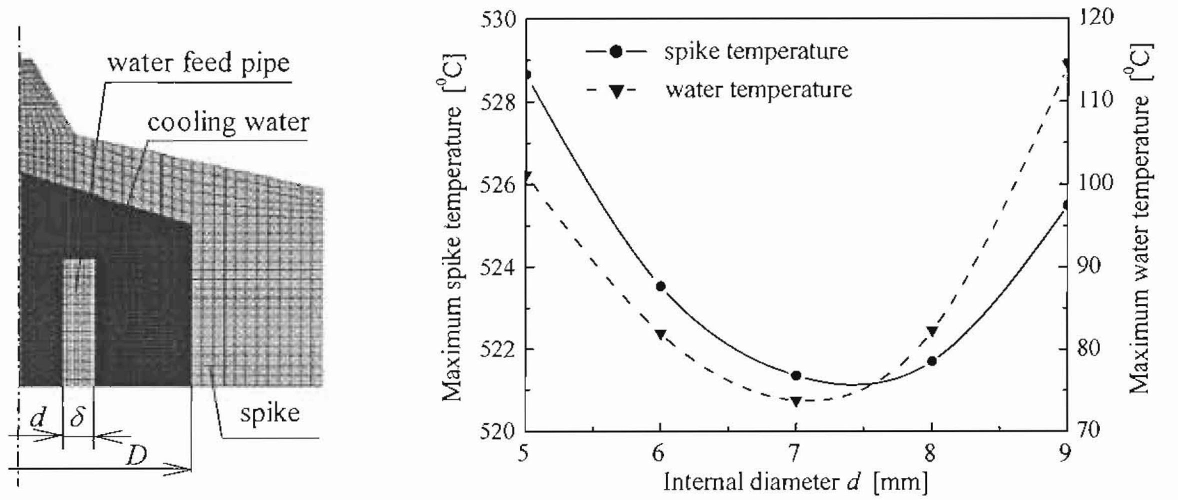


Fig. 11: Main geometrical characteristics of cooling system (a) and their influence on the maximum water and spike temperatures (b).

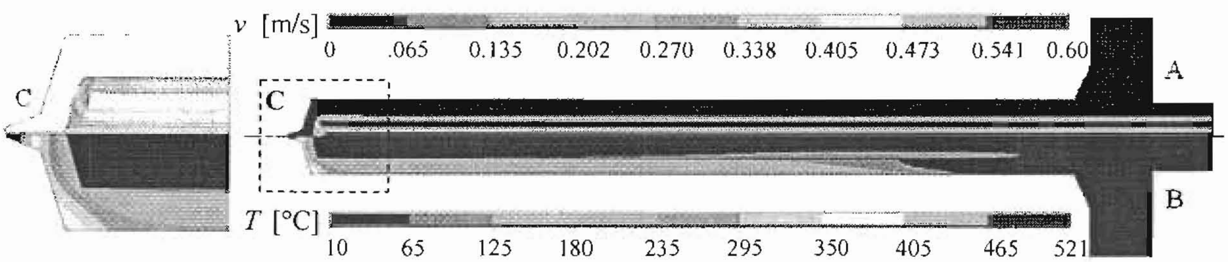


Fig. 12: Computed velocities (upper part - A) and temperatures (bottom part - B) in cooling system and spike for recommended geometrical parameters of internally cooled spike with a detail in part C.

The highest temperatures above 500 °C are reached locally at the tip of a spike (Fig. 12). However, the temperatures at the surface of conical part of a spike do not exceed the allowable value of 400 °C. As it follows from the velocity distribution in Figs. 12A and 12C, the optimisation of the hole frontal part is advisable in order to improve the water flow around the inside frontal wall of the spike. Finally, such modification can assure more intensive cooling of the spike tip.

6. Conclusions

Numerical simulation of technological processes enables to analyse investigated phenomena in mutual relationships and causalities and to optimise parameters of the process from many aspects. The main problem in the field of application of numerical simulation for complex comprehensive technological processes consists today particularly in input parameters, i. e. definition of material properties and material behavior, setting of reliable nonlinear and mostly also time dependent boundary conditions and loading. From this point of view, the verification of chosen numerical results by experimental measurements is unavoidable. However, the computer simulation represents a very efficient and powerful tool for design and optimisation of advanced unconventional technological processes.

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