Some recent developments in sheet metal forming for production of lightweight automotive parts

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Abstract. Low cost manufacturing in the automotive industry is one of the main targets due to the ever increasing global competition among car manufacturers all over the World. Sheet metal forming is one of the most important key technologies in the automotive industry; therefore the elaboration of new, innovative low cost manufacturing processes is one of the main objectives in sheet metal forming as well. In 2015 with the initiative of the Imperial College London a research consortium was established under the umbrella Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles. The primary aim of this project is to provide affordable low cost weight reduction in mass production of vehicles considering the entire life-cycle. In this project, 19 European Institutions (Universities and Research Institutions) from 9 European countries are participating with the above targets. The University of Miskolc is one of the members of this research Consortium. In this paper, some preliminary results with the contributions of the University of Miskolc will be introduced.

1. Introduction

The University of Miskolc as a member of this research Consortium has already substantial preliminaries in lightweight manufacturing due to the research activities performed in former national and international projects partly sponsored by the National Science Foundation of Hungary and partly by the European Commission through various European funds [1].

In this paper, we will summarize some results achieved so far concerning material developments including both different grades of high strength steels and lightweight aluminium alloys, technological process developments in sheet metal forming widely applied in car body manufacturing, as well as the application of various techniques of Computer Aided Engineering with special regard to the Finite Element Modelling and Simulation of sheet metal forming processes. The selection of these preliminaries is in strong connection with the main tasks of the University of Miskolc defined in this H-2020 research cooperation [2].

2. Preliminary research activities at the University of Miskolc in low cost materials processing

Low cost manufacturing is an important target in car manufacturing. Low cost production is often linked to lightweight construction principles, too.

There are two main trends for producing lightweight automotive structures with low cost manufacturing which are particularly valid for car body elements production by sheet metal forming. Application of high strength steels is one of the possibilities. The application of lightweight materials – particularly various aluminium alloys – is regarded as the other possible solution. First, we will shortly overview these research trends from the point of view of applied materials [2].
2.1. Application of high strength steels

For several decades the application of conventional cold rolled steels dominated the car body manufacturing. However, in the last 20-30 years there were very intensive developments in steel making mainly initiated by the requirements to produce lightweight, structurally sound car body structures with better crashworthiness and higher safety. To meet these increased requirements the development and widespread application of various generation of high strength steels should be mentioned. Obviously, with this increased strength parameters the extension of formability is another important issue, since with the increased strength usually the formability is reduced.

We tested the application and formability of different DP-steel grades (e.g. DP600, DP800 and DP1000) and the boron alloyed Manganese steels like 22MnB5. For these test results we refer to Research Reports and papers [1], [2] published from these investigations. All these material grades are widely used in car body manufacturing and the last one (i.e. the 22MnB5) in hot forming conditions.

2.2. Application of high strength aluminum alloys in car body manufacturing

Application of high strength aluminium alloys is the other possibility to meet the requirements in lightweight car body constructions. However, it is well known that aluminium has lower formability than steel; replacing steel with lighter materials such as aluminum, magnesium, etc. can be costly and is not simply straightforward. Aluminum sheet, in particular, has much lower formability at room temperature than typical sheet steels [2]. For replacing steel components with aluminum, we selected two groups of aluminum alloys: AA5754 H22 and AA6082 T6; both are widely applied in car manufacturing. AA5754 (AlMg3) alloy is widely used in sports cars like Jaguar XK, Lotus Evora and Chevrolet Corvette. This alloy has medium strength among aluminum alloys. AA6082 is commonly used for structural elements in most of luxury cars applying aluminum body components like BMW 6, BMW Z8, Ferrari 548, Jaguar XJ, Jaguar XK, Range Rover and Rolls-Royce Phantom. For both materials we performed standard material and formability testing. Formability investigations were performed with the modified Nakajima test applying a computer controlled universal sheet formability-testing machine equipped with an optical strain measurement system, which records the distortion of the grid; a 2×2 mm square grid is printed on the blank sheet before the tests. The system has 4 CCD cameras to obtain the 3D point cloud from the mesh. From the measurements, the Vialux-AutoGrid software is used to determine the grid deformation and to calculate the strain distribution along the curved surface. With these data, the FLC and FLD can be determined. In these investigations we followed mainly the ISO 12004-2 instructions, to obtain the Forming Limit Diagrams of tested aluminum sheets. The results of these experiments were summarized in journals [3] and conference papers [4].

3. Numerical modelling and simulation of vehicle components

The increasing complexity of automotive parts, as well as the continuous extension of the process window made necessary to develop new innovative forming processes. Among these processes, hot forming utilizing the advantageous effect of higher temperatures on the improvement of formability should be mentioned: even in certain fields hot forming processes become unavoidable. Considering for example the production of B-pillar with hot forming made of high strength boron-alloyed Manganese steel material (like 22MnB5) become part of everyday industrial practice. This process is usually referred as Hot Forming (HSF) or Press Hardening of Steels (PHS) [5]. This principle soon become potential research target for companies and research institutes applying high strength aluminum alloys, first of all due to the lower formability of aluminum alloys at room temperature. Obviously, aluminum alloys require different approach compared to steels due to not only the lower formability but the microstructural differences, too.

Among many research initiatives, the LoCoLite project financed by the European Union is one of the most outstanding ones leading to significant results concerning the application of aluminum alloys in car manufacturing [6]. The Hot Forming and Quenching (HFQ®) process patented by the Imperial College London (ICL) and the Impression Technologies (ITL) may be regarded as one of the main results of LoCoLite project. However, this innovative new process may only be competitive if it can offer production time cycle comparable to PHS of high strength steels. To elaborate low cost,
economic alternative of HFQ process is the main target in the new European project, LoCoMaTech started in September 2016 [7]. To achieve this goal, the numerical modelling of HFQ processes has also a decisive role. In the next subsection, we will overlook the potential numerical simulation programs capable to handle this problem.

3.1. General purpose commercial packages vs dedicated sheet metal forming simulation programs

In sheet metal forming, there are two main directions considering the numerical simulation of sheet metal forming processes. Application of general purpose FEM codes (like ABAQUS, MARC, LSDYNA, etc.) may be regarded as one of the possible routes in sheet metal forming simulation. Application of dedicated software packages developed particularly for sheet metal forming is considered as the second main route. The two most widely applied dedicated FEM packages in sheet metal forming are PAM-STAMP (product of ESI Group, France) and AutoForm (product of AutoForm Company, with its headquarter in Zürich, Switzerland). Both possibilities (i.e. general or dedicated FEM codes) have certain advantages and disadvantages. The flexibility to tailor to the needs of users may be regarded as the highest advantage of using general purpose FEM systems. However, using these systems requires a thorough knowledge in continuum mechanics and FE programming to develop a suitable FEM analysis for a technological process analyses.

On the other hand, dedicated sheet metal forming modelling software are well suited to the specialties of sheet metal forming processes, but these systems usually have less flexibility for particular programming. However, if we consider that industrial mass production is the main target field in the LoCoMaTech project we have to also consider that simulation packages fitted to the technological processes are more beneficial from this point of view. However, these systems originally were mainly developed for cold sheet metal forming processes and this project aims to simulate first of all hot forming of aluminum, this issue requires further considerations.

There were many publications in the recent years dealing with the numerical simulation of forming aluminum alloys. Most of these researches used general purpose FEM packages. Some authors preferred using ABAQUS [8], [9], while others (mainly overseas authors) performed a lot of simulation work using LS-DYNA [10]. As it was mentioned earlier, these systems can be programmed relatively easily; in these systems various realistic constitutive equations and damage modelling can be used. In the recent years, significant new developments were achieved in the description of material models of aluminum alloys [11], [12], and as a result of these developments good correlation were found between the real physical behavior and the results of numerical modelling. This is the reason that in this context the advantages of these systems are indisputable compared to dedicated packages.

However, new technological developments sooner or later will be introduced in the industrial practice. A practicing engineer should design and produce real industrial parts. The realization of new components starts with the technological process planning which today is strongly supported by computer engineering methods. The primary interest of a practicing engineer to produce components and products fulfilling the functional and quality requirements: to fulfil these requirements engineers in the practice require dedicated software packages: the knowledge of mathematical and numerical background is necessary only to that depth which is absolutely necessary for the process and tool design. As it was mentioned before, there are many dedicated software packages developed for sheet metal forming, and among them the two leading ones are the PAM-STAMP and the AutoForm. (We have to mention a third one, DynaForm, which is not a real competitor of the two above mentioned software, both concerning its performance and the industrial spreading: this last one is mostly applied in overseas areas.)

Material models built into these dedicated software packages obviously and necessarily have certain possibilities for the interaction of the user, too. The program developers follow the needs of users and continuously further develop them according to the new challenges, however they still have limited possibilities for users’ interactions. However, a significant advantage of these systems is that they are much more user friendly, and they logical structure is closely follow the technological process planning and die design process throughout the entire process chain starting from the product development up to the try-out and production phase as shown in Figure 1.
Figure 1. Software solution along the entire process chain in the AutoForm package.

3.2. Sheet metal forming simulation in the LoCoMaTech project
The sheet metal forming modelling planned in the LoCoMaTech project covers the HFQ® forming process modelling. The continuum models used include fundamental constitutive equations and material relations. For the Tool Life model, interactive friction models will be used correlating friction and wear as a response from a tribo-system; thus the life span of metal forming tools under multi-cycle loading conditions can be predicted.

These models will be developed further according to ICL’s previous knowledge. The core FE simulation is conducted using dedicated FE codes, e.g. PAM-STAMP since the ESI Group, France as a member of the research consortium has already participated in former research projects applying virtual analyses of HFQ® processes [6]. The University of Miskolc, as also a member of research consortium has significant background in sheet metal forming modelling and is using for this purpose first of all the AutoForm package. Therefore we decided to perform the validation of numerical modelling of HFQ® processes using the AutoForm program which is a worldwide applied sheet metal forming simulation package particularly in the automotive industry. Since in the LoCoMaTech project the numerical simulation and validation of experimental results is one of the main tasks of the University of Miskolc, therefore in the following sections we will focus mainly on this topic.

3.3. Simulation tasks in the project
According to the project plan some vehicle components will be selected for proving experimentally the suitability of aluminum alloys for processing economically with Hot Forming and Quenching (HFQ) process even in mass production. For this purpose, some structural body elements will be first selected (e.g. B-Pillar, Door inner and Door ring, etc.) Manufacturing of car body elements designed originally from high strength steels requires the redesign of these parts to be able for HFQ processing applying high strength aluminum alloys instead of steel materials. Besides redesigning the geometry, certain technological process parameters and die design principles should also be changed. This redesign is the task of Centro Ricerche Fiat SCPA. Since the decision on which parts will be investigated and what kind of redesign is needed will follow in the subsequent months, we decided to perform some preliminary analyses of hot forming of aluminum alloys through a unique test already done in general purpose FEM system (ABAQUS). It will provide a good chance to make comparisons between results obtained in general purpose and in dedicated programs, and to prove the suitability of the AutoForm package for numerical analysis of HFQ processes. The test for comparison is the well-known Hole Expansion Test made with ABAQUS [9] applying the target material AA6082 which is one of the most widely applied high strength aluminum alloys in car body manufacturing. For this comparison first it is necessary to investigate what possibilities are available in the AutoForm program to introduce and modify material parameters. This question is clearly demonstrated at the NumiSheet 2016 benchmark test where the springback behavior of aluminum alloys were investigated and compared applying various simulation packages [13].

3.4. Material models in the AutoForm program
The material model in the AutoForm program is based on an elastic-kinematic hardening anisotropic material model. In sheet metal forming the limits of formability is usually defined by the Forming Limit Diagrams (FLD). For the unambiguous description of the formability behavior of a given material we have to define four groups of material parameters. In hot forming, the material properties
and relationships should be known as a function of temperature, as well. The fundamental physical parameters that are required to define a suitable material model are summarized in Table 1.

| Basic Properties | Thermal Properties |
|------------------|--------------------|
| Young’s modulus (MPa) | Volumetric Heat Capacity (mJ/mm$^3$K) |
| Poisson’s ratio (−) | Conductivity (W/mK) |
| Specific Weight (N/mm$^3$) | Thermal expansion 1/K |

| | $7.1 \times 10^4$ | $2.42$ |
| | $0.31$ | $220$ |
| | $2.6 \times 10^{-5}$ | $2.2 \times 10^{-5}$ |

For the description of material behavior in hot forming conditions besides the temperature dependence of basic physical properties we have to know the material relationships between the stress and strain components (usually given by the hardening rule), the yield surface and the Forming Limit Curves (FLC). For all these rules and properties besides the temperature dependence we also have to consider the effect of the anisotropy. In the following, these fundamental relationships will be analyzed.

### 3.4.1. Hardening rule

From the point of view of mechanical behaviour the stress-strain relationships are of utmost importance. In sheet metal forming – particularly in cold forming – linearly elastic-non-linear hardening rules are widely applied. These relationships – known as Flow curves – can be described by well-known mathematical expressions. The AutoForm program also contains different relationships to take into account the stress-strain relationships.

A general problem of the determination of flow curves that they may be easily determined by simple material testing methods (e.g. uniaxial tensile test) and using simple expressions only in a very limited range, i.e. in the uniform elongations part ($\varepsilon \approx 0.2$). When necking starts the formerly uniaxial stress state becomes multi-axial, and the flow curves can be determined using more complicated expressions. There are several techniques to extend the flow curves to larger values of strains with reasonable accuracy. In the material module of AutoForm for this approximation the combined Hockett-Sherby expression is used for extending the strain range up to $\varepsilon_{\text{max}} = 1$. This function may be described by the following expression:

$$
\sigma = (1-\alpha) \left( C (\varepsilon_p + \varepsilon_0)^n \right) + \alpha \left( \sigma_{\text{Sat}} - \left( \sigma_{\text{Sat}} - \sigma_i \right) e^{-\frac{\varepsilon}{\varepsilon_0}} \right) e^{-\frac{\varepsilon}{\varepsilon_0}}.
$$

In Figure 2, it is illustrated how the AutoForm Material Editor extrapolates the points of flow curve determined experimentally for a limited range of strains for the plastic strain range required for modelling up to $\varepsilon_{\text{max}} = 1$ mm/mm. The flow curve shown in Figure 2 relates for $T=450^\circ\text{C}$ and $\dot{\varepsilon} = 1 \text{ s}^{-1}$ [8], [9].

Modelling of hot forming processes is more complicated from the point of view of flow curves, since in this case, the visco-plastic properties should also be considered. Therefore, the dependence of flow curves on the temperature and strain rate should be taken into account which requires the flow curves determination at different temperatures and strain rates. These multiplied flow curves should be input simultaneously. Obviously, before determining the flow curves at different temperatures and strain rates, we have to define what temperature and strain rate intervals are relevant for the given hot forming process and thus during the numerical simulation. In Figure 3 flow curves of AA6082 are shown for $T = 300, 450$ and $500^\circ\text{C}$ at $\dot{\varepsilon} = 1 \text{ s}^{-1}$ strain rate.
Figure 2. Flow curve extension with the combined Swift-Hockett-Sherby approximation (T=450°C and \( \dot{\varepsilon} = 1 \text{ s}^{-1} \)).

Figure 3. Flow curves at different temperatures (T = 300, 450 and 500°C) at \( \dot{\varepsilon} = 1 \text{ s}^{-1} \) strain rate.

Since in this paper, we will analyze a simple physical experiment, therefore, applying the same punch displacement velocity within the strain range applied in the process, practically there is no noticeable difference in the strain rates which would have meaningful effect on the flow curves. Therefore, the flow curves shown in Figure 3 are determined with the same value of strain rate (\( \dot{\varepsilon} = 1 \text{ s}^{-1} \)). The temperature range in the experiments and numerical validation will be between T = 300±500°C; this is the reason that flow curves given for these values [9]. In Table 2, the material constants determined by the combined Swift Hockett-Sherby function are summarized for \( \dot{\varepsilon} = 1 \text{ s}^{-1} \) constant strain rate.

Table 2. The material constants of Swift Hockett-Sheryby expression for different temperatures

| Temp.   | \( \varepsilon_0 \) | m | C (MPa) | \( \sigma_i \) (MPa) | \( \sigma_{sat} \) (MPa) | a | p | \( \alpha \) |
|---------|---------------------|---|---------|---------------------|--------------------------|---|---|---------|
| T=300°C | 0.0037              | 0.12 | 117.1 | 58                 | 320.5                   | 0.265 | 0.33 |
| T=450°C | 0.0085              | 0.0567 | 58.8  | 45                 | 56.9                    | 5.82  | 0.81 | 0.75   |
| T=500°C | 0.0107              | 0.0494 | 60.8  | 48                 | 58.8                    | 4.38  | 0.74 |

3.4.2. Yield Surface

In the AutoForm program, as default, the Hill‘90 model [14] is applied for the description of the yield surface for anisotropic materials. The deficiency of Hill classic model was already discussed in several papers [15], [16], and during the last decades, new theories were published better describing the anisotropic behaviour of sheet materials: here we just mention the Barlat’89 model [15] developed for aluminum and the BBC2005 model elaborated for steels by Banabic [17]. These two latter ones (i.e. the Barlat’89 models and the BBC2005) are also built-in the AutoForm program for describing the yield surface. In hot forming simulation describing the yield surface the temperature dependence of anisotropy coefficients has to be taken into consideration, as well. The applied values of anisotropy coefficients in the function of temperature are shown in Table 3.
Table 3. Temperature dependence of anisotropy coefficients

| Temperature (°C) | $r_0$     | $r_{45}$   | $r_{90}$   | $r_{b}$  |
|------------------|-----------|------------|------------|----------|
| T=450°C          | 0.710     | 1.080      | 0.730      | 0.937    |
| T=500°C          | 0.630     | 0.970      | 0.660      | 0.893    |
| T=525°C          | 0.600     | 0.880      | 0.670      | 0.763    |

The yield surfaces determined by these anisotropy coefficients are shown in Figure 4 for T=450°C, T=500°C and T=525°C temperatures. Note that in the investigated temperature range, the changes of the yield surface may be neglected compared to the stress values.

3.4.3. Forming Limit Curves
The limits of formability can be regarded as one of the most important input parameters in any forming simulation. These formability limits in the AutoForm are given by the Forming Limit Curves defined with the FLDs in the temperature and strain rate range that are characteristic for the investigated materials and processes. Concentration of points of strains may provide valuable information for process designers about the critical points of the process. In dedicated FEM packages, the feasibility of the forming process can be well illustrated by these clouds of points at different strain paths.

In hot forming simulation, where the temperature of sheet and even the strain rate can change from point to point, the Forming Limit Curve determined for a fixed temperature and strain rate may be used with acceptable accuracy in a limited range of parameters. This shortcoming may be regarded as one of the main problems in dedicated FEM packages. Software developers put the largest effort to solve this problem. It might be the reason that there are intensive research works in this field which are rather based on the application of various damage accumulation theories instead of the investigation of local necking [11], [12].

In the AutoForm, the user can take into account the temperature dependence of Forming Limit Curves to determine the formability limits. It is possible to define FLC curves for arbitrary...
temperatures and to input several FLC curves covering the whole temperature range of the given simulation. Applying the Material Generator we created the material files for the AA6082 material on the basis of AA5754_demo_material file created for the Numisheet 2016 Benchmark-3 [13].

3.5. Numerical modelling of Hole Expansion Test in hot forming conditions
To validate the suitability of AutoForm for hot forming simulation of aluminium alloys we decided to perform the Hole Expansion Test done by Lin and his co-workers and presented at the 11th ICTP Conference in Nagoya in 2014 [9].

The experimental and numerical investigation was performed in a tool setup with the following parameters: a hemispherical punch with $D = \phi 80$ mm diameter, and the die had a radius $R = 5$ mm. Square samples of AA6082 with the dimensions of 170×170×2 mm were used. In the middle of the blank a hole was made with predefined spacing intervals, and the specimen was formed at different temperatures applying the tool geometry shown in Figure 6. Before the test, the blank was heated up to $T = 470^\circ$C, and then transferred to the cold tool which is after positioning was closed with a closing speed $v_{die} = 0.166$ m/s. The blank is strongly gripped with the lock beads between the die and the binder, and after the tool closing, the heated sheet blank is formed. The applied binder force was selected to maintain the biaxial stress state until the end of the forming process.

In this study, a series of FE models were run with different diameter ratios ($\gamma = d/D$), where $d$ is the sample central hole diameter and $D$ is the punch diameter: $\gamma$ was kept within the range of 0 to 0.25. The simulation results were drawn in a diagram with the $\gamma = d/D$ diameter ratio on the horizontal axis and the punch displacement on the vertical axis measured from the first contact point of the punch and the blank until the appearance of fracture.

The thermo-physical properties concerning the heat removal and heat conductivity on the tool surfaces were set to the default values proposed by the AutoForm for general tool steels. The value of friction coefficient at the beginning was set to $\mu = 0.4$ (default for hot forming in AutoForm) but we also investigated the effect of changing the friction coefficient in a range $\mu = 0.1\ldots0.4$, however no meaningful differences were found. Concerning the simulation results, we were focusing to predict the appearance of failure on the basis of forming limit diagram.
3.6. Determination of the limit formability

We could see that the material module can handle different Forming Limit Curves at different temperatures. In cold sheet metal forming, the Forming Limit Curves can be applied easily to define the limit strain values at any point. However, in hot forming, the temperature may change from point to point (see in Figure 7) which means that different Forming Limit Curves should be applied theoretically from point to point, too, which is obviously impossible, and what is even more important, it is not necessary. The position of the individual points in the FLD characterizing the strain state is rather a function of flow curves and the yield surfaces: the FLC practically just a reference limit for the evaluation. Therefore, for the determination of the formability limits we can use the following procedure in hot forming. We can identify the highest points of strains for different $\gamma$ diameter ratios. The value of the temperature at this point follows from the simulation and we can apply the corresponding FLC as the limit curve accordingly. This is shown in Figure 8, where for the given state, the FLC determined at $T=400^\circ C$ applied as the limit boundary curve. Obviously, Forming Limit Curves are not available for any possible temperature. However, if we have FLC with reasonable temperature steps (in this case for example from $T=350^\circ C$ to $500^\circ C$ with a temperature step $50^\circ C$, the AutoForm is capable to approximate FLC for the required intermediate temperatures).

![Figure 7](image1.jpg) ![Figure 8](image2.jpg)

**Figure 7.** Temperature distribution for $\gamma = 0.0$ diameter ratio along the meridian section of test specimen in the state of limit deformation.

**Figure 8.** Points of strain values in the hole expansion test in the forming limit diagram. The Forming Limit Curve corresponds to the limit curve at $T = 400^\circ C$.

In Figure 7 it can be also seen that the difference in the temperature values is relatively small ($\Delta T < 20^\circ C$ for the given diameter ratio $\gamma = 0.0$) thus the supposition applied above is quite acceptable.

4. Results and Discussion

The comparison of the results obtained by a general purpose FEM system (ABAQUS) in the reference paper [9] and that of with a dedicated FEM program (AutoForm) is shown in Figure 9. The character of the two curves is very similar. The minimum and maximum punch displacements are within a 10 mm range for both curves. Similarly, there is good agreement concerning the position of maximum damage. For the diameter ratio in the range $\gamma = 0.0 \div 0.18$ the failure occurs on the surface of the dome, while in the range $\gamma = 0.20 \div 0.25$ the test mode is changed into a central hole failure. Above this ratio, the punch goes through the sample hole without tearing the sample.

It can be also observed in Figure 9 that there is a 15 to 20 mm offset between the two curves. It may be reasoned as follows: during the simulation, in the AutoForm program, the thermo-physical
properties that are significantly influencing the temperature distribution were set to the default values proposed by the program but we do not have any information about the values of these parameters used in the reference simulation. It may be one of the main reasons causing differences in the actual values of two different simulations.

![Figure 9](image)

**Figure 9.** Comparing the formability limits obtained by ABAQUS and AutoForm codes for AA6082 Al-alloys (forming rate 0.166 m/s with the different diameter ratios at temperature T = 470°C)

5. Conclusions

In this paper, first we shortly summarized the preliminary results achieved at the University of Miskolc in lightweight production of body elements made of high strength steels and aluminum alloys.

Then a comparative study was performed for hot forming of AA6082 aluminum alloy applying a general purpose FEM system (ABAQUS) and a dedicated FEM package (AutoForm) developed particularly for sheet metal forming analyses. For this comparison the experimental and numerical simulation of a hole expansion test was applied.

Three different test outcomes (Circumference failure, Central hole failure and Punch goes through the sample without tearing) were get depending on the ratio of central hole diameter over the punch diameter (d/D). In both simulation cases, there was a good agreement predicting the failure mode.

There is a slight difference in the curves illustrating the punch displacement in the function of the diameter ratios though the character of the two curves is very similar. This difference can be reasoned first of all with the differences in the values of thermo-physical properties (e.g. heat removal and heat conductivity) applied in the two different FEM systems.
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