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# Numerical analysis of thermo-mechanical behavior in flow forming

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## Abstract

Flow forming is a metal forming process for cylindrical workpieces where high velocity deformation leads to radial thinning and axial extension. In the current study, a thermomechanical, dynamic and explicit finite element model of a flow forming process is developed on ABAQUS software. The model is validated through the comparison of reaction forces and geometry obtained from the experiments. Coolant convection effect is analyzed in conjunction with roller and mandrel conduction cooling to study the thermal variations in the deformation zone during the process. The methodology detailed in this study facilitates a deeper understanding of the evolution of heat during the flow forming process and lays the groundwork for further exploration into the possible role of a material's thermal properties in the definition of flow formability.

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*Keywords:* flow forming; finite element method; thermo-mechanical modeling; incremental forming

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## 1. Introduction

Flow forming is an incremental cold forming process used to produce cylindrical or conical parts such as aircraft engine components, wheel rims, or gun barrels. Through the axial motion of rollers, a rotating, axially symmetric workpiece undergoes radial reduction, leading to axial growth as well as a significant enhancement in mechanical properties due to plastic deformation induced strain hardening. Due to the localized nature of the deformation, the loading forces and consequently power consumption remain low (see e.g. Plewiński and Drenger (2009)). Furthermore, there is no material waste and no need for further machining due to the superior surface finish achieved by the process.

Experimental studies on flow forming have explored the relation between process parameters and the final product (see e.g. Razani et al. (2011); Srinivasulu et al. (2012); Razani et al. (2014)), the effects of prior heat treatment (see e.g. Davidson et al. (2008)) and aging (see e.g. Karakaş et al. (2021)) on formability. With the advancement of technology, numerical methods have become a viable tool to study the process. The finite element method (FEM) has been used

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to study deformation mechanisms (see e.g. Roy et al. (2009); Mohebbi and Akbarzadeh (2010); Bylya et al. (2018)), stress and strain evolution (see e.g. Xu et al. (2001); Wong et al. (2004); Parsa et al. (2009); Notargiacomo et al. (2009)) and the prevalence of diametral growth defect (see e.g. Aghchai et al. (2012); Song et al. (2014)).

It is important to study whether the temperature of the part exceeds cold forming limit at any point during the process, which can lead to thermal softening. The temperature should be substantially below the recrystallisation temperature. Since flow forming is a cold forming process, the temperature of the product is often low. Despite this, the localized nature of flow forming can result in high temperature values in the contact area during forming, leading to a significant decrease in flow stress and thermal softening (see e.g. Singh et al. (2018)). To capture this effect, thermo-mechanical models have been used to create a design of experiments (see e.g. Nahrekhalaji et al. (2010)) and it has been observed that thermal softening leads to a significant decrease in roller reaction forces, particularly in radial direction (see e.g. Shinde et al. (2016)). However, there is still a lack of understanding on the mechanism behind the heat generation and the influence of the process parameters.

The core purpose of this work is to understand the evolution of heat during the flow forming process. This is done by studying the evolution of temperature in the deformation zone in the presence of coolant. The procedure involves numerical analysis via a thermo-mechanical model to capture the variations in temperature during the flow forming process. This is done with a dynamic explicit model that takes convection cooling effects and cooling due to conduction through the rollers and mandrel into account. The thermal models are not fully coupled. There is a one-way relationship between thermal and mechanical effects, where the mechanical aspects induce thermal evolution without being influenced by them. This assumption reduces computational time and it is valid for the aim of this work.

The paper is organized in the following way. First, model details are explained in Section 2. Afterwards, in Section 3, steps taken to verify the model are shown. Furthermore, in Section 4.1, supplemental adiabatic models with isolated heat generation from deformation and friction were used to study their contributions to the heating. Finally, in Section 4.2, axial and radial feed rates were varied to observe their influence on the deformation zone temperature.

## 2. Finite Element Model Definition

In this section, the finite element modeling approach is addressed and the details of different model cases are presented. Afterwards, the assumptions used during the modeling are discussed and justified.

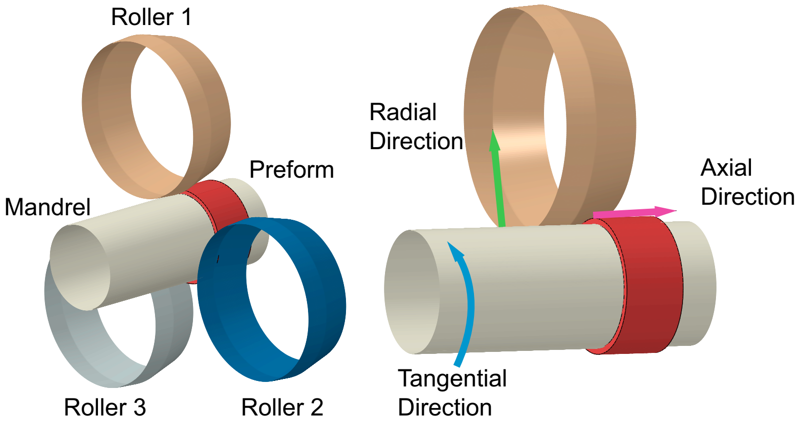
### 2.1. List of models

Before considering the thermo-mechanical model, a mechanical model is created initially. Since the solution time of a purely mechanical model is shorter than a thermo-mechanical model, the model verification and optimization procedures are conducted on the mechanical model. After verifying the mechanical model, the individual effects of friction and deformation on heating of the workpiece are examined separately under adiabatic conditions in two different thermo-mechanical models. Finally, a model that considers both heating effects and the influence of coolant is developed, resulting in total four model cases:

- Purely mechanical model
- Adiabatic thermo-mechanical model with only deformation heating
- Adiabatic thermo-mechanical model with only friction heating
- Coolant applied thermo-mechanical model with roller and mandrel conduction

### 2.2. Model assumptions

The finite element model for 3-roller staggered backward flow forming process developed in ABAQUS is shown in Fig. 1a. The initial thickness of the preform is 6 mm, and it will experience approximately 70 % thickness reduction. The model consists of rollers located around the mandrel with 120°angle between each other. Directions in the cylindrical coordinate system are shown in Fig. 1b. The motion in the model, unlike that in a real life flow forming process, occurs through the rotation and translation of the rollers around and along the mandrel, i.e. the tangential direction. So, instead of rotating the preform, it is kept stationary while the rollers rotate around it. This does not



(a) model components (b) model directions

Fig. 1: Visualization of the finite element model

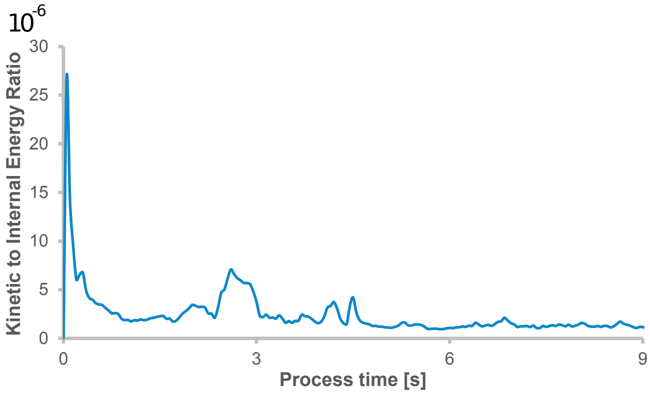


Fig. 2: Ratio of kinetic to internal energy of preform in FEM

change the mechanism of deformation, since the contact history between rollers and the preform still follows the same helix shaped path over time due to combined rotation and translation. The advantage of this approach, suggested by Wong et al. (2004), is that it allows the control the volume of preform that would otherwise change due to the large amounts of rotation in a geometrically nonlinear problem, while also greatly reducing the computation time.

The plasticity model used in this study is the classical Von Mises ($J_2$) plasticity with isotropic hardening. Stress versus strain data of AISI5140 is extracted from a uniaxial tensile test. The preform mesh consists of approximately 200,000 C3D8TR (8-node thermally coupled brick, trilinear displacement and temperature with reduced integration) elements. Reduced integration is preferred to avoid shear locking problem encountered with linear elements and to reduce computation times. However, since reduced integration elements show hourglass phenomenon, enhanced hourglass control is applied. A mesh convergence study has been conducted to achieve optimal mesh size. Since the deformation of the mandrel or the rollers is assumed to be insignificant, they are modeled to be rigid bodies that do not undergo deformation. Their simple geometries allowed them to be defined as analytical rigid bodies. This way, they would not require mesh, and computational time would be reduced further.

Since the explicit solvers are conditionally stable, they require extremely small time increments, which are defined based on the minimum length and the wave speed of the elements. By using mass scaling, the density of the material can be artificially increased so that larger stable time increments are achieved. However, mass scaling can directly influence the results, by increasing the kinetic energy of the material that is being deformed. To obtain a quasi-static response, it's important to keep the ratio of kinetic energy to internal energy acceptably low. 0.001 is considered as

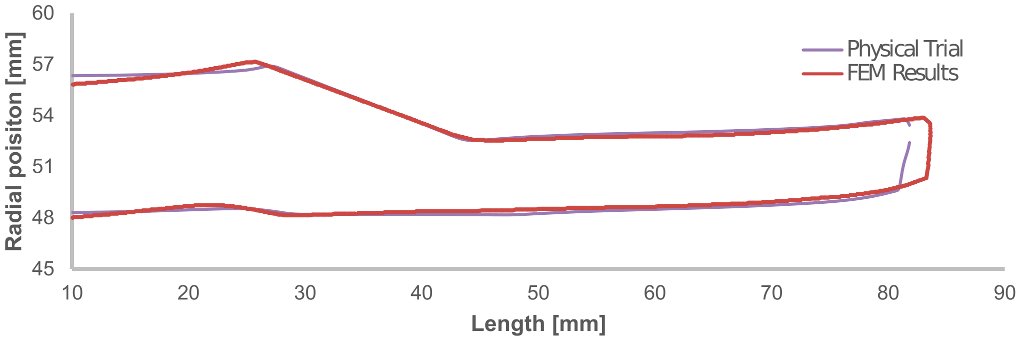


Fig. 3: Comparison of experimental and simulation cross section geometries

an acceptable ratio. Fig. 2 shows the ratio of kinetic energy to internal energy from simulation results, which suggests that quasi-static equilibrium is being conserved after mass scaling.

Surface to surface contact is used between all contacting surfaces. Additionally, frictional effects are included in the model, with a coefficient of approximately 0.1. However, if the rollers are fixed around their own axis, this friction will shear the preform immensely. To model the free rotation of rollers around their central axes, connector elements are used.

In the thermal models, heat is generated through friction and/or deformation, depending on the model. 90% of the deformation energy is dissipated as heat, and 100% of the friction energy is dissipated as heat but only 50% of this friction heat energy goes to the preform. The effect of coolant is implemented all over the preform surface as a heat sink with a convection coefficient of approximately $5000\mathrm{W/m^2K}$. Additionally, the rollers and the mandrel are also assumed to be heat sinks with a conduction coefficient of approximately $20000\mathrm{W/m^2K}$.

## 3. Finite Element Model Verification

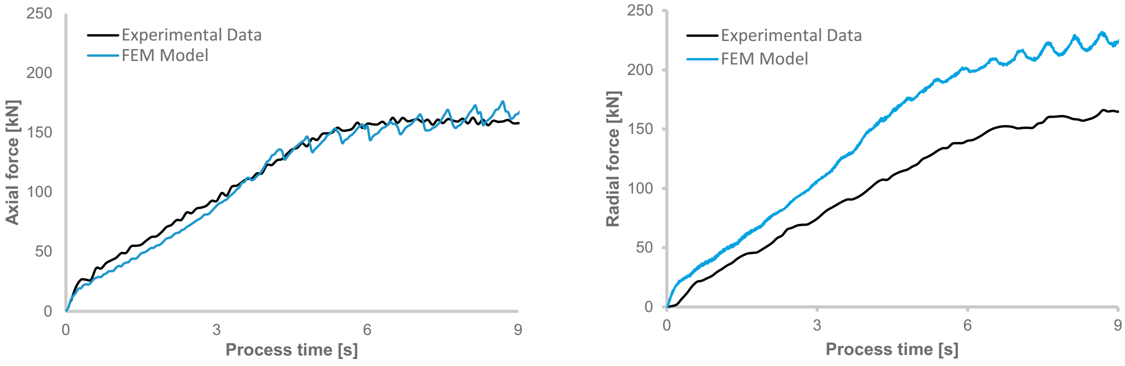
Verification of the finite element model is carried out in two subsections, i.e. by comparing geometries obtained from experiments, and then by comparing reaction forces acting on the rollers with force data obtained from experiments.

### *3.1. Comparison of geometries*

To validate the mechanical aspects of the model, simulation results are compared with the experimental ones. Fig. 3 shows the cross sectional profile of a flow formed cylindrical tube compared with finite element simulation results. Thus, despite previously mentioned inaccuracies caused by explicit solutions (see e.g. Song et al. (2014)), the results here show that the solution geometry is accurate. Measurement of cross sectional areas show a 2.3% error in FEM results. The difference in axial length at the tip could possibly be explained by the lack of an unloading step in the FEM analysis.

### *3.2. Comparison of roller reaction forces*

Fig. 4a shows the comparison of sum of reaction forces acting on all 3 rollers in axial direction measured from experiments with the simulation results which are in good agreement. Similarly, Fig. 4b shows the same comparison for radial forces in a single roller system. Since the rollers are being rotated around the mandrel at extremely high speeds, the centrifugal forces dominate the reaction force output in the simulations. Accordingly, centrifugal loads have been subtracted to obtain a correct estimate of the reaction. The radial forces are slightly overestimated, which could be related to several different factors, such as lack of softening effects caused by localized heating, or the plasticity model used in simulations.



(a) axial direction (b) radial direction

Fig. 4: Comparison of reaction forces on the rollers from experiments and FEM simulations

## 4. Results and Discussion

The effect of friction and deformation heating on the workpiece is studied initially under adiabatic conditions. Then, the influence of roller axial and tangential speed on the temperature is examined in a non-adiabatic, coolant applied model. The aim here is to have a model as close to real case as possible. Measuring temperature rise during the process would be a challenging task. Therefore, with a well defined model, the temperature distribution can be analyzed.

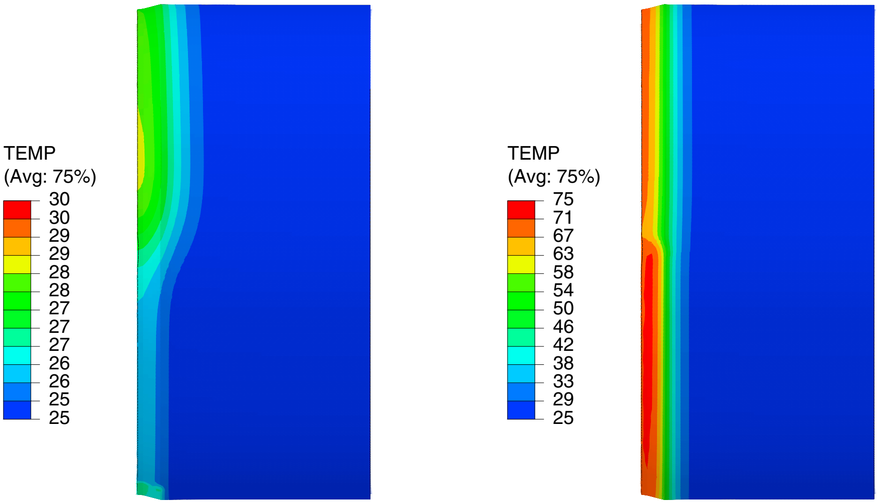
### 4.1. Comparison of friction heating and deformation heating

Fig. 5 shows the individual effects of deformation and friction heating represented in Fig. 5a and Fig. 5b respectively in 3 seconds of the process obtained from FEM simulations. Fig. 5c illustrate the comparison of contributions to the total internal heat energy of the preform. The results show that deformation contributes significantly more to temperature increase in the workpiece than friction.

One the reasons for deformation heating to be much larger is related to effect of redundant strains, which has been addressed previously in the literature (see e.g. Mohebbi and Akbarzadeh (2010)). The deformation area is larger than the contact area due to the pile-up, causing parts of material outside of the roller's contact zone to deform, which generates additional heat in a larger region. Moreover, the redundant strains observed on the workpiece that do not contribute to the final shape of the geometry cause unwanted heating. This effect can be observed in both radial and tangential directions and is shown in Fig. 6. Fig. 6a illustrates the geometry of an element in the model right before it comes in contact with a roller. The highlighted element undergoes shear strains in opposite directions over time. Fig. 6b presents its bottom edge deforming due to roller. Fig. 6c shows its top edge deforming due to roller again, where arrows indicate the direction of strain. Fig. 6d shows the amount of tangential strain over time. Clearly, there's a large amount of redundant strain in the intermediate steps that do not contribute to the final geometry. These redundant strains are a result of redundant work, which is converted to heat through deformation.

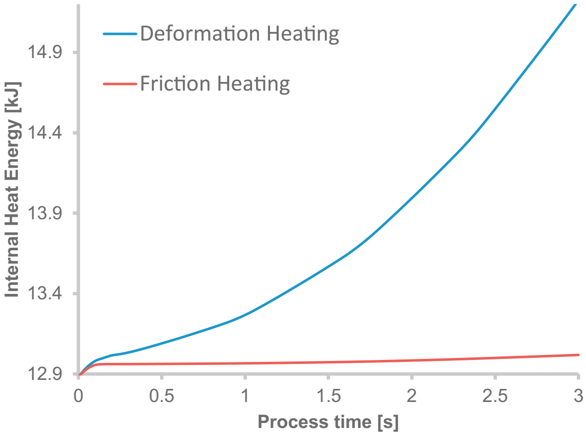
### 4.2. Effect of process parameters on temperature

In this subsection, the influence of rollers' axial and tangential speed on the rise of temperature is examined. It is important to note the diametric growth phenomenon here which is a type of defect observed commonly in flow forming process. The procedure results in an increase of final diameter of the workpiece due to the residual stresses in axial and tangential directions. To reduce diametric growth, increased axial feed rate and reduced tangential feed rates are necessary. However, changing these feed rates will have an influence on the temperature of the work-piece which could have softening effects that would go unnoticed in a purely mechanical simulation. If the temperature increase is too much, the material may not be formable anymore. This could be seen in materials with low specific heat or low



(a) deformation heating

(b) friction heating

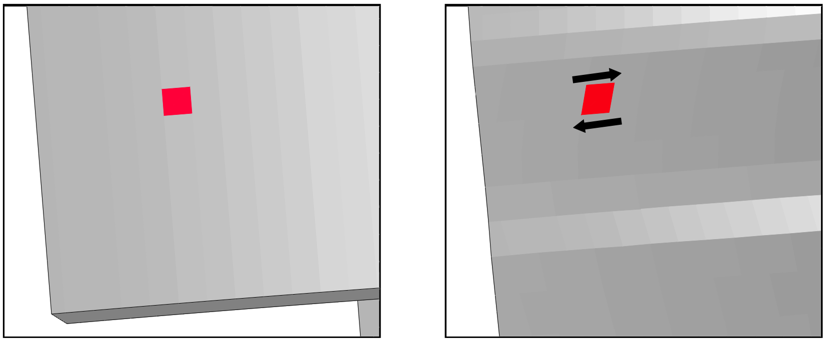


(c) comparison of internal heat energy

Fig. 5: Thermal analysis results for two types of heat generation

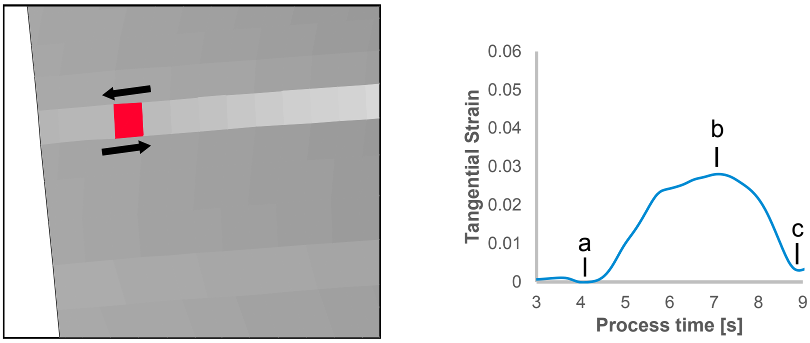
conductance. In such cases, temperature increase may become too quick and the heat would become trapped in the material.

Fig. 7 shows the temperature distributions, obtained from three different flow forming FE simulations after rollers have moved 13.75mm. The important observations are presented in Table 1. The difference between the cases are the axial and tangential speeds of the rollers. Interestingly, lower heating is observed when roller RPM is increased. Strain analysis reveals that the preform experiences slightly less strain under faster rotating rollers. It was previously shown that frictional heating constitutes a small portion of total heat generation. Therefore, even though there is more frictional heat generated with larger roller RPM around the mandrel, the fact that there is slightly less deformation reduces overall generated heat. This is not beneficial, since increased roller rotational speed is often not desired due to its contribution to diametric growth. More importantly, increasing the axial speed of rollers has a significant effect on temperature rise. A 50% increase in velocity resulted in approximately 25% more total heat energy generated in the simulations. Fig. 8 shows the temperature on an element close to the edge in this case. Here, it can be seen that temperature can reach up to 400 °C before starting to decrease, even if it is for a few seconds, much higher than what is seen in the other cases. This suggests that changing the axial speed of rollers plays an important role on thermo-mechanical characteristics, likely to bring softening effects on certain materials. Additionally, even at lower axial feed



(a) right before roller contact

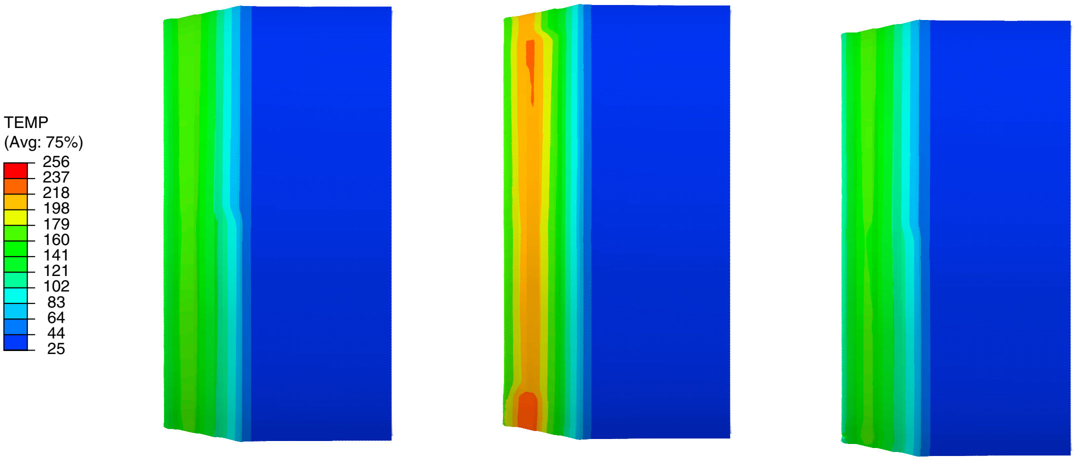
(b) after initial roller contact



(c) after full roller contact

(d) element’s tangential strain versus time

Fig. 6: Evolution of redundant strains on an element



(a) case 1 with default speeds

(b) case 2 with increased axial speed

(c) case 3 with increased tangential speed

Fig. 7: Workpice temperature distribution in FEM simulation after rollers moved 13.75 mm in axial direction

rates, temperatures up to 290 °C is observed. After that, temperature peaks and remains stabilized at that temperature around roller contact zones.

Table 1: Thermo-mechanical FEM analysis cases after rollers moved 13.75 mm in axial direction

| Case | Roller Axial Speed (*mm/s*) | Roller Tangential Speed (*RPM*) | Maximum Temperature (°*C*) | Increase in Heat Energy (*kJ*) |
|---|---|---|---|---|
| 1 | 1.375 | 300 | 191 | 15.157 |
| 2 | 2.0625 | 300 | 255 | 19.348 |
| 3 | 1.375 | 450 | 186 | 14.553 |

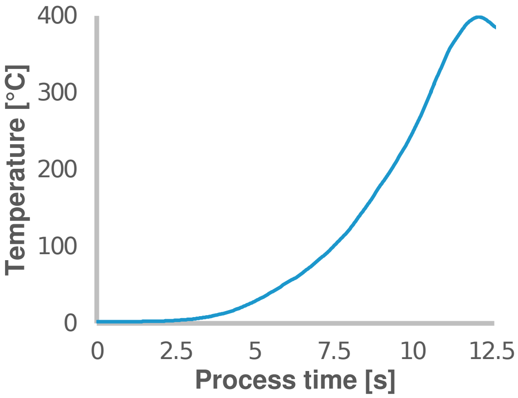


Fig. 8: Temperature versus time of an edge element in FEM analysis

## 5. Conclusion and Future Works

The thermo-mechanical analysis of flow forming process illustrates that the temperature response of the preform depends heavily on rollers' axial speed. A significant portion of the generated heat is caused by the deformation, and this is explained by the presence of large amounts of redundant strains in the process. High temperature values after around 10 seconds show that thermal softening effect cannot always be neglected even if flow forming is a cold forming process, especially on highly conductive materials. Since it is challenging to measure local temperature values during flow forming process, a suitable approach to validate thermal effects should be found. As a future work, a fully coupled thermo-mechanical model for FE simulation will be implemented and verified. Then, analytical methods to measure hardness in a cold forming process will be used for comparison with experimental results. Another important modeling aspect of the process is to address the failure mechanisms during the forming (see e.g. Vural et al. (2021) for an initial attempt in this special issue), which could be conducted through a proper ductile failure modeling framework (see e.g. Yalçinkaya et al. (2019)).

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