NUMERICAL ANALYSIS OF COOLING SYSTEM IN WARM METAL FORMING PROCESS

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Abstract

This paper presents the results of the numerical analysis of the formation process of a turbine engine deflector. In the finite element model we considered thermo-mechanical phenomena occurring during industrial forming of the drawpiece in the hydraulic press. In the simulation it was assumed that heat is transferred to the environment by convection and radiation. The aim of the simulation was to estimate the temperature of the blank after its transfer from the furnace to the press; to analyse the temperature distribution and sheet thinning after the warm forming process and estimation of the drawpiece temperature. It has be concluded that channel cooling reduces tool temperatures by about 60 °C in comparison with the forming tool used without the forced cooling. Furthermore, cooling of tools decisively determines the range of occurrence and the value of the maximum temperature of the forming die.

Keywords: Cooling channels, Impetus Afea, warm forming, stainless steel

1. INTRODUCTION

The aim of warm metal forming processes is to eliminate such defects associated with hot forming, such as intensive oxidation on product surfaces and low dimensional accuracy, while maintaining the smallest deformation resistance [1, 2]. Determination of the range of temperatures in hot and warm forming processes is made on the basis of the variation of yield stress as a function of temperature and taking into account the effect of strain rate and the expected level of material effort [3, 4]. Material forming can be performed at the same temperature as the tool and formed material, although usually the tool temperature is lower and thus influences the relationship between the tool material strength and the deformation resistance of formed material [1, 5, 6].

Changes in temperature during formation may adversely affect the quality of manufactured products (i.e. changes in dimensions, surface scratches due to changes in friction conditions or unfavourable internal structure) [7]. Therefore, it is important during the process to ensure proper conditions of heat flow to maintain relatively constant tool temperature; for example, by heating the tool before the start of the forming process and cooling during the stamping [8]. The highest temperature of the workpiece occurs in the first stage of stamping and then decreases due to heat loss to the environment by radiation and convection and by heat conduction into the tool [9, 10]. Investigations related to the design of the cooling channels of injection moulds, casting moulds and tools for warm and hot material formation are the topic of many research studies [e.g., 11, 12]. The elevated tool temperatures sometimes cause easy adhesion of lubricants to tool surfaces, particularly in hard to reach locations [11, 13].

In this paper a practical application of the Impetus Afea program for thermo-mechanical analysis using the finite element method (FEM) of stamping process for a turbine engine deflector made of AMS5604 stainless steel is presented.

2. MATERIAL AND METHODS

The experiments of warm sheet metal forming presented in this paper were performed using AMS5604 stainless steel with a sheet thickness of 1.35 mm. The chemical composition of the tested sheet (**Table 1**) is in agreement with standard ASTM A240 [14]. The mechanical parameters determined in the universal testing machine are (**Table 2**): yield stress R_e, ultimate strength R_m, relative elongation A_r and Young's modulus E. The stress-strain $\sigma(\varepsilon)$ relations were approximated by Hollomon's law, in the form of $\sigma = C\varepsilon^n$, to evaluate the strain hardening coefficient C and the strain hardening exponent n. The tensile tests were performed at temperatures of 20 °C (ambient temperature), 400 °C, 500 °C, 600 °C, 650 °C and 700 °C. The strips for tensile testing were cut at 0°, 45° and 90° according to the rolling direction (RD) of the sheet.

Table 1 Chemical composition of AMS5604 stainless steel sheet / mas. % [14]

C	Cr	Ni	Mn	Si	Mo	Nb
0.07	16,5	4.0	1.0	1.0	0.50	0.30

Table 2 Selected mechanical properties of AMS5604 stainless steel sheet

Temperature °C	R_e (MPa)	R_m (MPa)	A_r (-)	C (MPa)	n (-)	E (GPa)
20	904	1061	0.040	3436	0.373	206
400	642	815	0.044	2607	0.362	186
500	537	694	0.052	1346	0.306	183
600	324	464	0.029	714	0.178	158
650	276	361	0.040	578	0.149	146
700	173	224	0.118	309	0.134	148

3. NUMERICAL MODELING

The aim of the numerical research was to conduct numerical analyses, using an IMPETUS Afea simulation system, of thermo-mechanical phenomena occurring during warm forming of the deflector of the turbine engine. The scope of the numerical modelling included selected stages of the deflector formation (**Figure 1**): the transfer of the sheet from the furnace to the stamping tool (model A) and warm forming of the drawpiece (model B).

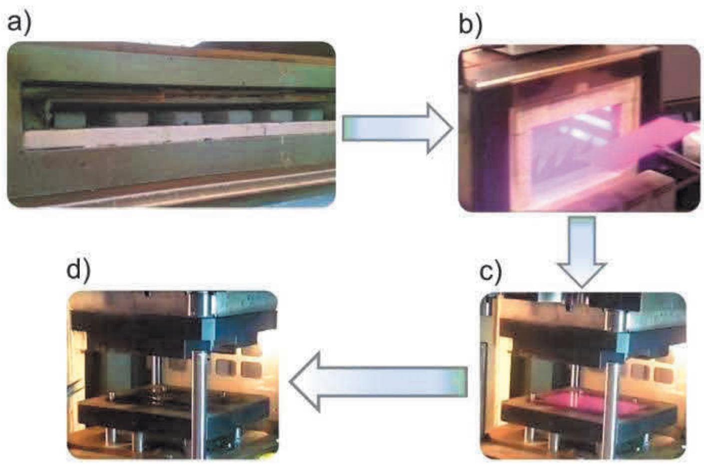

Figure 1 Stages of forming of element: a) heating of the sheet in furnace, b) transfer of the sheet to the stamping tool, c) positioning of the blank, d) forming and holding of the blank in the stamping die

The aim of the simulation was: to estimate the temperature of the blank after its transfer from the furnace to the press; to analyse the temperature distribution and sheet thinning after the warm forming process and estimation of the drawpiece temperature after withstanding the blank in the stamping die. In the simulation it was assumed that heat is transferred to the environment by convection and radiation. The values of the parameters of the thermomechanical analysis were as follows: thermal conductivity of the tool material $k = 20$ W/m^{2}K, the thermal conductivity for cooling channels $k = 40$ W/m^{2}K, convective heat-transfer coefficient $h = 5$ W/m^{2}K, Stefan Boltzmann constant $\sigma = 5.67$-8 W/m^{2}K^4, the emissivity $\varepsilon = 0.2$ and ambient temperature $T = 20$ °C. The warm forming simulation consisted of three stages: the positioning of the blank, forming (**Figure 2**) and withstanding the blank in the stamping die for a certain time. In the numerical model the tools were modelled as non-deformable bodies. For the discretisation of the sheet geometry the shell elements were used. Additionally, two numerical models of the temperature distribution in the tools were considered. The first model (model C - **Figure 3**) took into account a channel cooling. The second one (Model D) did not take into account tool cooling. The analysis of the temperature distribution on the tool surfaces was carried out for 10 cycles of forming.

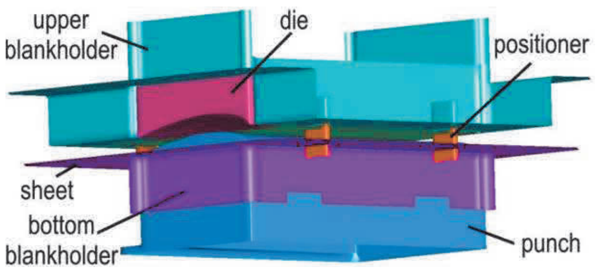

Figure 2 The tool model for simulation of stamping

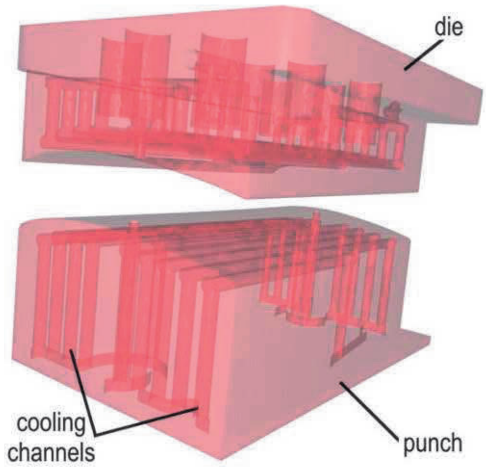

Figure 3 Cooling system in the punch and die

4. RESULTS AND DISCUSSION

After annealing of the workpiece for five seconds, the uniform temperature distribution is observed (**Figure 4**). At the location of the contact of the grip and the workpiece the temperature was about 300 °C, while the temperature of the grip was about 57 °C higher (**Figure 5**). The cyclic nature of the stamping operation causes an increase in the temperature of the tool as a result of heat conduction to the tool. The rate of increasing temperature depends on the time of the contact and a number of forming cycles.

The highest temperature of the blank occurs in the first stage of formation, after which it decreases as a result of heat removal to the environment and the tool via convection and radiation. A rapid decrease of temperature during the transfer of the workpiece from the furnace to the stamping die makes it necessary to preheat the workpiece to a higher temperature than that optimal for warm forming. This often leads to a coating of the sheet surface with a dark oxide layer that must be removed at a later stage of the manufacturing process.

The temperature distribution in the drawpiece after the first cycle is shown in **Figure 9a**. Due to the specificity of the forming process it is necessary to use the auxiliary sheet surfaces, which introduce tensile stress in the flat surface of the drawpiece as a consequence of blankholder action. Furthermore, the use of the blankholder reduces the elastic springback phenomenon of the sheet. In the next stage, the auxiliary surfaces are cut.
The high temperature gradient that occurs on the auxiliary surface of the drawpiece (**Figure 6**) can generate large thermo-mechanical deformation but in the final stage of the forming process these surfaces are cut off.

Thinning of the sheet not exceeding 1.7% (**Figure 7**) is within the tolerance of ± 0.063 mm, specified in the technical documentation. The results of the temperature distribution both on the punch and die surfaces after the first and 10th forming cycles are shown in **Figures 8-10**. The presented results include withstanding of the workpiece in the forming tool for 0.1 second.

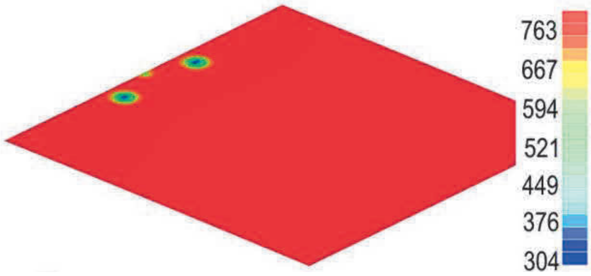

Figure 4 Temperature distribution (ºC) of blank after 5 seconds annealing

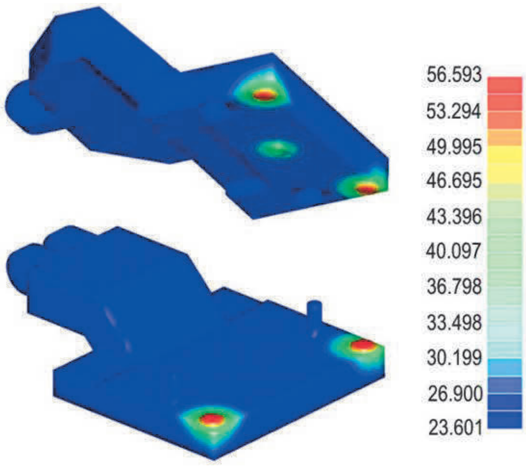

Figure 5 The final temperature of gripper (ºC)

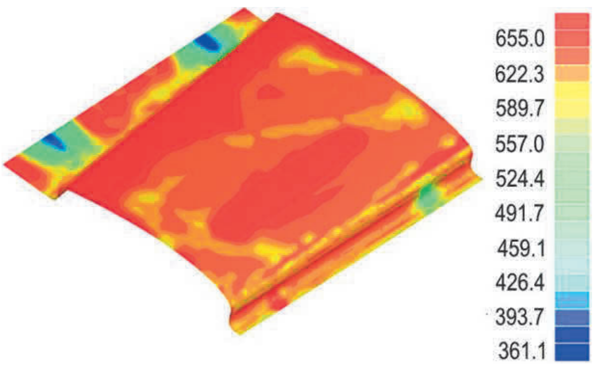

Figure 6 Distribution of drawpiece temperature (Celsius degrees)

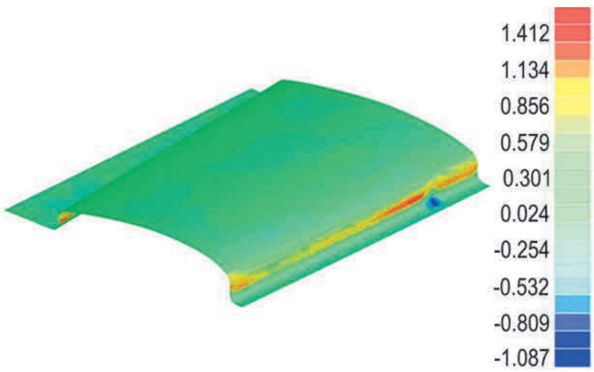

Figure 7 Percentage variation of sheet thickness

A decrease in temperature in the tools after withstanding the sheet is equal to about 65 °C (**Figure 8**). Simultaneously, channel cooling of the tools decreased the area of the highest temperature on the working surface of the punch. A decrease in the tool temperature, which is caused by the tool material being subjected to variable cyclic thermo-mechanical loads, occurs after removing the drawpiece and after air or channel cooling of the punch surface. Significant internal stress in the tool leads to the intensification of fatigue wear.

Similar conclusions regarding the impact of the type of cooling on the value of the maximum temperature of the tool can be extended to the die surface. After the first forming cycle, there was no significant difference in the distribution and the maximum temperature for both variants of cooling (**Figure 9**). Channel cooling led to a reduction of the maximum die temperatures of about 67 °C in relation to the uncooled tool after 10 formation cycles (**Figure 10**).

The highest gradient of the temperature occurs on convex surfaces of tools and around the change of the curvature of the tool profile (edge rounding). A long contact time of the sheet with tools, in combination with high pressures, is observed in these places. After 10 forming cycles the tool temperature is much lower than the admissible working temperature of tools made of an alloy tool steel (600-640 °C).

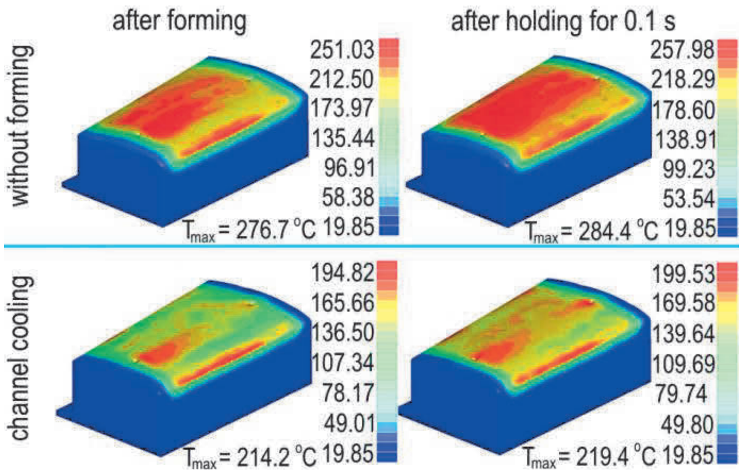

Figure 8 Temperature distribution on the punch surface after 10th cycle of forming

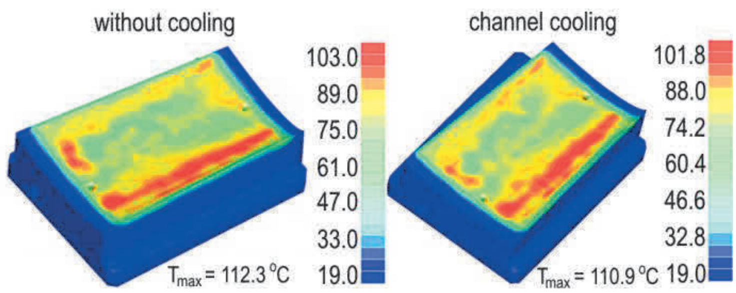

Figure 9 Temperature distribution on the die surface after 1st cycle of forming

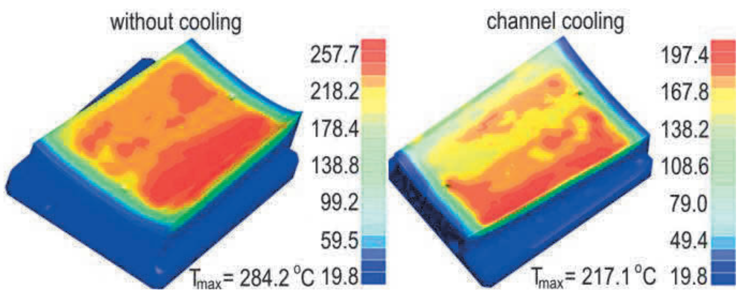

Figure 10 Temperature distribution on the die surface after 10th cycle of forming

5. CONCLUSIONS

As a result of numerical calculations by finite element method, it can be concluded that channel cooling reduces tool temperatures by about 60°C in comparison with the forming tool used without the forced cooling. The used

Impetus Afea program allows prediction of the temperature changes under the conditions of long-term forming processes. Cooling of tools decisively determines the range of occurrence and the value of the maximum temperature of the forming die. However, further research on the selection of the shape and cross-section of the cooling channels is necessary. The numerical results of the temperature distribution on the tool surfaces are close to the values recorded in production conditions using a pyrometer.

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