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INVESTIGATING DIMENSIONAL AND GEOMETRICAL ACCURACY OF ISOTHERMALLY FORGED BLADES

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Abstract. Compressor blades are one of the well-known products made of titanium alloys. They are usually manufactured by a forging process followed by a sequence of machining processes. Precision forging eliminates a considerable amount of machining; however, due to the close tolerances, the process should be designed in a manner to meet dimensional and geometrical tolerances as well as the desired mechanical and metallurgical properties. In this paper, effects of two main process parameters, the process temperature and strain rate, on the dimensional and geometrical accuracy of the isothermally forged blades are investigated experimentally. The results are analyzed by the response surface method (RSM). In order to justify the results and have a tool for further studies, a coupled thermo-mechanical finite element method model is developed and verified by the experimental results. The results show that the process temperature and pressing speed and their interaction have a meaningful effect on the thickness error; however, the interaction effect of the process temperature and pressing speed on the twist error is not considerable and moreover the bow error of the forged blades is not significant. Finally, the results show that for a given geometry, by selection of appropriate process parameters, a sound workpiece with acceptable dimensional and geometrical aspects can be manufactured without any need for a die shape compensation.

1 INTRODUCTION

The titanium and its alloys, including Ti-6Al-4V the workhorse of titanium alloys, have widespread applications in various industries. One of these applications is in the field of compressor blades manufactured by the forging process. Considering the raw material and machining costs, the precision forging may result in reducing the final price of the product. Besides, because of a considerable dependence of its flow stress on the temperature and deformation rate, using the isothermal forging results in a more uniform mechanical and metallurgical properties [1].

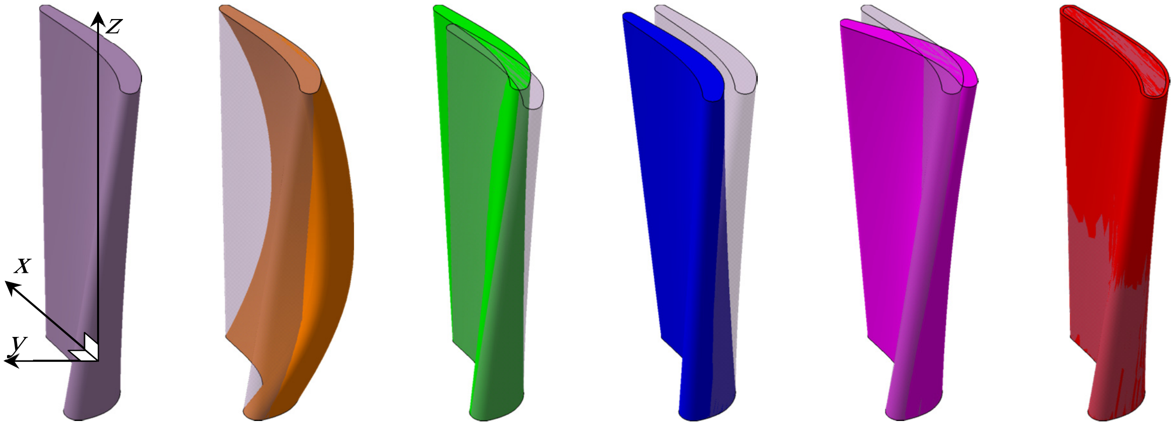
Ou and Balendra studied a non-isothermal airfoil forging process, including the airfoil geometrical deviation due to the elastic die deflection numerically [2]. They compensated the airfoil geometrical deviation by modifying the die profile in the opposite direction to the elastic die deflection. Moreover, they studied the effect of preform cross-sections on the elastic die deflection by the 2D finite element method (FEM) [3]. Hu and Balendra studied the airfoil section's form errors arisen from the die elasticity and cooling by the 2D FEM simulations. They concluded that the process temperature had a great impact on the thickness error [4]. Ou et al. simulated a non-isothermal airfoil forging by 2D FEM and presented a compensating factor to adapt the die profile to the airfoil errors [5-10]. Bruschi and Ghiotti investigated the effects of different cooling sequences on the cooling-induced errors of AISI430 forged blade. Their results showed that applying turbulent air to cool down the forged blade, increased the airfoil geometrical stability [11]. Lu et al. compared the application of one or two compensating factors to recompense the forging errors during the non-isothermal forging of a compressor blade by 3D FEM simulations. Their results demonstrated the usefulness of the single factor method to recompense the forging errors [12]. In order to increase the forging accuracy, Lu and Ou studied stochastic aspects of a blade forging process to optimize the systematic and random errors [13]. Lu and Ou presented an approach to assess the contribution of press machine deflections on the accuracy of a forged blade. Their results showed that the press deflection had a considerable effect on the accuracy of the forgings [14]. Makem et al. presented an automated technique to assess the dimensional and geometrical accuracy of the blade forgings in the design and modeling steps [15]. Simonetto et el. developed an approach consist of numerical and experimental studies to evaluate the distortions of stainless steel forged blades in order to optimize the die design [16].

The literature review showed that although the Ti-6Al-4V blades have been manufactured by the forging process since several decades ago, but many researchers are still interested in optimization of various aspects of the blade forging. The process temperature and pressing speed are two main factors that govern the mechanical and metallurgical properties of the forgings; however, the effects of these factor on the geometrical and dimensional aspects of the forgings, which is a significant subject in the case of the precision forging, are not well addressed in the literature. In the current paper, a comprehensive numerical and experimental study of the effects of the temperature and pressing speed on the geometrical aspects of the isothermally forged blade is presented.

2 THE BLADE'S DIMENSIONAL AND GEOMETRICAL ASSESSMENT

2.1 The Blade's Dimensional and Geometrical Errors

During the manufacturing process of the blades, several dimensional and geometrical errors may arise. Some geometrical errors can be eliminated during the subsequent machining processes; however, some of them may not be modifiable which result in scraping the blade. The blade's geometrical errors are shown schematically in Figure 1. The excessive rotation of the airfoil around the x-axis and y-axis results in the *lean* and *tilt* errors, respectively. These errors can often be compensated during the machining processes. The rotation of the tip cross section respect to the platform cross section around the z-axis is defined as the *twist*. The deviation of the twist from its nominal value results in the *twist* error. The out-of-tolerance twist error is not often modifiable by the machining processes. The airfoil thickness is defined according to Figure 2. The chord line is a straight line between the leading (A) and trailing (B) edges. At a particular distance from the leading edge on the chord line (C), a line perpendicular to the chord line intersects the airfoil section at two points (D and E). The distance between two intersection points (DE) is defined as the airfoil thickness at C.



Desired geometry | Bow | Tilt | Lean | Twist | Thickness Error

Figure 1: Common geometrical errors arisen during blade manufacturing

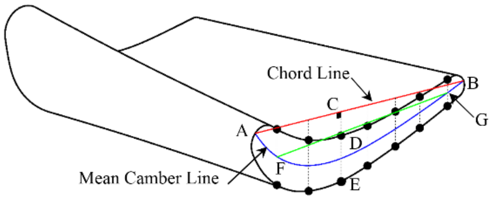


Figure 2: A typical airfoil section

2.2 Error measurement

After the precision forging of the blades, Bow, twist and thickness errors should be considered to be in the permissible tolerance range to prevent the blade scrappage. Behind the forged blades were cooled down and the lubricant removed from their surface, they were subjected to coordinate measurement in order to determine various types of the dimensional and geometrical accuracy. The locating of the blades was done by the 3-2-1 rule at the root as shown in Figure 3. The coordinate measuring was done at four sections from the root to the tip (Figure 3). At each point, the blade's thickness and consequently thickness error was determined. The twist error was calculated by measuring the rotation difference between the first and the last cross-section. The bow, lean and tilt errors were considered at the stacking line.

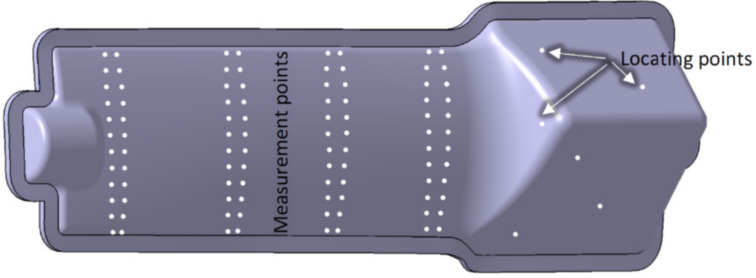


Figure 3: Locating and measuring points of blade.

3 MATERIALS AND METHODS

3.1 Experimental Study

Preform preparation

Forging of compressor blades is a complex forming process that needs an accurate design of the preform to ensure complete die-filling as well as meeting the mechanical and metallurgical properties. In this study, the preforms made of Ti-6Al-4V were formed by using the extrusion process. All the preforms were manufactured with the same processing parameters. Before the isothermal forging process, the preforms were glazed to prevent the formation of alpha-case and also lubricate them.

Experimental setup

In order to carry out the isothermal blade forging process and study the dimensional and geometrical errors during the forging process, there was a need to precisely control the deformation rate and the process temperature; so, a 6 MN hydraulic press was equipped with a servo-hydraulic power-pack and a PLC control system. An electric furnace, isolated from the press bed by water-cooled plates, was used to heat the dies. The dies were fabricated from a nickel-base superalloy to withstand the forging stresses at the high processing temperatures. Both of the preform and dies were held enough in the furnace to remove the temperature gradient inside them. In the die design step, the cavity orientation was chosen in a manner to minimize the lateral forces, in addition, preventing the locating of the preform incorrectly.

Experimental tests

The process temperature and pressing speed are two main factors that govern the forging process of the blades. Inappropriate selection of these factors may result in the unsuitable mechanical and metallurgical properties. In order to assess their effects on the geometrical aspects, a set of experiments was designed based on the face-centered central composite response surface method. The dies and preforms were held enough in the furnace to have a uniform temperature at the test points 890, 920 or 950 °C and then the forging tests were conducted at the mean strain rates 0.179, 0.036 or 0.007 s^{-1} at the middle of the airfoil. All the tests at the factorial and axial points were replicated two times, and three times at the center point in a random sequence. After the cooling sequence of the forged blades and removing the lubricant from their surface, they were subjected to coordinate measurement in order to determine various types of dimensional and geometrical accuracy.

3.2 Numerical Simulations

A finite element method (FEM) model was developed and verified by the experimental results to better understand the mechanisms governing the experimental results and prepare a verified tool for further studies (Figure 4). The workpiece was considered as rigid-viscoplastic and elastic-plastic during the forging and cooling processes, respectively. The flow curves of Ti-6Al-4V were determined by the isothermal compression tests and presented in [17]. The friction factor at the die-workpiece interface was determined as a function of the temperature and deformation rate by the isothermal ring compression tests [18] and implemented in the model. The simulation parameters were chosen as the experimental ones. To simulate the isothermal forging process, the temperatures of the workpiece, dies, and environment were set to the selected process temperature at the start of the simulation.

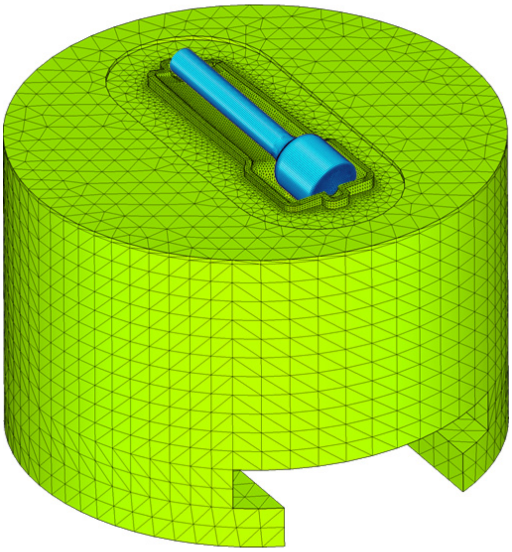


Figure 4: Developed FEM model.

4 RESULTS AND DISCUSSION

After conducting the tests, all the isothermally forged blades were subjected to coordinate measurement to determine the geometrical and dimensional accuracy. The results of various errors are presented and discussed here. The isothermal forged and trimmed blade is shown in Figure 5.

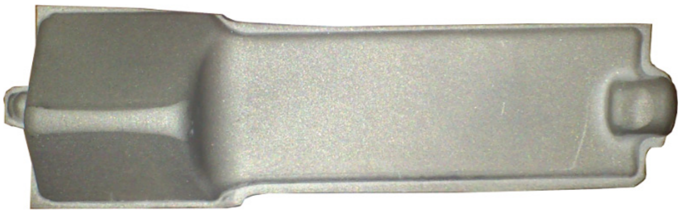


Figure 5: Isothermally forged and trimmed blade.

4.1 Thickness Error

The thickness error in the non-isothermal forging is the most considered aspect of the dimensional accuracy in the literature [2, 5, 6, 8, 9, 12]. As a rule of thumb, an increase of the forging pressure (force) and/or a decrease of the die elastic modulus result in more thickness error; however, how the process temperature and forging speed alter these parameters should be assessed more precisely.

Step-by-step evolution of the elastic die deflection and accordingly thickness error during the isothermal forging process at 890 °C and strain rate 0.179 s^{-1} is shown in Figure 6. As the process proceeds, the forging force increases and thus the die's elastic deflection grows. At the end of the process, the maximum elastic die deflection was 0.131 mm in the middle of the airfoil near the platform. Several parameters affect the elastic die deflection, including the friction factor at the workpiece-die interface, the flow stress of Ti-6Al-4V and the elastic modulus of the dies at the process temperature. Increasing the process temperature results in lower flow stress and elastic modulus, and higher friction factor [18]. The former results in lower forging force and consequently less die deflection. To consider the elastic die deflection, flow stress has an opposite effect on elastic modulus and friction factor. Increasing deformation rate increases the flow stress, but at the same time decreases the friction factor that has opposite effects on elastic die deflection and consequently thickness error.

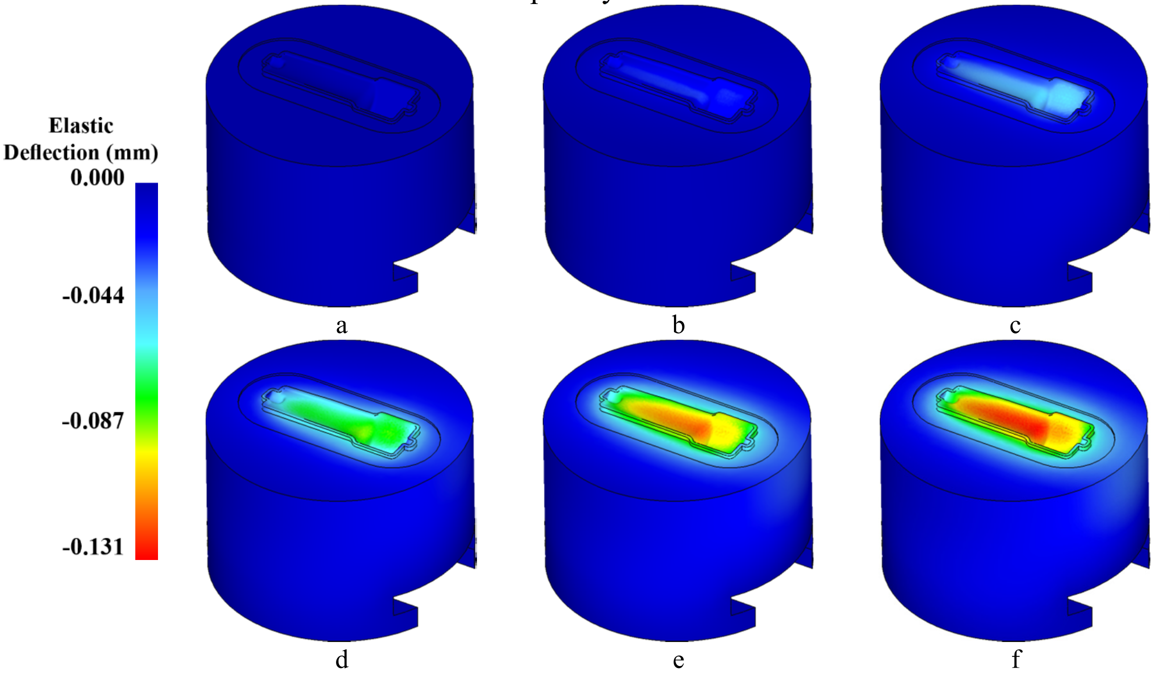


Figure 6: Evolution of die elastic deflection during the isothermal forging at 890 °C and strain rate of 0.179 /s.

By conducting the forging process isothermally at various process temperatures and deformation rates, according to the design of experiments, superimpose of the different effects results in a variety of thickness errors as a function of the process temperature and the strain rate. The effect of the mentioned factors on the thickness error was evaluated by analysis of variance which is presented in Table 1. The modeled response surface is shown in Figure 7.

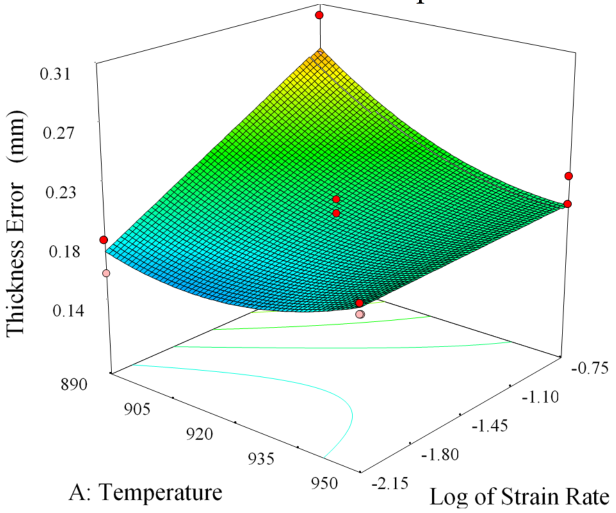


Figure 7: The thickness error as a function of the process temperature and speed.

Table 1: ANOVA table of effective parameters on thickness error

Source	Sum of Squares×10^{-4}	df	Mean Square×10^{-4}	F Value	p-value Prob > F
Model	290.0	4	72.3	16.33	<0.0001
A-Temperature	39.1	1	39.1	8.84	0.0060
B-Strain Rate	130.0	1	130.0	29.97	<0.0001
AB	92.0	1	92.0	20.79	<0.0001
A^2	25.3	1	25.3	5.72	0.0237
Residual	120.0	28	4.4		
Lack of Fit	35.0	10	3.5	0.71	0.7060
Pure Error	88.9	18	4.9		
Cor Total	410.0	32			

According to Figure 7 the maximum elastic deflection and consequently thickness error was taken place at the lower process temperature and the higher deformation rate and was approximately 0.28 mm. At lower strain rates, the effect of the process temperature on the thickness error was not considerable; however, at higher strain rates, the process temperature had a significant effect on the thickness error. From another point of view, at 890 °C, the strain rate had a much more effect on the thickness error rather than 950 °C. Two phenomena govern this finding. First, the measured flow curves showed a more dependence of the flow stress to the strain rate at lower temperatures. Second, at the lower temperature, strain rate doesn't have a considerable effect on friction factor; however at a higher temperature, increasing the strain rate decreases the friction factor significantly that reduces the effect of strain rate on the flow stress and consequently forging force. The results show that by selection of an appropriate region in the process window, acceptable thickness error within the blade's tolerance can be achieved.

4.2 Twist and Bow Errors

The twist and bow errors are two temperature-related errors that happen during the cooling sequence. The initial process temperature, deformation rate, and non-uniform deformation affect the temperature distribution inside the forged blade at the end of the forging process. The leading and trailing edges undergo a more deformation and so a more adiabatic temperature rise (Figure 8). Increasing the deformation rate results in a higher adiabatic temperature rise. Moreover, the lower initial process temperature leads to a more flow stress and a higher adiabatic temperature rise. The temperature distribution coupled with the varying thickness of the airfoil profile results in a non-uniform cooling of the blade and consequently deviation of the airfoil. Because of small thickness in the leading and trailing edges, they cool down faster than the central portion of the airfoil that increases their strength. The contraction of the central area results in the warpage of the airfoil and twist and/or bow formation.

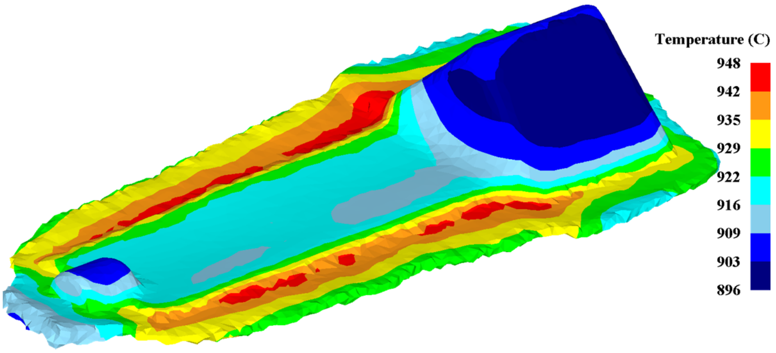


Figure 8: The temperature distribution at the end of forging process for the initial temperature 890 °C and 0.179 s^{-1}.

The resulted response surfaces as a function of the process temperature and speed for the twist and bow errors are presented in Figure 9 and 10, respectively. The results show that both of increasing the initial temperature and decreasing the velocity result in a more uniform temperature at the end of the process that cause a more twist error. This finding shows that the geometry and its effect on the cooling sequence has a significant influence on the warpages after the forging process. In other words, for the temperature-related errors, non-uniform cooling is more important than non-uniform temperature distribution at the end of the process.

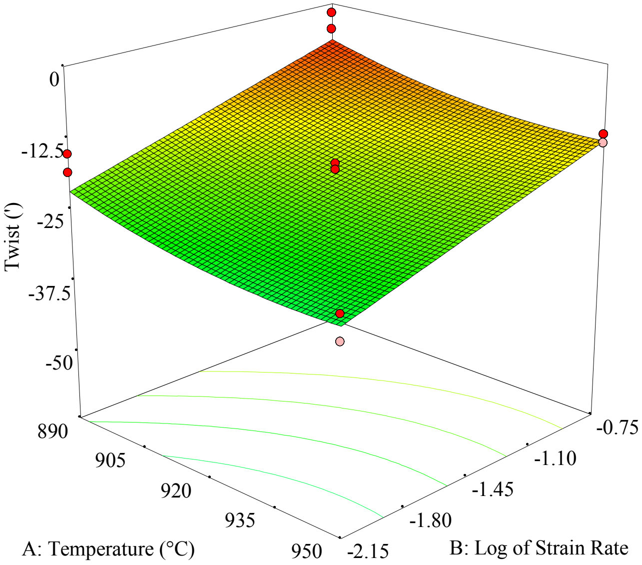


Figure 9: The twist error as a function of the process temperature and speed.

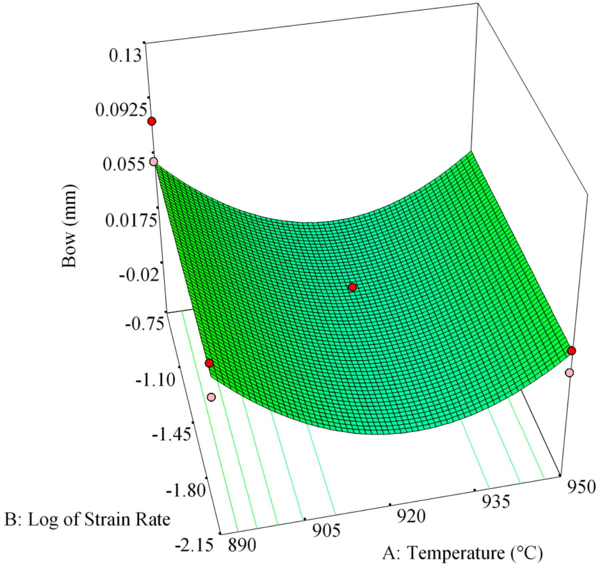


Figure 10: The bow error as a function of the process temperature and speed.

4.3 Tilt and Lean Errors

As stated in the previous section, the non-uniform cooling of the airfoil may result in the buckling of the airfoil. Because of high bending strength around the y-axis in Figure 1, there is no considerable tilt and lean after the process. Moreover, the lean and tilt errors can be readily compensated in the machining process of the blade's root.

5 CONCLUSION

The compressor blades made of titanium alloys are commonly manufactured by forging process. By conducting the process isothermally, the desired control on the geometrical aspects as well as the mechanical and metallurgical properties is achievable. Investigating the temperature and the strain rate effect in the isothermal blade forging revealed their significant interaction effect on the dimensional and geometrical accuracy. Concerned about the thickness error, increasing the process temperature has a positive effect on the flow stress, however, a negative effect on the elastic modulus of the dies and the friction factor. Increasing the forging speed improves the lubricity in the die-workpiece interface, but at the same time rises the flow stress. These parameters have an opposite effect on the die elastic deflection and consequently airfoil thickness error. Such opposite effects govern the geometric deviations. In the other words, increasing the forging speed results in a more thickness error; however, initial process temperature determines the significance of this finding. So, an appropriate selection of process temperature and forging speed will result in acceptable dimensional and geometrical tolerances without any need of die shape compensation.

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REFERENCES

[1] Ermachenko, A., and Karavayeva, M. High-temperature precision forming of titanium blades. *J. Mater. Eng. Perform.* (1996), 5:589-592.

[2] Ou, H., and Balendra, R. Die-elasticity for precision forging of aerofoil sections using finite element simulation. *J. Mater. Process. Technol.* (1998), 76:56-61.

[3] Ou, H., and Balendra, R. Preform design for forging of aerofoil sections using fe simulation. *J. Mater. Process. Technol.* (1998), 80:144-148.

[4] Lu, X., and Balendra, R. Temperature-related errors on aerofoil section of turbine blade. *J. Mater. Process. Technol.* (2001), 115:240-244.

[5] Ou, H., and Armstrong, C. Die shape compensation in hot forging of titanium aerofoil sections. *J. Mater. Process. Technol.* (2002), 125:347-352.

[6] Ou, H., Armstrong, C., and Price, M. Die shape optimisation in forging of aerofoil sections. *J. Mater. Process. Technol.* (2003), 132:21-27.

[7] Ou, H., Lan, J., Armstrong, C., and Price, M. An fe simulation and optimisation approach for the forging of aeroengine components. *J. Mater. Process. Technol.* (2004), 151:208-216.

[8] Ou, H., Lan, J., Armstrong, C., Walløe, S., and Ward, M. Direct die shape compensation for forging of ni-based aerofoil blades; In *Proceedings of the 8th International Conference on Numerical Methods in Industrial Forming Processes*, 2004: AIP Publishing.

[9] Ou, H., and Armstrong, C. Evaluating the effect of press and die elasticity in forging of aerofoil sections using finite element simulation. *Finite Elem. Anal. Des.* (2006), 42:856-867.

[10] Ou, H., Lan, J., Armstrong, C., Price, M., Walløe, S., and Ward, M. Reduction in post forging errors for aerofoil forging using finite element simulation and optimization. *Modell. Simul. Mater. Sci. Eng.* (2006), 14:179-193.

[11] Bruschi, S., and Ghiotti, A. Distortions induced in turbine blades by hot forging and cooling. *Int. J. Mach. Tool. Manu.* (2008), 48:761-767.

[12] Lu, B., Ou, H., Armstrong, C., and Rennie, A. 3d die shape optimisation for net-shape forging of aerofoil blades. *Mater. Design.* (2009), 30:2490-2500.

[13] Lu, B., and Ou, H. Stochastic finite-element modelling and optimization for net-shape forging of three-dimensional aero-engine blades. *Proc. Inst. Mech. Eng. L J. Mater. Des. Appl.* (2011), 225:71-85.

[14] Lu, B., and Ou, H. Quantification of press elasticity in the forging of three-dimensional complex shapes. *Proc. Inst. Mech. Eng. B J. Eng. Manu.* (2012), 226:466-477.

[15] Makem, J. E., Ou, H., and Armstrong, C. G. A virtual inspection framework for precision manufacturing of aerofoil components. *Comput. Aided Des.* (2012), 44:858-874.

[16] Simonetto, E., Bruschi, S., Ghiotti, A., and Savio, E. Prediction of distortions in hot forged martensitic stainless steel turbine blades by numerical simulation. *Procedia Manu.* (2015), 1:804-813.

[17] Mirahmadi, S. J., Hamedi, M., and Parsa, M. H. Investigation of microstructural uniformity during isothermal forging of Ti-6Al-4V. *J. Mater. Eng. Perform.* (2014), 23:4411-4420.

[18] Mirahmadi, S. J., Hamedi, M., and Cheraghzadeh, M. Investigating friction factor in forging of ti-6al-4v through isothermal ring compression test. *Tribol. T.* (2015), 58:778-785.