Preform and Process Design of Ti-6Al-4V Compressor Blade using Equipotential Lines and 3D FE Simulation

Mahdi Soleimanzadeh
Department of Mechanical Engineering,
Islamic Azad University, Jasb Branch, Iran
E-mail: msoleimanzadeh@ymail.com

Mohammad Meghdad Fallah*
Department of Mechanical Engineering,
Shahid Rajaee Teacher Training University, Iran
E-mail: m.fallah@srttu.edu
*Corresponding author

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Abstract: Forging is one of the most important processes for production of titanium parts. Selection and evolution of forging parameters such as the forging preforms, part and die temperatures and strain rate are of great importance to achieve optimal process. In this work, a comprehensive study on the near net hot forging of a Ti-6Al-4V compressor blade is performed through designing several preforms and simulating the process in several die and preform temperatures. The Equipotential lines method is used for the optimal design of preforms and Johnson-Cook constitutive model is used for 3D FE simulations and the criteria for selecting the parameters was the material temperature during the process that is necessary for achieving desired properties of Ti-6Al-4V parts. According to the results, performing the isothermal forging process in increased speeds could lead to increasing the temperature over the β-transus and improper mechanical properties development. So, finding a proper die and preform temperature is necessarily accomplished in this work. According to results the appropriate temperatures for performing the process using modified 0.1v preform and ram speed of 1mm/s were 1050˚C and 450˚C for the preform and die respectively.

Keywords: Equipotential lines method, FE Simulation, Hot forging of the Blade, preform design, Titanium alloy Ti-6Al-4V

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Biographical notes: M. M. Fallah received his PhD in Mechanical Engineering from Amirkabir University of Technology in 2011. He is currently Assistant Professor at the Department of Mechanical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran. His current research interest includes hot forging process and microstructure evolution in manufacturing processes. **M. Soleimanzadeh** has received his MSc in Mechanical engineering from IAU University, Jasb Branch, in 2017. His current research focuses on hot forging process in gas turbine industry.

1 INTRODUCTION

In the forge process design, the temperature of part and die, designed preforms and intermediate stages, geometry and dimensions of the original blank, speed and lubrication, are the most important process parameters of the forge. Ti alloys are widely used in high technology industries because of its relatively high strengths to weight specification e.g. compressor blades. The preliminary manufacturing process of these parts is forging and several researches have been done on this subject for optimizing this complex process experimentally and numerically. The forming properties of this material is very sensitive to process temperature and strain rate and controlling these parameters is necessary for achieving product mechanical properties. In 2001, Dean and Hu [1] examined the influence of temperature and strain rate on forging process of Ti-6Al-4V blade using finite element simulation. For more accurate simulation, process conditions such as the mechanical behavior of alloys and boundary conditions were found by experimental tests. Finally, the hot die forging of titanium blade was introduced as an effective and economical way to produce nearly the final shape of the part. Alimirzaloo et al. [2] investigated the forging process of a gas turbine blade. They studied material mechanical behaviour and boundary condition gained by ring compression test using FE method. In their study, material flow, die cavity filling, strain and temperature was investigated and approved by experimental verifications. Liu et al. [3] examined preforms design for powder metallurgy turbine disk using Equipotential lines method. According to the results of their study that mostly focuses on the formulas and numerical issues of equi-potential lines method, the electric potential equation in an electrostatic field is similar to the velocity potential equation in material deformation process and as Laplacian equation uses the energy's lowest principles. Cai et al. [4] attempts to optimize the forging process, including reducing the tonnage force and increasing the capacity of material filling. They used the Equi-potential lines and geometric conversion method to design the preforms. For this purpose, two axisymmetric parts and one longitudinal part have been studied for FE simulation of the forging stages using DEFORM-3D software.

Sadeghi and Barooghi [5] used the equipotential lines method to design the forging preforms of blades with Al6082 alloy. Then the equipotential lines in ABAQUS software were used for designing three preforms and FE simulation was performed in DEFORM-3D. The die filling, strain, temperature and forces distribution were studied as process parameters. Guan et al. [6] also used equipotential lines for designing preforms for complex part and examined some preforms and volume ratios to achieve the proper condition for filling the dies cavity. Lv et al. [7] in 2007 simulated the forging process of a compressor blade using 3D FEM in four steps. They investigated the temperature and strain distribution and increased the steps achieving the appropriate distribution.

The aim of this work is investigating the impact of process temperature and preform shape on the hot forging process of Ti-6Al-4V blade with considering die filling, defects of product, distribution of stress, strain and temperature of the part. So, the precision hot forging of a Ti-6Al-4V compressor blade is studied through designing several preforms using equipotential lines method and simulating the process in different temperature patterns. The considered ram speed in this work is relatively more than used in industrial applications. The Johnson-Cook constitutive model is used for 3D FE simulations and the criteria for selecting the parameters was the β-transus temperature that is necessary for achieving desired properties of Ti-6Al-4V parts. According to the authors knowledge this approach was not used in the literature.

2 FORGING OF TI-6AL-4V ALLOY

Ti-6Al-4V alloy has two phases: α-phase with hcp structure and β phase with bcc structure. The deformation of material in beta phase due to its bcc structure is easier than the α-phase, but mechanical properties will be decreased. Because of the high flow stress of this alloy, more tonnage is needed for forging. So forging of this alloy at temperatures near and above the beta transformation temperature is easier and more economical. This metal has a super-plastic behavior at temperatures higher than 950˚C and strain rates lower than the 1 s^{-1} that makes the ability to reduce the height up to the 75% of the possible height without any defects [8].

3 DESIGNING THE PREFORMS

In this work a compressor blade was designed with width of 110 mm and height of 346 mm (Fig. 1). After designing final die (Fig. 2), preforms were designed using equipotential lines method. This method, that its scientific nature is based on the intrinsic impact of geometry on the material flow, is an applicable method for designing preforms. Based on the theory of this method and similarity criterion, if the mathematical model of a physical field, e.g. mechanical, magnetic and heat flow field, is similar to the mathematical model of an electrostatic field, the intended field can be simulated using electrostatic field [3].

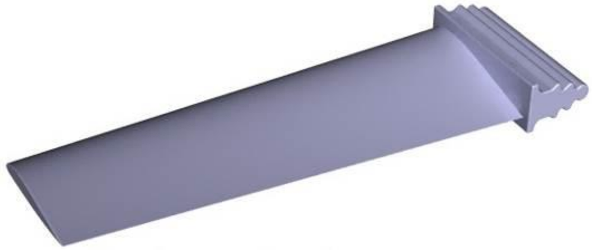


Fig. 1 Compressor blade model

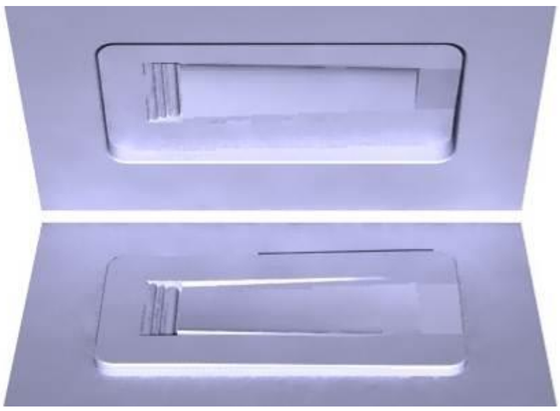


Fig. 2 Final die of compressor blade

In preform design process, ElecNet software was used to simulate the electrostatic field. For this purpose, five transverse cross-sections were selected from the blade and it's blank. The cross-sections of the blade were placed inside the cross-sections of the blank and zero and one voltage was applied respectively to them. After running the simulation of the electrostatic field, the contour of equipotential lines appeared and the equipotential lines of 0.1, 0.22, and 0.5 v were extracted as the main preform contours. Then regarding the criterion of complete filling of the final die cavity, the optimal volume ratios was determined within several stages of simulation. Figure 3 shows the equi-potential lines of 0.1, 0.22, and 0.5 v of voltage contour obtained from the electrostatic field simulation.

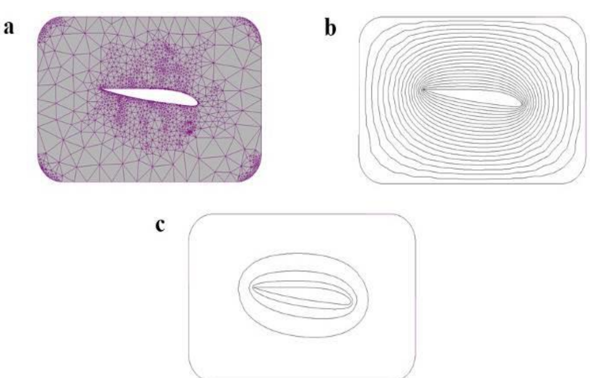


Fig. 3 Cross-section of tip of airfoil a. ElecNet mesh b. voltage lines contour c. three equipotential lines of 0.1, 0.22, and 0.5 v

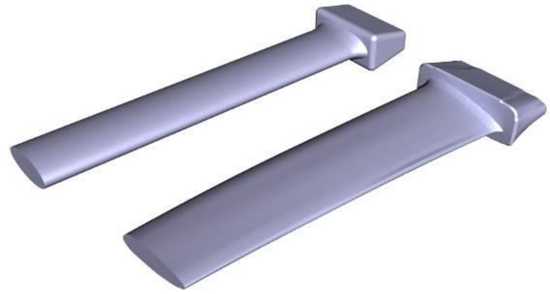


Fig. 4 The blade preforms, modified 0.1 v and oval preforms

Due to the proximity of the geometry of lines 0.22 and 0.5 v to oval shape in the airfoil area, an oval design with a simple root, was designed and replaced by them. Also by reducing the flash volume of the 0.1 v preform and increasing the fillets radius, the modified 0.1 v preform was obtained. Figure 4 shows modified 0.1 v and oval preforms.

4 SIMULATION

In simulation study, firstly each of the preforms (0.1 v, modified 0.1 v and oval) was investigated taking 1050 ˚C for part and 450 ˚C for dies to select appropriate preform. In hot forging, the process temperature should be more than half of melting temperature that is about 1650˚C for Ti6Al4V. Besides, the preferred temperature for forging of this alloy is below β-transus for conventional forging process and a little above β-transus for β forging process [9]. So, the process was simulated in several temperatures according to Table 1. Table 2 and 3 shows the simulation parameters and input properties for the Ti-6Al-4V alloy.

Table 1 The process temperatures in simulations

Forging temperature (˚C)	Part	950		1050	
	Die	450	950	450	750
Process label		A	B	C	D

Table 2 The simulation parameters

Parameter	Value	Unit
Environmental temperature	20	˚C
Environmental Convection coefficient	0.02	N/s mm ˚C
Ram velocity	1	mm/s
Frictional coefficient	0.3	———
Interface heat transfer coefficient	5	N/s mm ˚C

Table 3 The material properties

Properties	Value	Unit
Density	4.43	gr/cm^3
Passion's ratio	0.34	———
Young's modulus	-0.02464 T + 114.4928	GPa
Expansion	0.002174 T + 7.9565	˚C $^{-1}$
Conductivity	0.01109 T + 6.4783	W/m˚C
Heat capacity	0.002877 T + 2.2725	J/kg˚C

In this study, Johnson-Cook structural model was used due to its appropriate adaptation to the behavior of the Ti-6Al-4V alloy especially in high temperatures and low strain rates [10]. This model was first introduced in 1983 by Johnson and Cook [11]. Equation (1) shows Johnson-Cook behavioural model in the prediction of flow stress.

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln \dot{\varepsilon}/\dot{\varepsilon}_0\right)\left(1 - \left(\frac{(T - T_{room})}{(T_{melt} - T_{room})}\right)^m\right) \quad (1)$$

In the above equation, σ is the Von Mises flow stress, A is the Yield Strength, B is the hardening modulus, ε is the Equivalent plastic strain, n is the work-hardening exponent, C is the strain rate stiffness coefficient, $\dot{\varepsilon}_0$ is the reference plastic strain rate, T_{room} is the reference temperature, m is the thermal softening coefficient and T_{melt} is the material's melting point. A, B, C, n, and m are material constants.

Table 4 reports some of the J-C coefficients for Ti6Al4V alloy used in researches. In this work, for selecting the proper coefficient some trial simulations are performed using the literature data and the results are compared to an experimental study [8]. Then the more compatible one is used as table 5.

Table 4 Johnson-Cook coefficients used in the literature

Reference	A (MPa)	B (MPa)	C	n	m
Lee & Lin (1998) [12]	782.7	498.4	0.028	0.28	1
lesuer (1999) [13]	1098	1092	0.014	0.93	1.1
Meyer & Kleponis (2001) [14]	896	656	0.0128	0.5	0.8
Seo et al. (2005) [15]	997.9	653	0.0198	0.45	0.7
Özel & Karpat (2007) [16]	987.8	761.5	0.01516	0.41433	1.516
Kotkunde et al. (2014) [17]	869.4	649.5	0.0093	0.3867	0.7579

Table 5 Johnson-Cook coefficients used in simulation

A (MPa)	B (MPa)	C	n	m
950	760	0.014	0.34	1.1

For meshing of preforms, about 60,000 elements was selected to achieve proper result as shown in figure 5. After generating mesh in DEFORM-3D software, exact number of elements were specified. Table 6 shows number of meshing elements for preforms and dies.

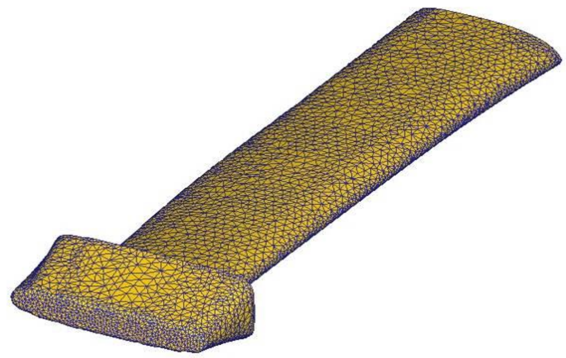


Fig. 5 Meshed view of modified 0.1 v preform

Table 6 Number of mesh elements

Part	Number of Elements
0.1 v preform	47375
0.1 v optimized preform	46000
Oval preform	56575
Top Die	72809
Bottom Die	83757

5 THE SIMULATION RESULTS

Figure 6 shows the process simulation results for three designed preforms. As illustrated, using the modified 0.1 v preform leads to a blade without any defect and proper flash.

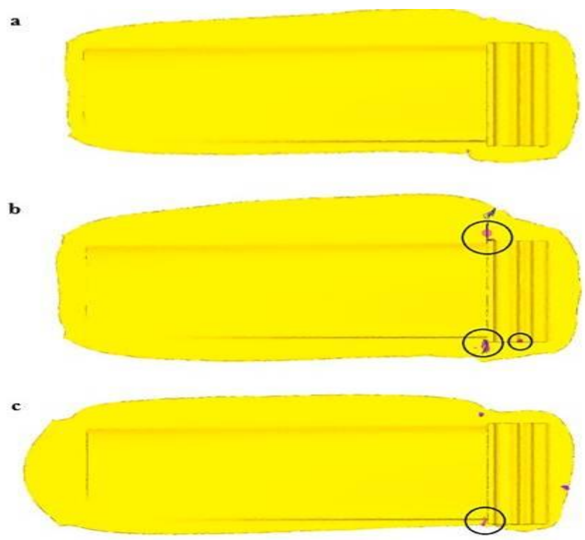


Fig. 6 Flash value and defects a) modified 0.1 v preform forging b) 0.1 v preform forging c) oval preform forging

Figure 7 shows the Loud-Stroke diagram resulted from forging simulation of three preforms. According to diagram, lower tonnage is needed for forging of modified 0.1 v preform.

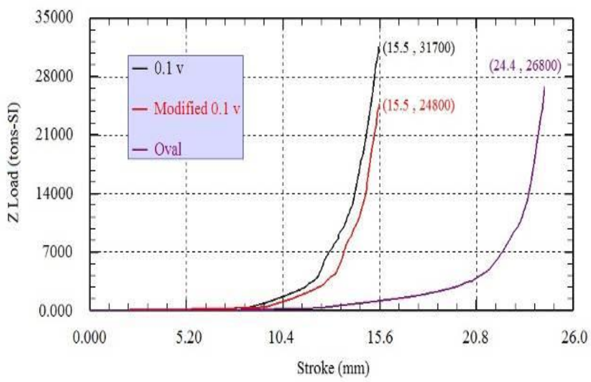


Fig. 7 Loud-Stroke diagram of preform forgings

After determining the appropriate preform, it was used for simulation of the process in different temperatures (Table 1). For deeply studying the process, a point tracking of worst stress, strain and strain rate condition (Figure 8) is selected near the flash within the blade platform as shown in Figure 9.

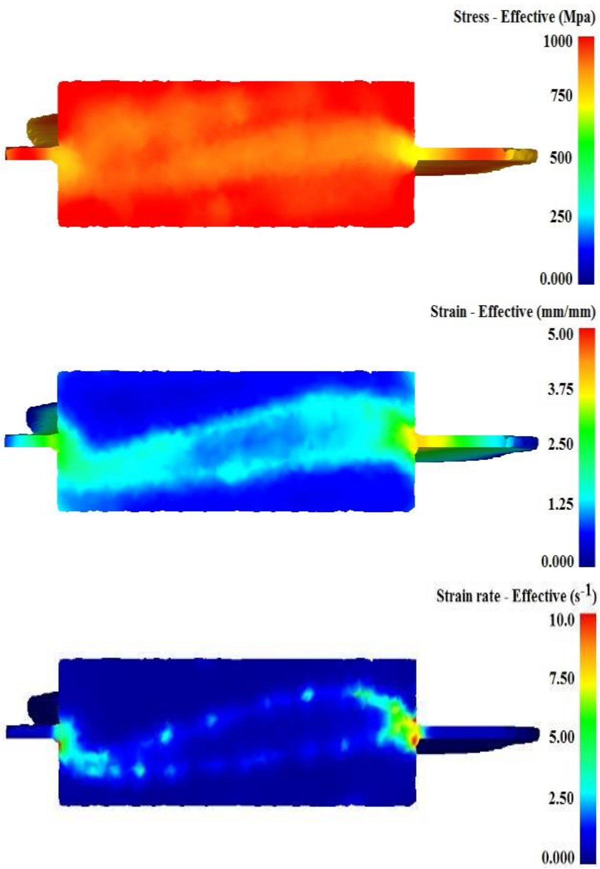


Fig. 8 Stress, strain and strain rate distribution in platform section

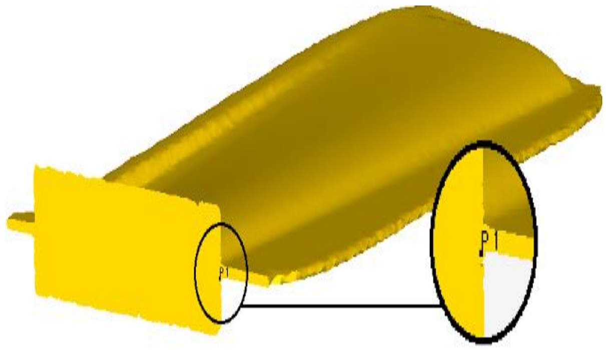


Fig. 9 Chosen point using tracking point tool within platform section

Figure 10 shows strain rate diagram of the process in temperature conditions of table 1 for selected tracking point. In temperature condition A, due to relatively low temperature of dies, the strain rate is larger relative to other conditions. In conditions B and D, the strain rate is relatively lower than A that could be due to higher process temperature of them. The process condition C has the smaller strain rate that is more appropriate for forming Ti-6Al-4V alloy as mentioned before.

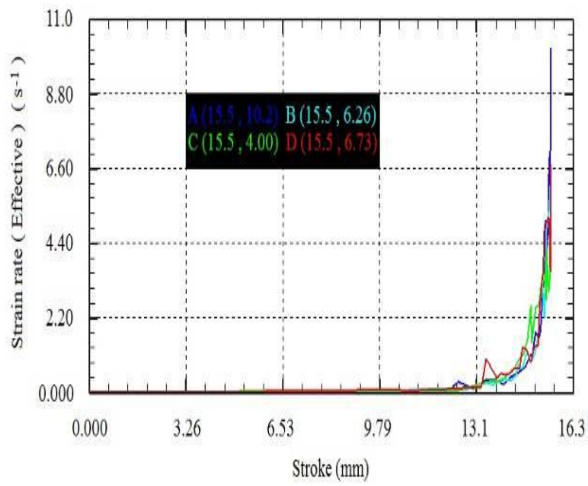


Fig. 10 Strain rate diagram of temperature conditions

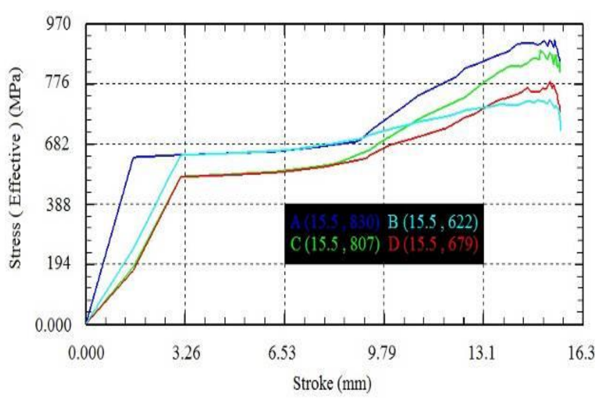


Fig. 11 Stress diagram of temperature conditions

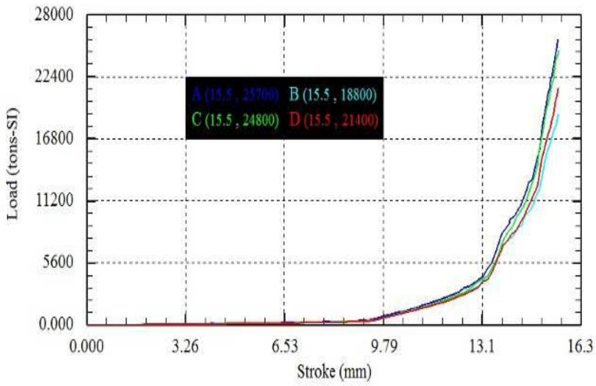


Fig. 12 Loud-Stroke diagram of temperature conditions

Figure 11 shows stress diagram for different temperature condition. As shown, A and C have relatively larger stress values because of smaller temperature of die. Figure 12 shows tonnage diagram of processes. As stress diagram predicts, process conditions of A and C need about 10% more tonnage value relative to other conditions B and D. Figure 13 shows the temperature variation in process conditions of A to D. In process conditions of A and C due to lower temperature of dies relative to blanks, initially the temperature decreases and finally in die closing step increases up to about 1070℃. In process condition of B, due to temperature equality of blank and dies, temperature increases up continuously and reach to 1230℃. The process condition of D is almost like the A and C, but due to the higher temperature of the dies in condition D, the temperature drop is lower and, after increasing the temperature, ultimately reaches a temperature of 1190℃.

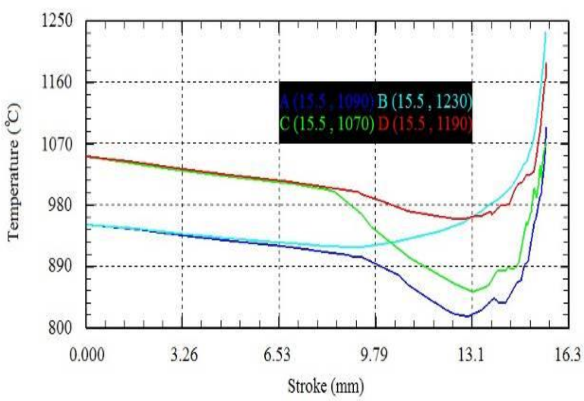


Fig. 13 Temperature diagram of temperature conditions

Figure 14 shows the temperature distribution in the blade for process conditions of A to D. As shown in figure the temperature in process condition of A and C did not exceed to 1250℃ that is 75% of melting point of the alloy and selected as maximum temperature limit.

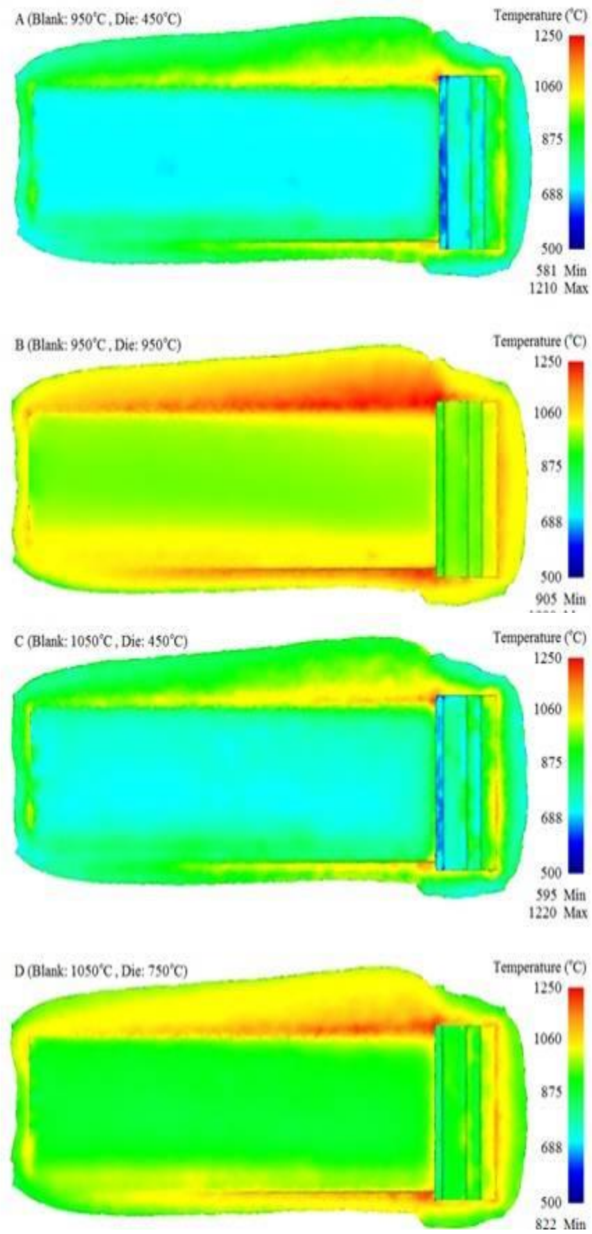
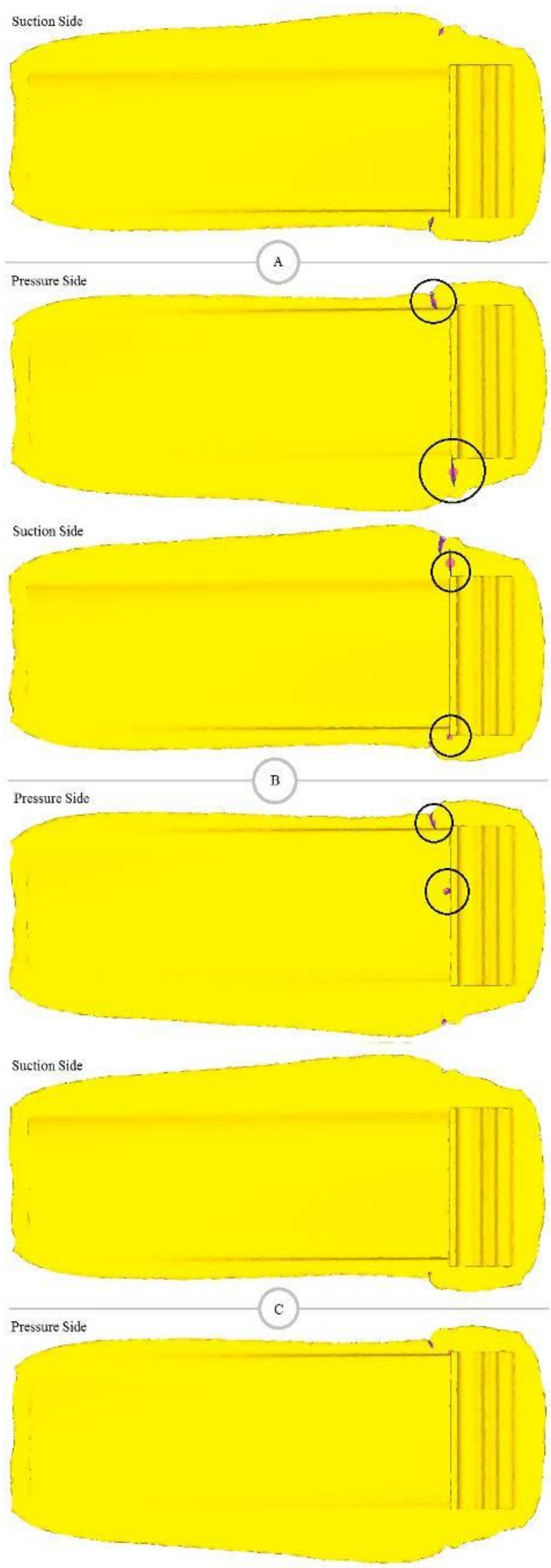


Fig. 14 Blade temperature distribution in process conditions of A to D, respectively

The predicted defects in the blades forged via temperature conditions A to D are shown in figure 15. As illustrated the A, B, and D processes lead to some defects in the airfoil, platform and root of forged blades whereas in blade entitled C no defect have been seen in the blade body.

Figure 16 shows strain rate distribution in simulated conditions, and demonstrates that maximum strain rate in condition C is lower than other samples except condition B which its maximum strain rate is right on the airfoil. So condition C with uniform and low strain rates have better situation.



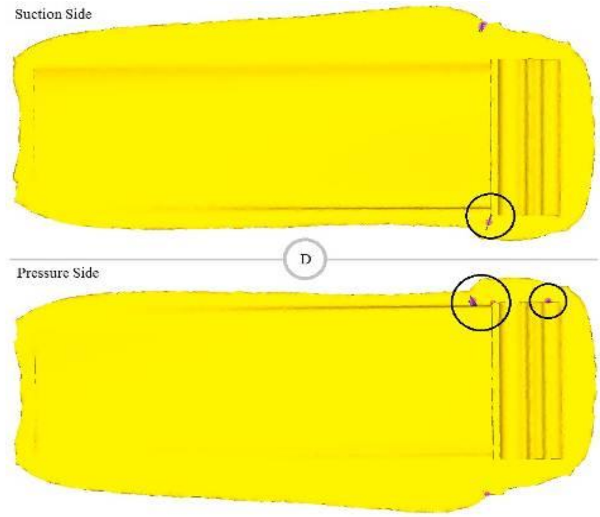


Fig. 15 Blade defects in process conditions A to D, respectively

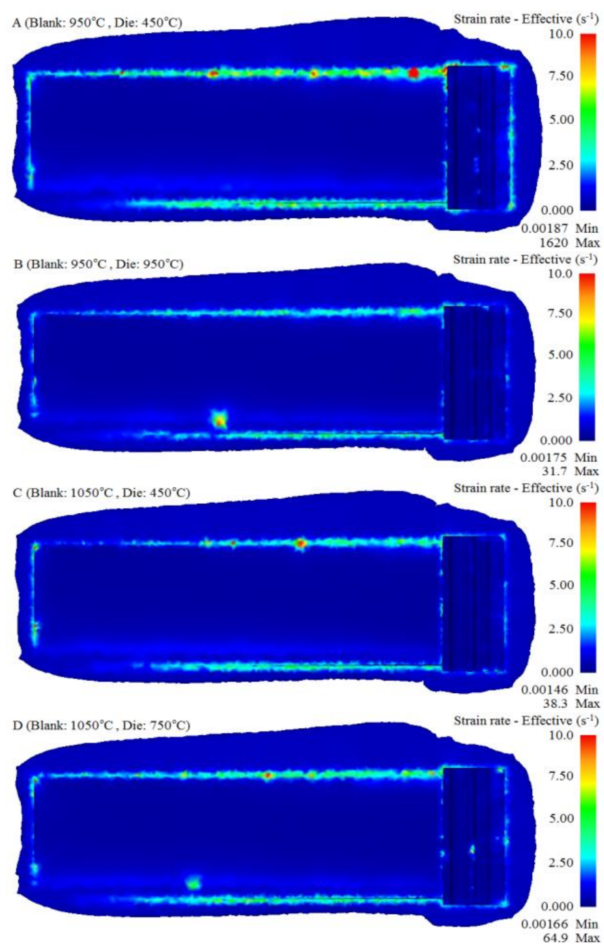


Fig. 16 Blade strain rate distribution in process conditions A to D, respectively

The strain rate is more important criteria relative to stress and others, and should be lower as possible to achieve stable plastic flow [18].

6 CONCLUSION

Forging is one of the significant processes for production of titanium parts. Studying the forging parameters such as preforms, part and die temperatures and strain rate are of great importance to achieve optimal process. In this work, preform design through equipotential lines method and process temperature for material and die are studied in near net hot forging of Ti-6Al-4V compressor blade. Initially, final die and preforms were designed using equipotential lines method. The results have shown that the modified 0.1V preform is the appropriate one for hot forging of the final blade. Then using the 0.1V modified preform, the FE analysis of the process was performed in several temperature configurations for die and preform. According to investigations, using 950℃ for preform and 450℃ for dies results in more appropriate process based on material temperature during the process, controlling the strain, strain rate, stress and necessary tonnage.
In the future works, the effect of final product shape on the process steps and temperature should be studied in hot near net forging of the parts.

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