

Research Article

Optimization of Preform Die Shape for Forging AA2017 Turbine Disk Using Electrostatic Field Theory

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Abstract: Equipotential lines were used to optimize the shape of a preform die for producing aluminum alloy (AA2017) turbine disks. The optimization criteria were complete filling, reduced forging loads and uniform effective plastic strain. Using the optimal preform die identified by the adopted optimization method, the maximum and minimum effective plastic strains were increased from 1.09 and 0.1562 to 1.429 and 0.218, respectively. Moreover, the required forging force was reduced from 3.12 to 2.58 E4 kN. This shows that the preform die reduced the maximum press capacity required to forge the disk. It also produced good results in terms of full filling and the absence of dead zones, which were evidenced by the die contact.

Keywords: Equipotential lines, forging force, plastic strains

INTRODUCTION

The low-cost improvement of the quality of preform dies is of paramount importance in the forging industry because the die determines the quality of the final product. The target factors of the quality control are complete filling of the die without the creation of dead metal zones, mechanical properties that afford uniform effective strain, fine grain size and reduced forging power. There are many methods for determining the preform shape, including the B spline method and backward forging process. In the present study, the electric field method, which is one of the latest techniques, was employed.

This section reviews methods for determining the shape of preforms, with an emphasis on the importance and advantages of improving the mechanical properties. The first part is a review of previous studies on methods for analyzing the performance of preform dies and the second part highlights previous published studies that focused on the use of equipotential lines for determining the form of pre-configuration preform dies.

Forging is used to produce a complex geometry by compressing a billet between dies. The conversion of a rectangular billet into a complex 3D shape requires successive passes through dies, each of which involves the consumption of significant amounts of energy and time. The minimization of the number of die passes without sacrificing the net shape and tolerances is of great interest to researchers and paramount importance to industry. Researchers have used experimental and computational methods to determine the optimum shapes of preform dies.

Lu *et al.* (2009) developed an FE model for optimizing the net 3D shape of a die for forging blade airfoils. They developed B spline methods for surface approximation, which significantly reduced the dimensional and shape tolerances. Thiyagarajan and Grandhi (2005) developed a 3D preform shape optimization method for forging. They used the reduced basis technique, which involves a weighted combination of many trial shapes, to optimize the combination of weights used for a billet. Tumer and Sonmez (2009) optimized the design of a preform and die to achieve better hardness distribution in the final product by cold forging. They used an FE method to evaluate the effective strain distribution in the produced part. Lv *et al.* (2008) conducted a 3D FEM simulation of the multistage forging of a gas turbine compressor blade. The results were validated by comparison with industrial trials. Sedighi and Tokmechi (2008) also proposed a novel two-stage algorithm. The first stage of the algorithm was used to select a preliminary preform and the latter stage was used to improve the geometry. Yanhui *et al.* (2010) used the response surface method together with FEM to improve the deformation uniformity in aerospace forgings. They developed novel parameters for evaluating the effective strain distribution. Zhou *et al.* (2011) used the FEM software Deform 3D to optimize the design of a preform used for forging TA15 Ti-alloy components. They experimentally determined the preforms with good macroscopic forming qualities and fine microstructures. Guan *et al.* (2009) applied micro-genetic algorithms and FEM to the preforming and final forming of the H-shaped forgings. Yang and Ngaile (2011) also studied a two-stage preforming process as well as wrinkle

formation and its elimination from the forming stages. The results were validated by application to SS 304 tubing.

Many researchers have recently used the theory of the similarity of equipotential lines to optimize the shapes of forging preforms. The equipotential lines between two conductors with a potential difference between them exhibit characteristics similar to those of the minimum work lines between an initial undeformed shape and a final deformed shape. Lee *et al.* (2002) introduced the application of equipotential lines to the determination of suitable preform shapes. They also used artificial neural networks to optimize the related parameters. Cai *et al.* (2011) used electrostatic field simulation to design preforms for forging large Ti-alloy aircraft frames and introduced the deformation uniformity index for determining the most appropriate preform. Liu *et al.* (2006) used the equipotential line method to design turbine disks by means of powder metallurgy. They proved that the differential equation of the electric potential ($\nabla^2 \phi = 0$) was similar to that of the velocity potential ($\nabla^2 \varphi = 0$). They also compared the equipotential preform method with traditional preform design methods and demonstrated the practicability of the former. Xiaona and Fuguo (2009) introduced the preform method to the design of P/M superalloy disks. They used the industrial software MSC/SuperForm to determine the equivalent strain distribution in the final forging and the uniform deformation during preforming and final forming.

The objective of the current study is to find an optimum shape of a preform die for a forged AA2017 turbine disk using the method of equipotential lines. Section two presents the materials and methods used, the analysis is discussed in section three and the conclusions are summarized in section four.

MATERIALS AND METHODS

The shape of the equipotential lines is one of the factors that simplify the choice of the best preforming die. The steps for designing the preform die are shown in Fig. 1. The first step is the initial design of the workspace of the raw material in the form of a bucket and the design of the shape of the final product using CAD.

The second step is the creation of the equipotential lines around the product. An initial value of 1 V represents the raw material and 0 V represents the final shape. The simulation of the equipotential lines is done using ANSYS. The third step is the choosing of the best shape of the equipotential lines for achieving the best shape of the preform die.

The scale-down factor in the use of equipotential lines is worth mentioning. Forging is a constant volume process and the volumes of the billet and the final product are fixed. Regarding the equipotential lines, because they are drawn in three dimensions, each line generates a different volume when rotated. Each of these volumes has to be scaled down in the modeling.

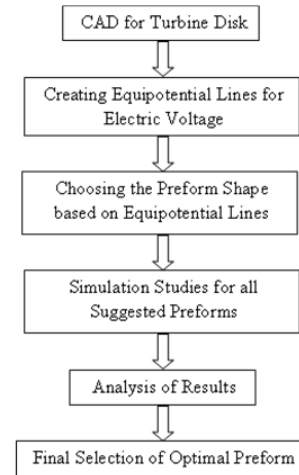


Fig. 1: Process for selecting final shape of die



Fig. 2: Three dimensional CAD model of turbine disk in bucket

Table 1: Simulation parameters for modeling

Die temperature	Billet temperature	Air temperature	Forging velocity
230°C	430°C	50°C	300 mm/sec

The scaling down is done to match the final constant volume of the forged product while maintaining the shape of the equipotential line. Using this method in our study, eight forms were generated from the equipotential lines surrounding a turbine disk. The 3D forms of the equipotential lines were graphically represented.

The fourth step is the analysis of the preforms to determine the effective plastic strains and complete die contacts. These values are analyzed in the fifth step to choose the final preform.

Figure 2 illustrates the first step in determining the final shape of the product and the form of the raw material. The figure is shown in a bucket that contains the final form of the product.

The determination of the FEM mesh is an important step in assessing the accuracy of the shape of the pre-forming mold. In Fig. 3, there are eight lines that show the possible preform shapes after the generation of the equipotential lines. Their values range from 0 to 1.

Choosing the best operation parameters facilitates the production of good quality products by hot forging. Such parameters enable the mass production of forged parts at minimal costs. Table 1 shows the parameters used to simulate the die and the billet. The temperatures

of the die and billet were considered to be 230 and 430°C, respectively. The ambient air temperature was considered to be 50°C and the forging velocity was maintained at 300 mm/sec.

RESULTS AND DISCUSSION

Figure 4 shows the shapes of the equipotential lines ranging from 0 to 1. The final shape of the product represents the equipotential line when the value is 0 and 1 represents the raw material. A total of eight equipotential lines were generated, each of which had a value between 0 and 1. It might be noted that Fig. 4 represents a band of values between 0 and 1.

A vertical cross section of the turbine disk showing the equipotential lines is shown in Fig. 5. The outermost line, which has a value of 1, represents the shape of the raw material. The three adjacent lines also closely match the shape of the raw material to varying degrees. The innermost line, which has a value of 0, represents the shape of the final product. The shapes of

Table 2: Effective plastic strains for different preform die designs

Electric voltage	Effective plastic strain			
	Die	Min.	Max.	Range
0.11-0.22	Preform 1	0.100	1.125	1.025
0.22-0.33	Preform 2	0.102	1.112	1.010
0.33-0.44	Preform 3	0.078	0.858	0.780
0.44-0.56	Preform 4	0.071	0.793	0.722
0.56-0.67	Preform 5	0.058	0.802	0.744
0.67-0.78	Preform 6	0.047	0.730	0.683
0.78-0.89	Preform 7	0.043	0.505	0.462
0.89-1.00	Preform 8	0.031	0.330	0.299

Min.: Minimum; Max.: Maximum

the lines adjacent to it are close to that of the final product to varying degrees.

The values of the effective plastic strain obtained for variations of the preform die design are given in Table 2. Eight equipotential line simulations were conducted for the different preforms shapes suggested earlier. The first column gives the range of the electric voltage for each preform shape. The table also gives the minimum and maximum effective plastic strains and

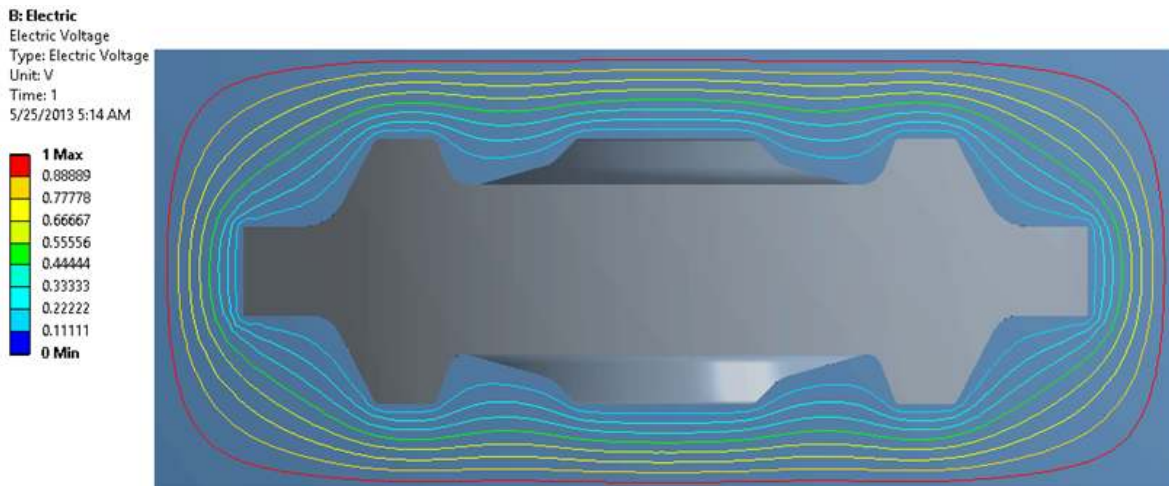


Fig. 3: Equipotential lines between 0 and 1 to optimize the shape of the preform

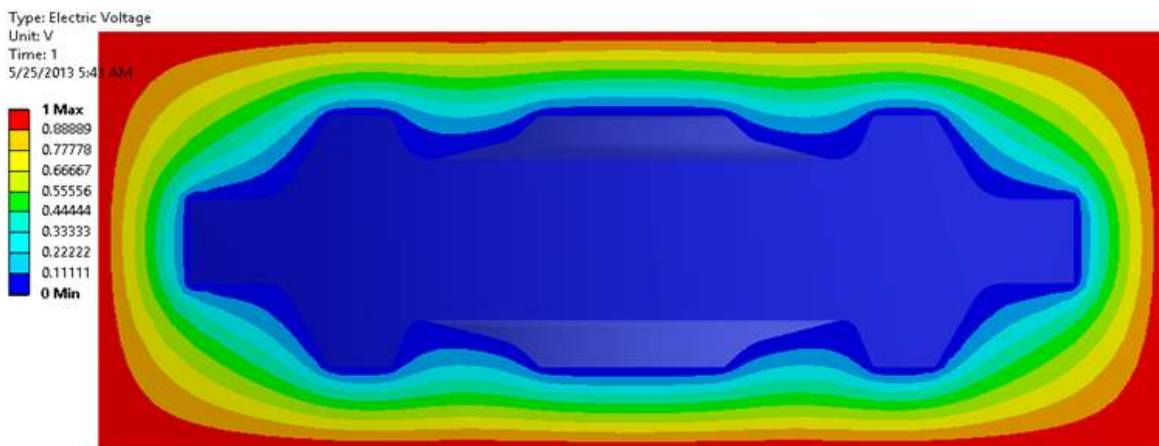


Fig. 4: Equipotential fields showing bands ranging between 0 and 1

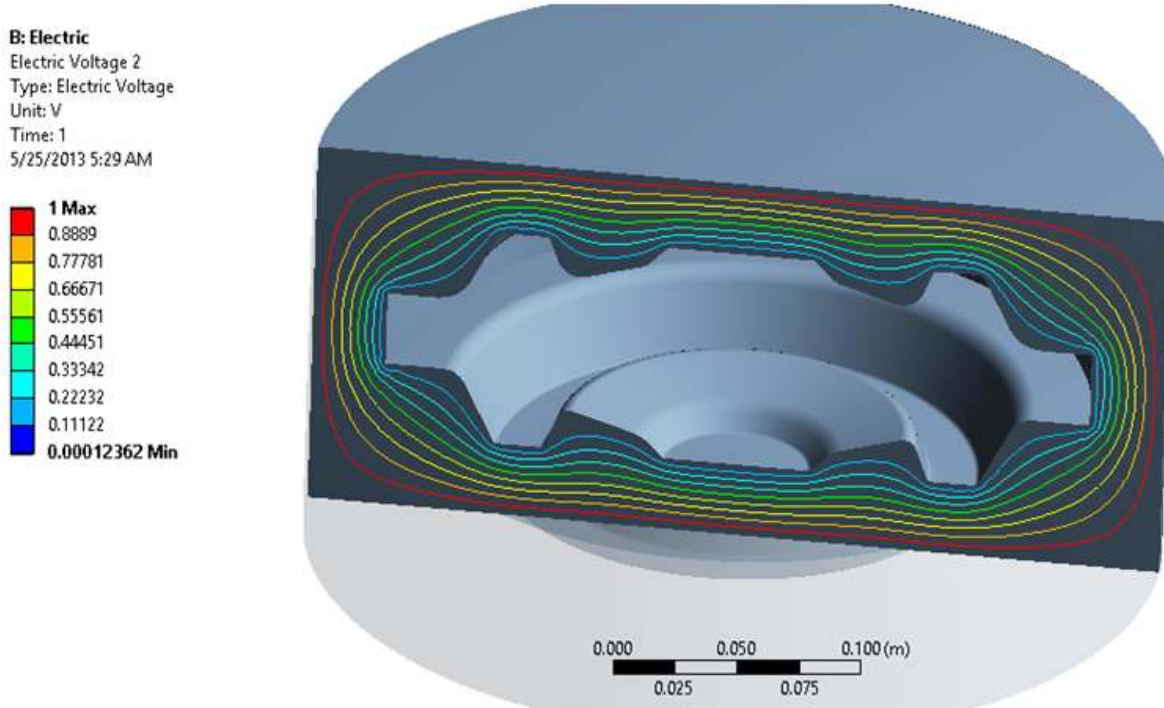


Fig. 5: Vertical cross section of turbine disk showing equipotential lines

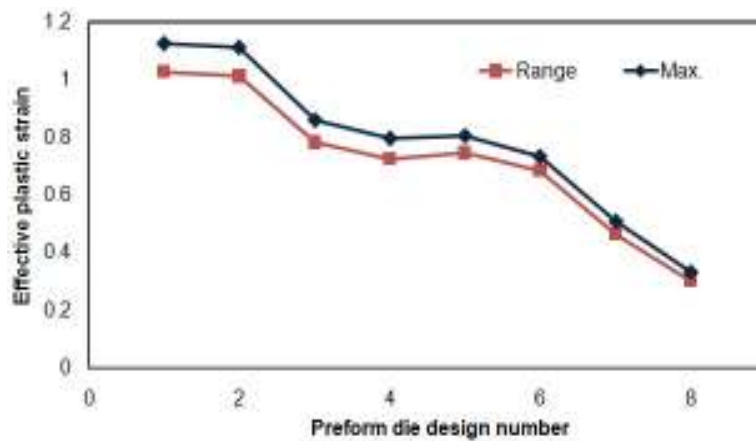


Fig. 6: Effective plastic strains for different preform designs

the range for each preform. The strains were obtained at the vertical cross section in the plane of symmetry.

The analytically determined effective plastic strains in Table 2 were used for the analysis used to obtain the final die design. The final effective plastic strains are given in Table 3. The last line of the table contains the effective plastic strain for the case in which there was no intermediate preform die. It can be seen that final die 4 gives a desirable maximum strain and optimal range.

Figure 6 is a graphical representation of the effective plastic strains given in Table 2, which correspond to the eight preform analyses. It can be seen that a maximum effective plastic strain of 1.125 and range of 1.025 were obtained for preform die 1,

Table 3: Effective plastic strains for final forging die designs

Electric voltage	Effective plastic strain			
	Die	Min.	Max.	Range
0.11-0.22	Final die 1	0.1705	1.396	1.2250
0.22-0.33	Final die 2	0.1770	1.320	1.1430
0.33-0.44	Final die 3	0.2180	1.374	1.1560
0.44-0.56	Final die 4	0.2180	1.429	1.2110
0.56-0.67	Final die 5	0.0000	1.364	1.3640
0.67-0.78	Final die 6	0.2100	1.260	1.0500
0.78-0.89	Final die 7	0.0000	1.209	1.2090
0.89-1.00	Final die 8	0.2250	1.218	0.9930
-	Direct forging	0.1562	1.090	0.9338

Min.: Minimum; Max.: Maximum

whereas the maximum effective plastic strain and range for preform die 8 were 0.33 and 0.299, respectively.

The results tabulated in Table 3 are graphically represented in Fig. 7. It should be noted that nine results are plotted in the figure, with the ninth corresponding to direct forging die. It can be clearly seen that the highest maximum plastic strain was obtained for die 4, which also has the optimal range.

The effective plastic strains on the surface of the turbine disk in the first stage of preforming are shown in Fig. 8. It can be observed that the deformed shape had a good match with the equipotential field lines. Most of the effective plastic strains were uniform and within the range of 0.071-0.929. The range of the strains is also relatively small, which indicates uniform deformation.

The effective plastic strains on the surface of the disk at the final stage are represented in Fig. 9. It can be seen that the effective plastic strains were quite uniform and well within the range of 0.218-1.429. The final values of the effective plastic strain were also higher compared to current prevalent values in forging without preform.

The completeness of the die contact is shown in Fig. 10. Most of the values are in the vicinity of 1.0, which indicates excellent die filling and contact. The lower values of the contact are in the region where there were flashes during the forging and are not detrimental to the final die.

The results of the effective plastic strain analysis of the forging process are shown in Fig. 11. The analysis was performed by dividing a cross section into four zones. An examination of the cross section of the turbine disk reveals that the total effective plastic strain was well within the range of 0.218-1.429, which indicates uniform strain in the entire body. The results are also depicted in Fig. 12. The effective plastic strain range shown in blue will mostly not be present in the actual disk because a hole will be drilled in the center of the disc.

The average effective plastic strain values for the four zones mentioned above are plotted in Fig. 12. The figure compares the effective plastic strains in the final forging after using preform 4 with one without using any preform. The effective plastic strains are clearly greater in all the four zones when using the preform.

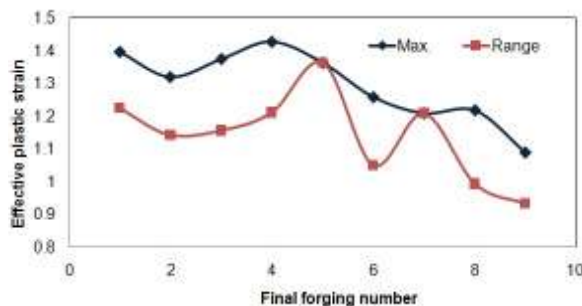


Fig. 7: Effective plastic strains for different preform dies

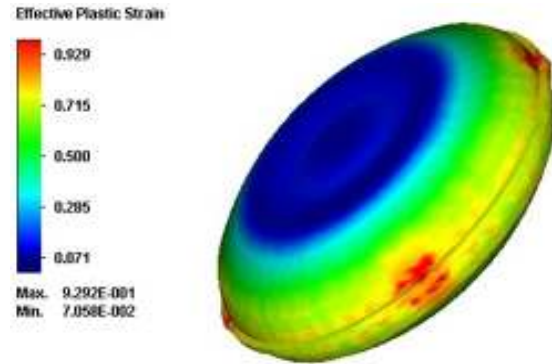


Fig. 8: Effective plastic strains on surface at intermediate stage

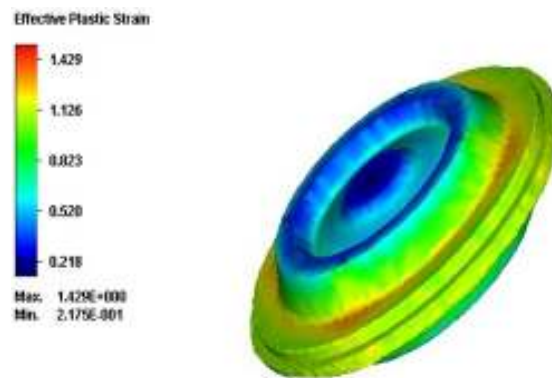


Fig. 9: Effective plastic strain on surface at final stage

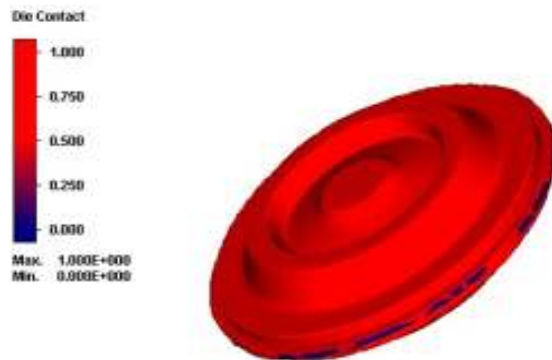


Fig. 10: Flow of material and contact with die form

Areas of low effective plastic strain constitute a known problem in the design of turbine disks and the use of the performing die increased the effective plastic strain in all areas of the disk. As indicated in Table 3, the die increased the maximum plastic strain at the final stage from 1.09 to 1.429 and the minimum plastic strain from 0.1562 to 0.218.

For preform die 4, the average effective plastic strains in the four zones of the vertical cross section were between 0.295 and 1.168. The corresponding values without using the preform were between 0.218 and 0.817.

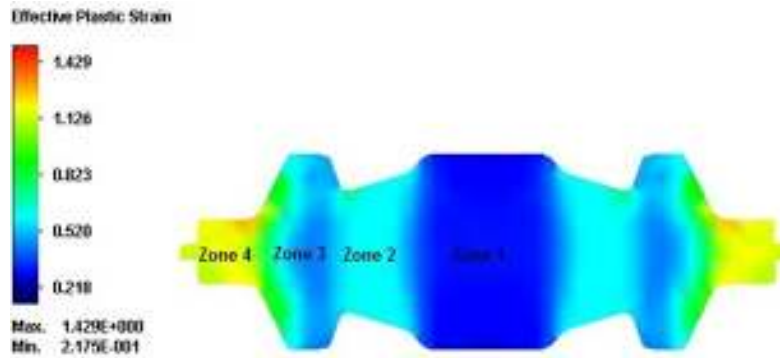


Fig. 11: Effective plastic strains at vertical cross section

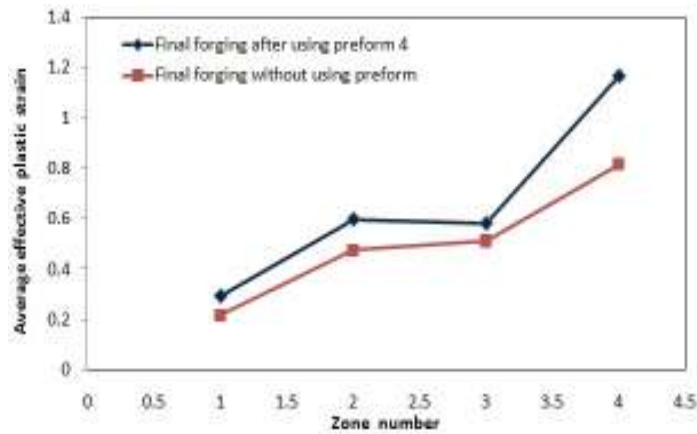


Fig. 12: Comparison of effective plastic strains with and without preform

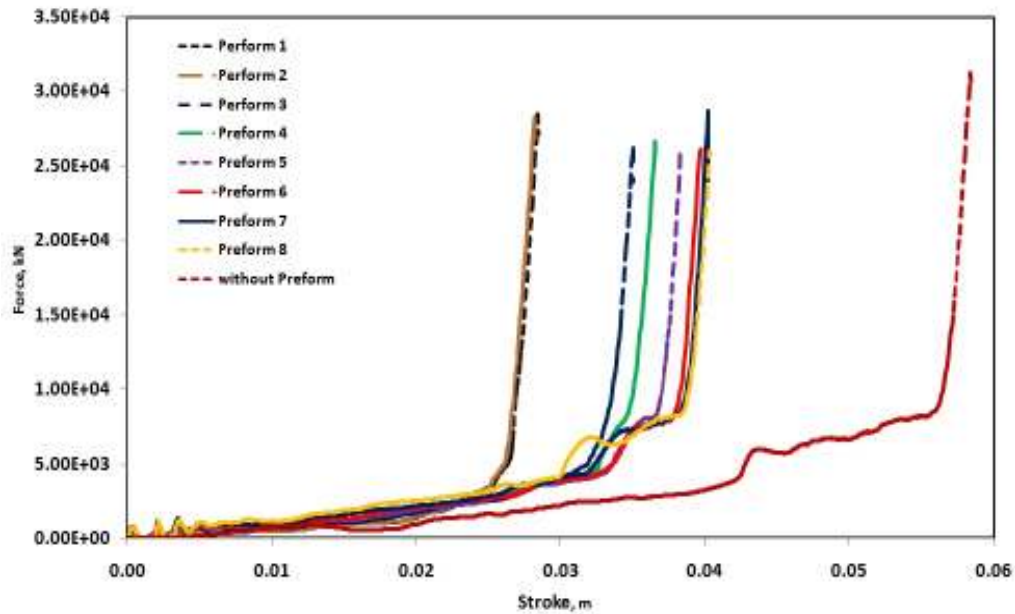


Fig. 13: Forces required for forging in final stage for eight preforms and without using preform

Figure 13 shows the force required for forging in the final stage. The analysis was carried out for all the eight preforms. As can be seen, the required force

without using a preform is 3.12 E4 kN, whereas the minimum required force using preform 4 is 2.58 E4 kN. This clearly shows that the use of the preform reduced

the maximum capacity of the press required for the forging.

The results of the foregoing analyses clearly indicate that using the shape of the equipotential lines for the design of preforms produces good results. It produces homogeneous effective plastic strain and filling of the die within the limits of the available forging press power.

CONCLUSION

The use of equipotential lines for the design of preforming dies increased the maximum plastic strain from 1.09 to 1.429 and the minimum plastic strain from 0.1562 to 0.218. Without using a preform, the required forging force was 3.12 E4 kN, whereas when a preform was used, the minimum required force was 2.58 E4 kN. This clearly shows that the preform reduced the maximum capacity of the press required for forging.

The proposed use of equipotential lines for the design of preforms was shown to improve the quality of the preform, promote complete filling of the die, reduce flash and produce uniform effective plastic strain throughout the forging process. Analyses showed that preforming die 4 used in the study increased the effective plastic strain in all areas of a turbine disk. The results of the study showed that the use of a preform was an effective and low-cost method for determining the shape of the preforming die. It can be used to increase production volume and reduce costs.

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