A Three-Dimensional Simulation of Isothermal Turbine Blade Forging by the Rigid-Viscoplastic Finite-Element Method

D.Y. Yang, N.K. Lee, and J.H. Yoon

This study is concerned with the three-dimensional analysis of isothermal turbine blade forging by the rigid-viscoplastic finite-element method. In the present finite-element simulation, the interface friction along the curved die surfaces is included, and as a remeshing technique, so-called modular remeshing is used. Comparison between the initial and final computed product shows a three-dimensional deformed configuration of a turbine blade and demonstrates that the length of the final deformed blade is increased. The computational results may be effectively applied to other types of three-dimensional turbine blade forging processes.

Keywords:
isothermal, modular remeshing, turbine blade

1. Introduction

THE turbine blade is one of the most important mechanical components in industry, and it requires high precision in die design and manufacturing. The design and manufacturing of dies for forging of turbine blades involve typical applications for the integration of CAD/CAM and CAE. Turbine blade forging has been analyzed so as to predict the load, optimal die design, best preform position before forging, and the minimum stock volume necessary to fill the die cavity. The turbine blade geometry is obviously three dimensional, because it has a twisted shape from the root to the end of a blade. Until now, most of the experimental analysis of turbine blades has been simulated as two-dimensional plane-strain problems. The plane-strain condition prevails in blade forging where metal does not flow practically in the length direction of the blade section. As for two-dimensional forging of blades, there have been some analytical and numerical approaches for forging airfoil section blades.

Aksenov *et al.*[1] used the slip-line method for determining the working pressure in plane-strain side-pressing of circular rods to form turbine blade sections. Akgerman and Altan[2] described the application of CAD/CAM in forging a turbine blade and obtained the approximate stresses and forging load by using the slab method. Rebelo *et al.*[3] and Dung and Mahrenholtz[4] simulated the closed die blade forging process by the model technique as well as by the rigid-plastic finite-element method. In determining a preform for forging of an airfoil section blade without flash, Kang *et al.*[5] used the backward tracing technique by the finite-element method.

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In the above research, forging of an airfoil section blade or a turbine blade was treated as a two-dimensional plane-strain problem. However, to obtain a more realistic deformed configuration and more precise information for deformation, a three-dimensional finite-element simulation is required, which is applicable to three-dimensional blade forging with an arbitrarily curved die. To date, only Argyris *et al.*[6] successfully analyzed the process for all the deforming stages from the initial billet to the final product using the three-dimensional finite-element method by considering the thermal effect. In the analysis, however, the frictionless condition is assumed at the contact surfaces between the material and the die, which is far from the actual situation in hot forging. In frictionless forging of a turbine blade, remeshing may not be required. With friction considered in hot forging of a turbine blade, a remeshing stage might be required for the full computation to the end of the forging process.

In the present work, a three-dimensional finite-element analysis of isothermal forging of a turbine blade is carried out on the basis of a rigid-viscoplastic material model and by considering the frictional condition. The modular remeshing scheme[8-10] is effectively used for the simulation of the turbine blade forging process.

2. Rigid-Viscoplastic Finite-Element Formulation

The variational equation for a rigid-viscoplastic material model is given by the following:[7]

$$\int_{V^w} (\bar{\sigma} + \alpha \Delta t \dot{\bar{\varepsilon}} H')\delta \dot{\bar{\varepsilon}}\, dV + K\int_{V^w} \dot{\varepsilon}_v \delta \dot{\varepsilon}_v dV - \int_{S_f^w} (f_i + \alpha \Delta f_i)\delta v_i\, dS = 0 \qquad [1]$$

where

$$\bar{\sigma} = \sqrt{(3/2)\sigma'_{ij}} \quad \dot{\bar{\varepsilon}} = \sqrt{(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad \dot{\varepsilon}_v = \dot{\varepsilon}_{ii}$$

and K, σ'_{ij}, H', and α are the penalty constant, deviatoric stress, strain-hardening rate, and the constant in considering the workhardening effect ($0 \le \alpha \le 1$), respectively. V^w and S_f^w denote the volume and tractional boundary surface of the workpiece, respectively.

The frictional boundary condition is given by the following vector form:[7]

$$\mathbf{f} = -\frac{2}{\pi} m\, k \tan^{-1}\left(\frac{|\mathbf{V_s}|}{u_o}\right)\mathbf{t} \qquad [2]$$

where m is the friction factor, k is the local flow stress in shear, and u_o is a very small positive number as compared to $|\mathbf{V_s}|$; $\mathbf{V_s}$ is the velocity vector of the workpiece relative to the die, and $\mathbf{t}$ is the unit vector in the direction of $\mathbf{V_s}$. An initial velocity field is generated by assuming a linear viscous material.[7] The velocity boundary conditions and the frictional boundary conditions on arbitrarily curved surfaces are imposed by using the skew boundary condition successively. Equation 1 is discretized at the elemental level with isoparametric elements.

3. Modular Remeshing in Turbine Blade Forging

In the modular remeshing scheme, the computational region is divided into several zones, each of which is characterized by its geometry and plastic flow. Such a unit zone is called a module, which has its mesh-structural characteristics of geometric complexity and physical flow and geometric adaptability. Each module facing the contacting surface has a so-called surface adaptive layer of aligned elements. When using hexahedral elements, any inner transverse surface of each element is constructed such that it is normal to the die surface. The arrangement of nodal points is made in such a way as to retard the mesh degeneracy by considering the geometric and flow characteristics of each module. Each module is designed so that different modules are independently generated and that the developed modules are stored as a library of geometric parts.

Some basic modules have been selected for the present analysis, as shown in Fig. 1. Figure 1(a) is the simplest module in which elements are regularly connected. This module is most frequently used, whereas Fig. 1(b) is used to economize the computation time by refining the element size locally. Figures 1(c) and (d) are used at the free end of the workpiece geometry where the workpiece is free from contact and is likely to come into contact with the die. If the topology of the modules remains the same, then the modules are treated as the same module.

In the present article, the concept of sensitive planes or surfaces[8] is introduced for the design of a three-dimensional module. Figure 4 shows the shape of the initial finite element

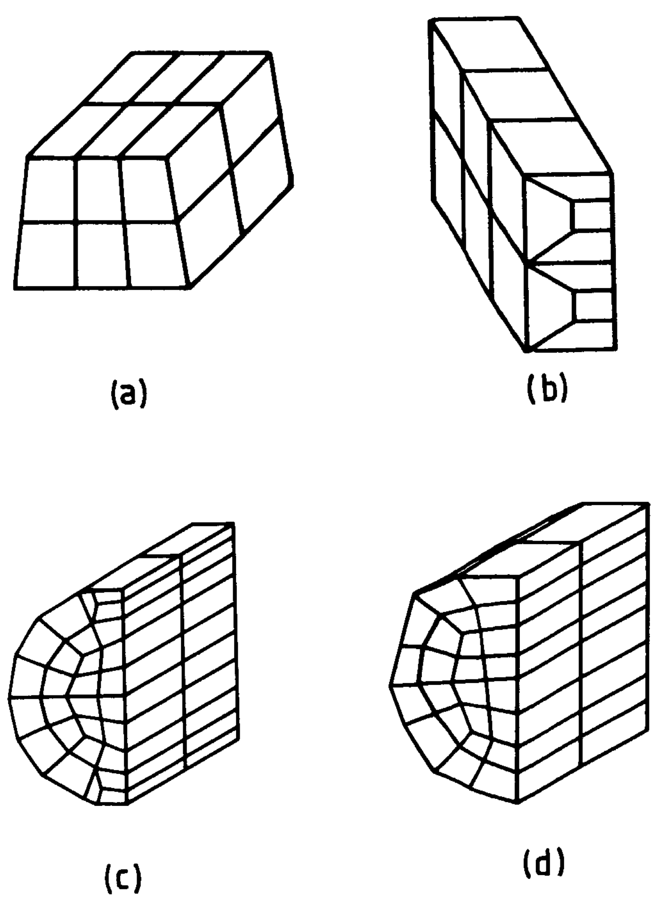

Fig. 1 Selected modules for the analysis of turbine blade forg-

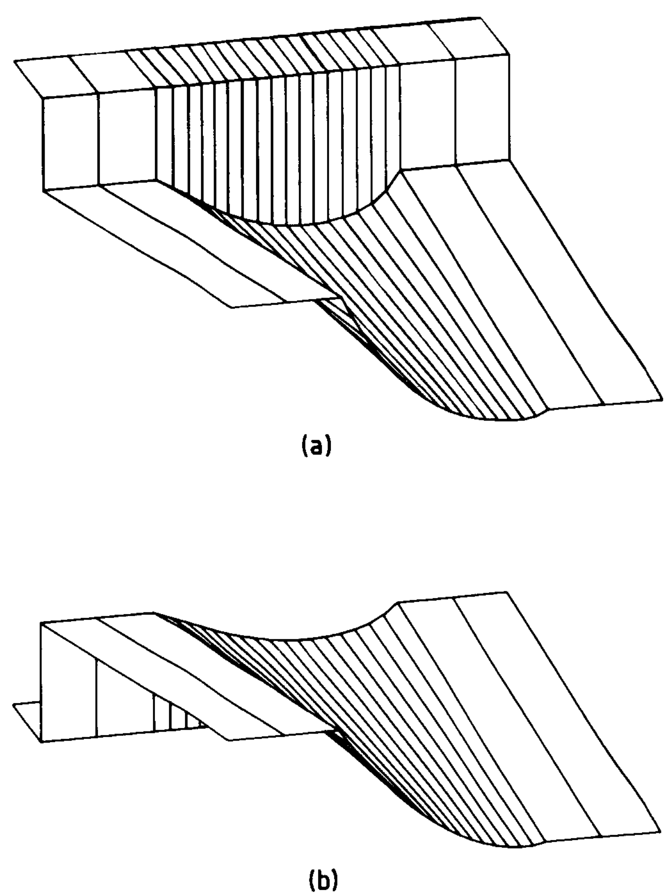

Fig. 2 View of the upper and lower die.

mesh system designed by using the sensitive surface concept.[8] The remeshing criteria also are used as introduced in the previous work.[8,9]

4. Finite-Element Simulation of Forging of a Turbine Blade

Using the formulation of the rigid-viscoplastic finite-element method, forging of a turbine blade has been simulated. A perspective view of the upper die and lower die used in the simulation is shown in Fig. 2. The shape of the dies is represented by the ruled surface, which is constructed from linear interpolation of the blending functions.

The material of the workpiece used in the analysis is Ti-6Al-4V, and the stress-strain rate relationship (measured in MPa) at the working temperature of 1237 K is obtained from Ref 6 as the following:

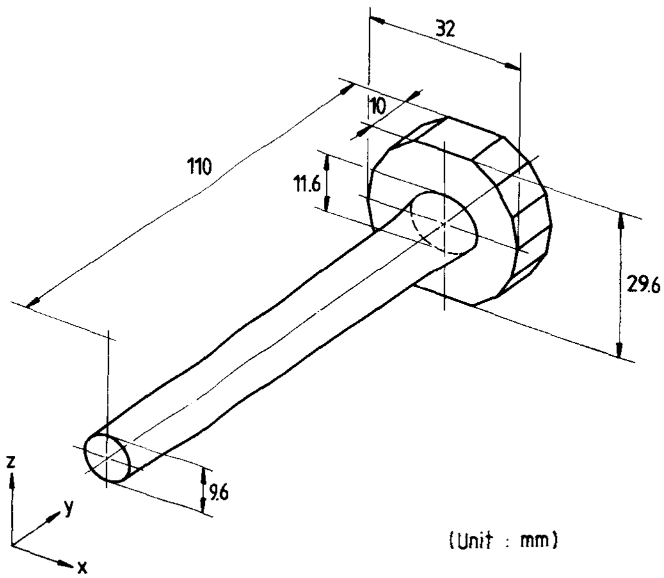

Fig. 3 Initial billet for the simulation of turbine blade forging.

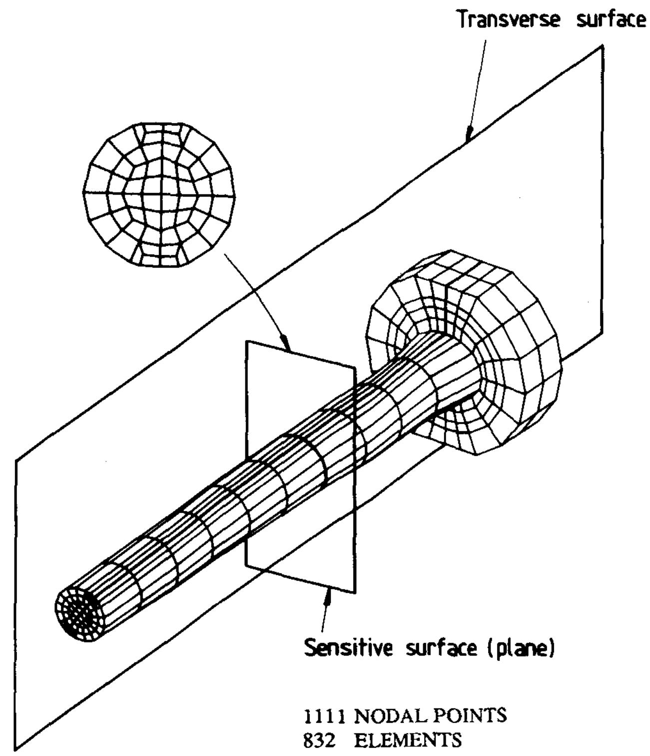

Fig. 4 Initial mesh system and concept of S.-T. (sensitive-transverse) surface for turbine blade forging.

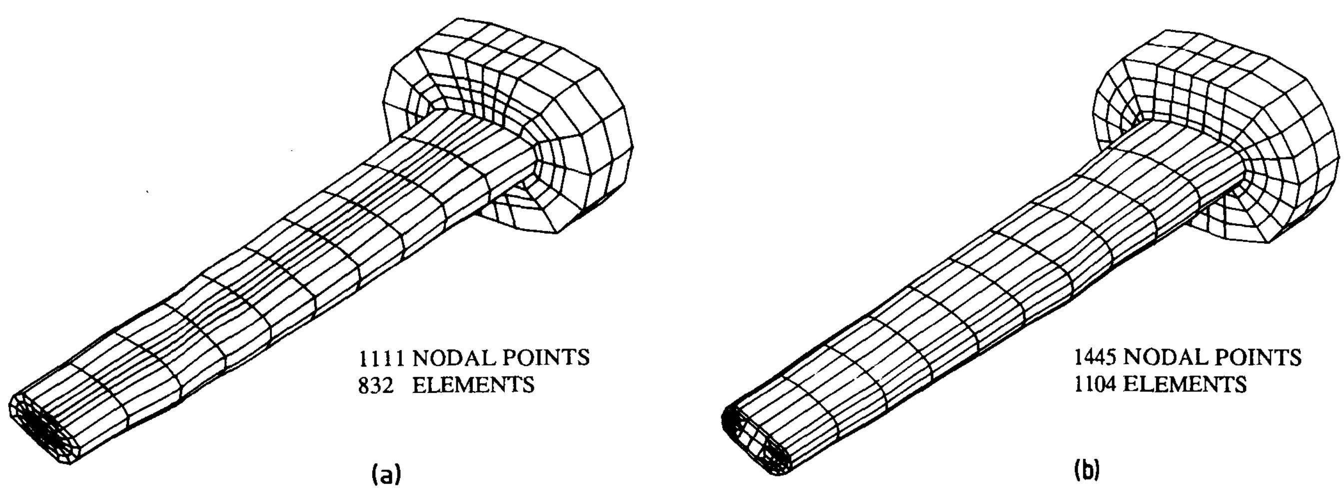

Fig. 5 Computed deformation pattern at a height reduction of 4.8 mm for turbine blade forging. (a) Before remeshing. (b) After remeshing.

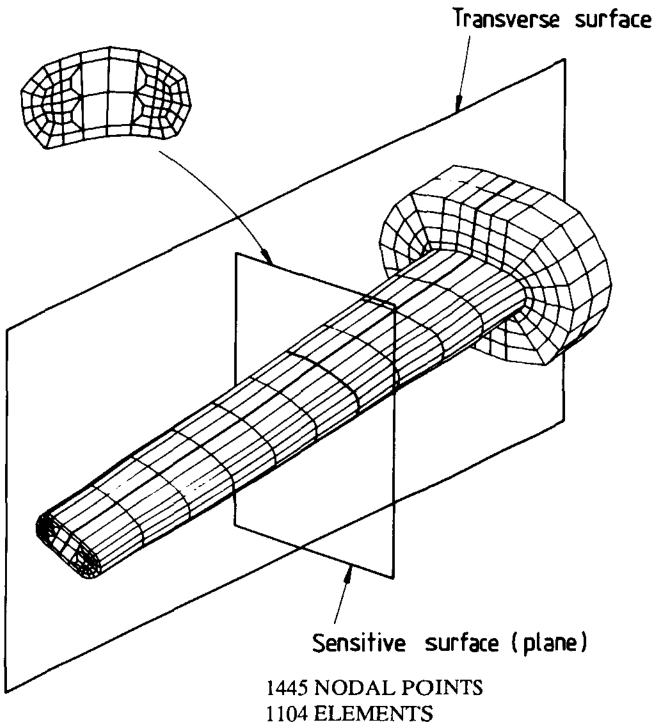

Fig. 6 Concept of S.-T. surface of modular remeshing.

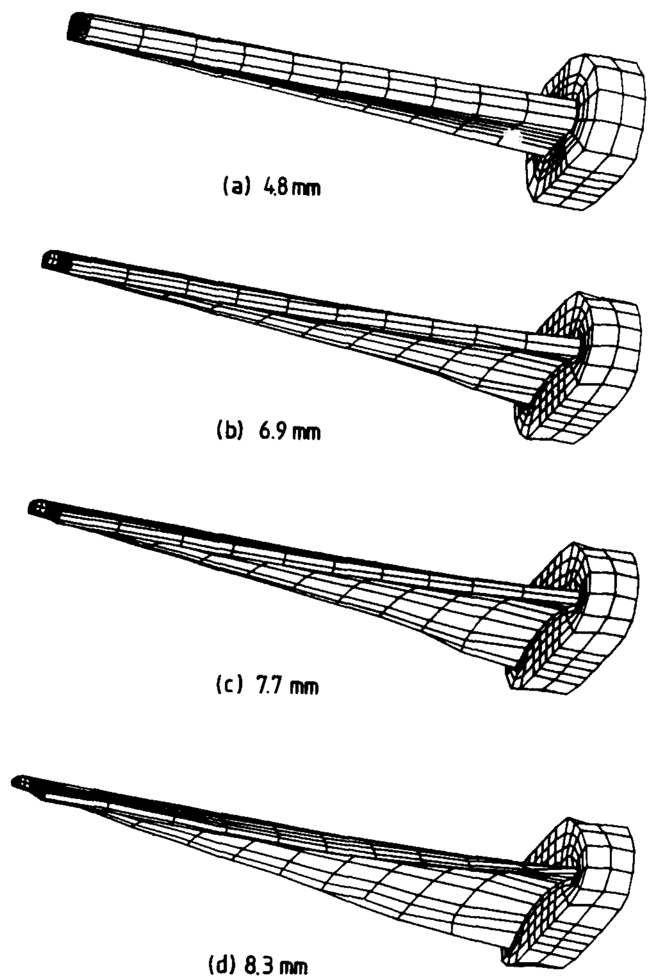

Fig. 7 Computed deformation pattern at a height reduction of (a) 4.8 mm, (b) 6.9 mm, (c) 7.7 mm, and (d) 8.3 mm.

$$\bar{\sigma} = 62.93\,(\dot{\bar{\varepsilon}})^{0.5} \qquad [3]$$

The upper die velocity is taken to be 50 mm/s, and the friction factor m is taken to be 0.12.

Figure 3 illustrates the detailed dimensions of the initial billet, and Fig. 4 shows the initial finite-element mesh system. A total of 832 elements and 1111 nodal points were used for construction of the initial finite-element mesh system.

Figure 5(a) shows the computed deformed pattern at the height reduction of 4.8 mm. The deformed configuration just before arriving at the mesh degeneracy is obtained at this stage. For the mesh structure shown in Fig. 5(a), remeshing was carried out with the mesh structure of Fig. 5(b), which was constructed by using the sensitive surface concept, as shown in Fig. 6. The mesh system in Fig. 5(b) is composed of modules (see Fig. 1(a) and (b)). A total of 1104 elements and 1445 nodal points were used for remeshing.

Figure 7 illustrates the stages of deformation during the forging process at height reductions of 4.8, 6.9, 7.7, and 8.3 mm. Figure 8(a) and (b) show the distribution of the effective strain rate at the height reduction of 7.7 and 8.3 mm, respectively. Figure 8(b) demonstrates that the distribution of strain rate is large at the lateral edge of a turbine blade section along the lengthwise direction. These figures show that deformation is severe near the lateral edge of a turbine blade section because the deformation velocity of the material is high at the final forging stage. Figure 9 shows a three-dimensional deformed configuration of a turbine blade and demonstrates that the length of the final deformed blade is increased by 11.75 mm compared to the initial billet. The total computation including one remeshing stage required about 10,000 CPU seconds on a CRAY-2S computer. The forging load versus height reduction curve obtained from the computation is shown in Fig. 10. A steep increase in the forging load takes place at the final forging stage as a typical characteristic of closed die forging.

5. Conclusions

Using the rigid-viscoplastic finite-element method, isothermal forging of a turbine blade was simulated. The frictional boundary condition was considered at the contact surfaces between the material and the dies. The modular remeshing scheme was used effectively. Computation was carried out with one intermediate remeshing stage. The three-dimensional deformed configuration at various stages, as well as the forging load curve, was obtained from the finite-element simulation. It was thus shown that a three-dimensional finite-element analy-

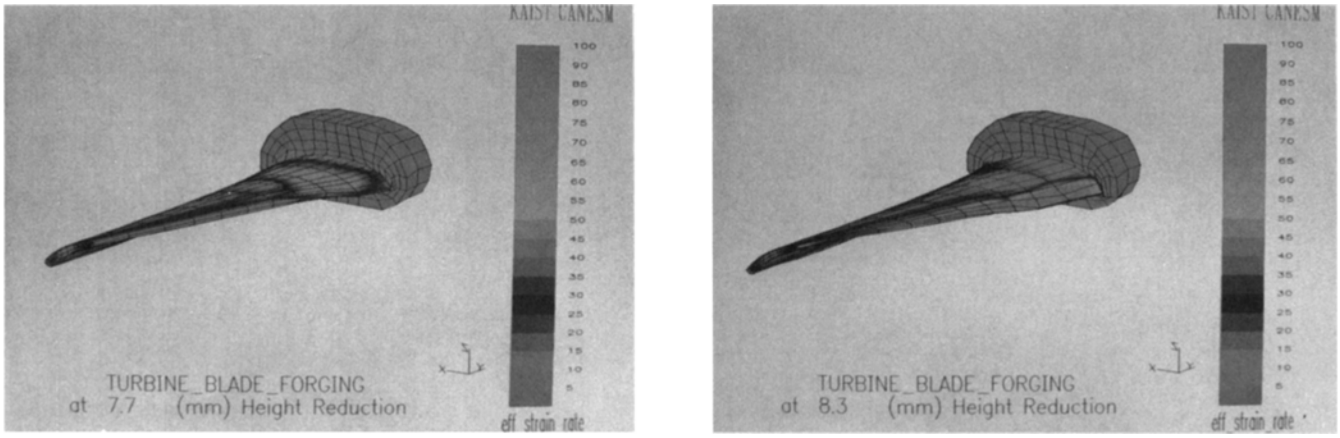

Fig. 8 Computed deformation pattern and distribution of the effective strain rate at a height reduction of (a) 7.7 mm and (b) 8.3 mm.

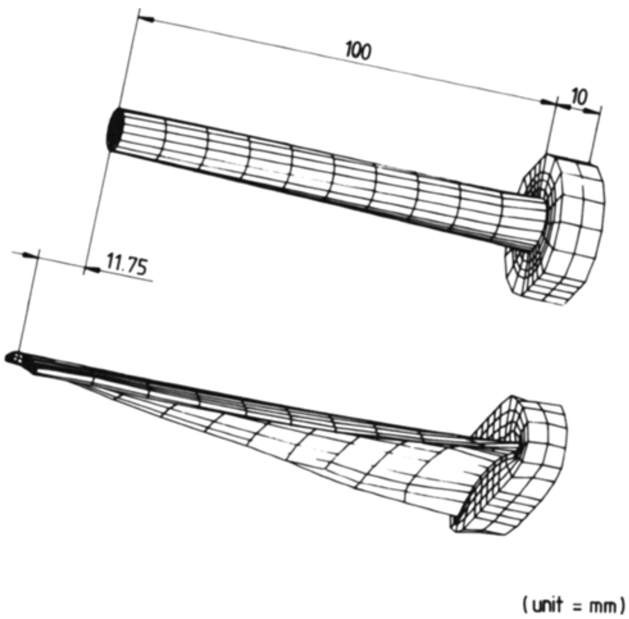

Fig. 9 Comparison of deformed shape between initial billet and final turbine blade product.

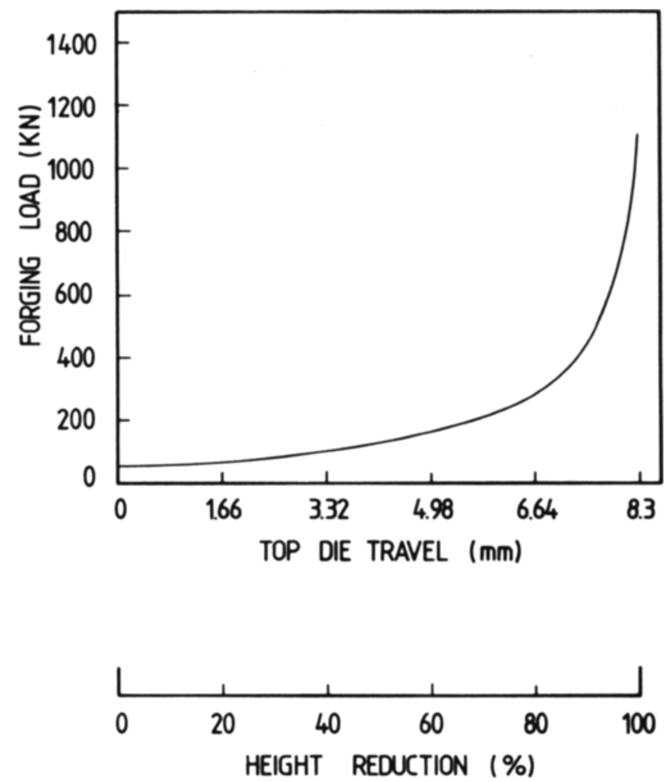

Fig. 10 Variation of forging load with respect to percentage reduction of height for turbine blade forging.

sis will provide valuable aid for the design and manufacturing of dies for turbine blade forging.

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