Punch Design for Uniaxial Forging Process of γ-TiAl using Comsol Multiphysics

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Abstract: The increasing demand for improved metallurgical products strongly motivates the optimization of manufacturing processes and design of γ-TiAl products. Among the large variety of available forming processes, cold closed-die forging is particularly suitable for producing net shape bulk products having good surface finish with better mechanical properties. Pressing punches of suitable profile are required to plastically form the material into desired geometries.

Computer modeling represents an effective and cost effective method to find optimal process setup conditions together with optimal product geometry and material properties.

The present work focuses on the feasibility study of uniaxial cold closed-die forging of shaped and flat γ-TiAl thick disks by computer modeling. Three different punch profiles are examined, namely, flat, concave and convex. The results show that the convex-punch/flat-disk configuration exhibits the highest stress state within the punch/die/disk system. Convex punches promote larger stress states than flat punches, whereas flat punches enhance plastic flow compared to concave punches.

Keywords: uniaxial cold forming, γ-TiAl, thick disk, closed-die forging, elasto-plastic, contact mechanics.

1. Introduction

Over the last 20 years many efforts have been focused on the development of γ-TiAl intermetallic alloys as new candidate structural materials for high temperature applications in aerospace and automotive industry thanks to their excellent creep and oxidation resistance and mechanical specific properties [1,2]. However, γ-TiAl alloys exhibit very low ductility at room temperature (about 0.5-1% fracture strain) which makes them very difficult to form or machine via conventional manufacturing routes.

A recent study shows the successful workability of a TiAl alloy during isothermal closed-die forging at 1100-1150 °C taking advantage of prior grain refinement of the initial microstructure[3].

To the authors' knowledge, the workability of a prior refined γ-TiAl alloy by cold closed-die forging is not studied yet.

In the present work, a feasibility study on the net-shape cold forming of flat and shaped (e.g. convex) γ-TiAl thick disks by uniaxial closed-die forging is performed by computer modeling. The forming pressure is exerted by two counter sliding steel punches. To produce net shaped disks, the shape of the pressing punches has to be adequately designed. The final aim of the work is twofold: a) improve the basic understanding of the net-shape cold forming of flat and shaped γ-TiAl thick disks; b) study the convergence behaviour of the elasto-plastic model when curvilinear boundaries are assigned either to punches (i.e. master) or to disk (i.e. slave). The underlying process model is figured in the general class of elasto-plastic/contact problems accompanied by large strains. An attempt is made to model closed-die forging process using COMSOL Multiphysics.

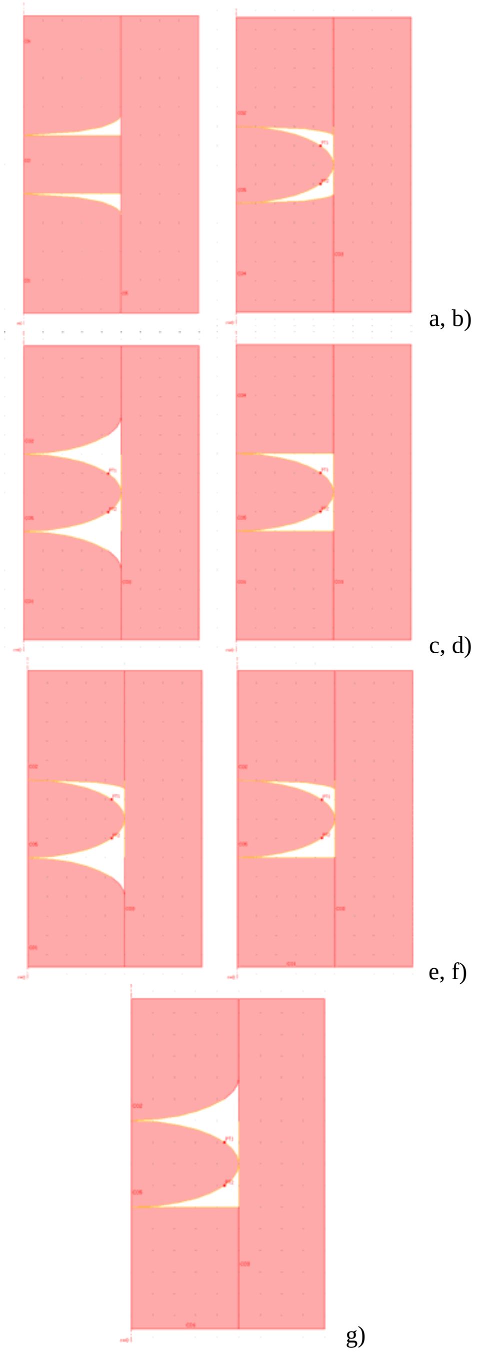
2. The Physical Model

When assessing the workability of a closed-die forged alloy three basic factors are taken into account: a) friction, b) geometry and c) material. For simplicity, the former factor is neglected here, whereas the latter two are investigated in detail.

The axial-symmetric geometry of the investigated mould/punch/sample assembly is shown in Fig.1.

The closed-die forging process is modeled by invoking a static elasto-plastic analysis as a function of a variable displacement parameter. A sequence of successive steady state configurations can be computed assuming constant boundary/point contact conditions and non linear material properties under a displacement control mode.

The punches as well as the disk are designed to have either or both flat, convex or concave surfaces.


a, b)

c, d)

e, f)

g)

Figure 1. Profile geometries of investigated punches (p), sample disk (d) and mould (m).

The disk is assumed to deform elasto-plastically with a specified experimental hardening model.

To make sure that the contacting moulds are sufficiently constrained they are drawn in contact since the initial position (assembly mode is used). In addition, an initial contact pressure of 10^{-3} Pa is applied.

3. Governing Equations

The total effective strain ε_{eff} in the disk is written as the sum of plastic strain ε_{pe} and elastic strain:

$$\varepsilon_{eff} = \varepsilon_{pe} + \frac{\sigma_e}{E}$$

where E is Young's modulus and σ_e is effective stress. The latter can be computed using the von Mises criterion. The isotropic hardening function σ_{yhard} is defined as:

$$\sigma_{yhard} = \sigma_{\exp}(\varepsilon_{eff}) - \sigma_{ys} = \sigma_{\exp}\left(\varepsilon_{pe} + \frac{\sigma_e}{E}\right) - \sigma_{ys}$$

where σ_{exp} is a user's experimental stress function and σ_{ys} is the yield stress of γ-TiAl.

2. Implementation

The uniaxial closed-die forging model of γ-TiAl disk is solved using the Structural Mechanics Module of Comsol Multiphysics [5, 6, 7]. The static elasto-plastic analysis and the parametric solver are selected. A displacement parameter (displ_param) is defined to control the relative approach of the two punches. The scale of this parameter is set to 1 mm.

The isotropic hardening function is entered as an experimental tensile test table [6]. The materials properties for punches and mould are taken from Comsol Multiphysics database (steel) and are assumed to be isotropic, according to the experimental evidence.

The direct (PARDISO) solver is used to solve the linear system. The "large deformation" box is enabled to allow a large displacement solution.

The contact problem at the disk/punches or disk/mould interfaces is managed by the "contact pairs" mode and is solved by the augmented

Lagrangian method which includes the augmentation components (for the contact pressure) and the segregated solver. No friction is assumed along contact sliding surfaces. The punches and the mould are set as a master whereas the disk is set as a slave to prevent relative penetration. The new contact points, arising during uniaxial pressing, are detected by the direct search method.

2.1 Boundary/point conditions

The disk is free of displacing either axially or radially, except for two points in contact with the two punches and for the periphery line around the shaped disk in contact with the mould (a-g). The contact points under the two punches are set to roller point condition along the axis (a-g). The circular peripheral line is assumed to be either fixed (b, c, d) or roller (a, e, g).

The punches in contact with the disk are constrained by prescribing the radial displacement to zero.

The proper choice of the master (punches and mould) and the slave (disk) is fundamental to enhance model convergence. The stiffness of the disk has to be lower than that of the master.

The mesh density of the slave's contact boundaries is at least twice than that of the master (i.e. punches and mould) contact boundaries. The inner part of the disk is meshed very fine.

2. Results and Discussion

The accurate prediction of the plastic behaviour of the disk is essential to evaluate the suitability of the closed-die forging of γ-TiAl alloys. The distribution of the effective plastic strain in γ-TiAl disk is significantly influenced by the punches' profile although each configuration shows similar qualitative behaviour with increasing displacement parameter.

Figures 2a-d show the progress of von Mises stress state with increasing displacement parameter for b) configuration although these results are qualitatively similar to the other hardware configurations.

In Fig. 2a, despite the disk is also in contact with the mould, for the initial displacement parameter (0.001), the stress concentration mainly develops at the punch/disk contact points.

With small increasing displacement parameter (0.008), the two contact zones underneath the punches extend as far as they touch each other (Fig. 2b).

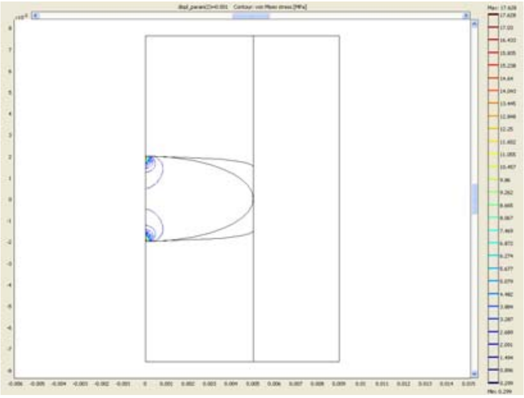


Figure 2a. Von Mises stresses in a biconvex disk with concave punches for a value of the displacement parameter of 0.001.

As they fully collapse axially, a larger stressed region originates with a different concavity, which propagates radially. A new contact zone also originates at the disk/mould interface.

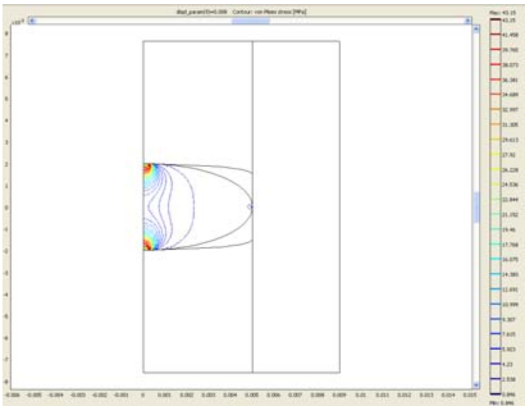


Figure 2b. Von Mises stresses in a biconvex disk with concave punches for a value of the displacement parameter of 0.008.

In Fig.2c, as the displacement parameter increases (0.05), the higher stresses, originating at the new contact points, are directed along the 45 degree directions.

The disk/mould contact region extends further and its lines of influence propagate toward the core of the disk interfering with the lines propagating from the punch/disk contact zones.

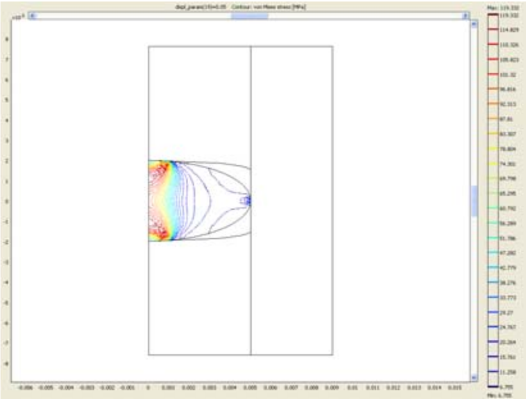


Figure 2c. Von Mises stresses in a biconvex disk with concave punches for a value of the displacement parameter of 0.05.

Figure 2d shows a more developed stress state where the disk is remarkably squeezed by the punches and the punch/disk interface is enlarged.

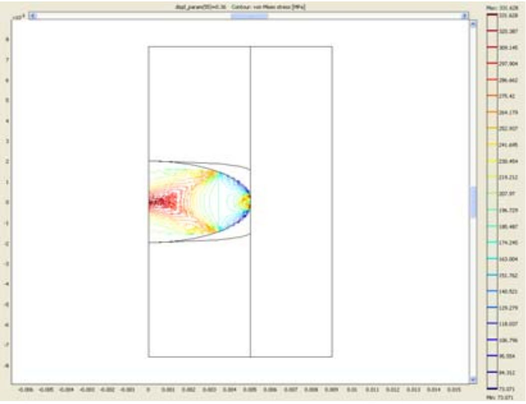


Figure 2d. Von Mises stresses in a biconvex disk with concave punches for a value of the displacement parameter of 0.36.

The higher stresses are concentrated in the core of the disk with further increasing displacement parameter. In addition, the 45 degree stress regions experience higher stresses and move radially depending on the current punch/disk contact areas.

The von Mises stress distribution in the disk also indicates that the material yields in the disk core first.

Figure 3 shows the effective plastic strain in the disk for the b) configuration. The plastic region directly reproduces the von Mises stress state.

The deformed shape reproduces the desired net shape product.

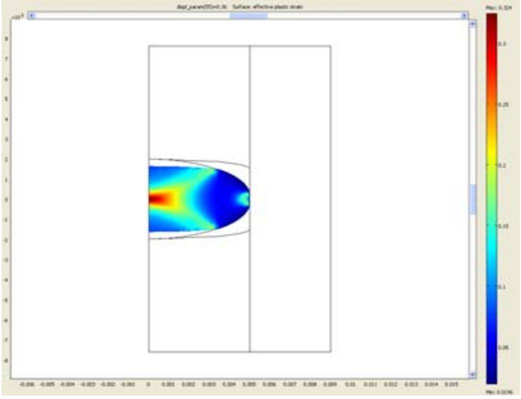


Figure 3. Effective plastic strain in a biconvex disk with concave punches for a value of the displacement parameter of 0.36.

Small parameter steps are used in two critical stages, namely the initial contact stage and the incipient plastic flow stage. Conversely, large displacement parameters are used in the elastic range. So, every simulation has been started twice, in order to find the displacement parameter corresponding to the incipient yielding.

As shown in figure 4 and 5, stresses in the flat disk are distributed more uniformly than in biconvex disk.

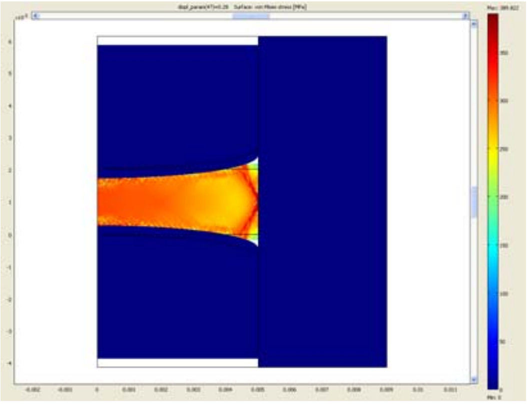


Figure 4. Von Mises stresses in flat disk with convex punches for a value of the displacement parameter of 0.28.

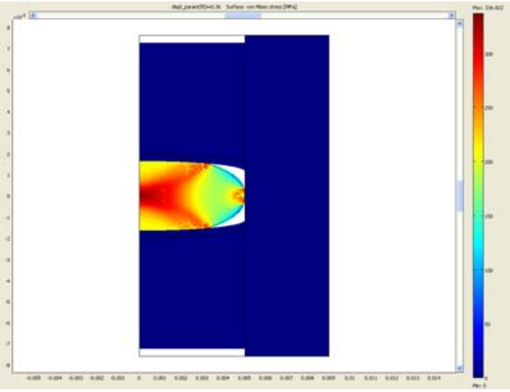


Figure 5. Von Mises stresses in a biconvex disk with concave punches for a value of the displacement parameter of 0.36.

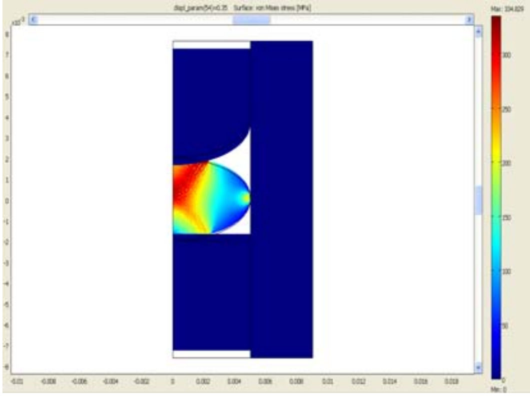


Figure 6a. Von Mises stresses in a biconvex disk with convex and flat punches for a value of the displacement parameter of 0.35.

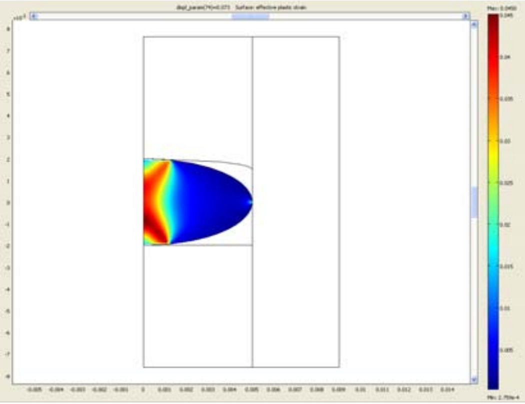


Figure 6b. Effective plastic strain in a biconvex disk with concave and flat punches for a value of the displacement parameter of 0.073.

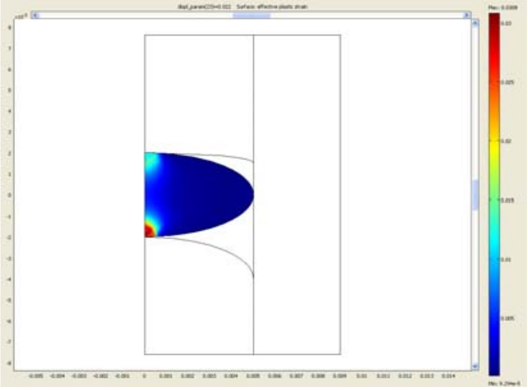


Figure 6c. Effective plastic strain in a biconvex disk with convex and concave punches for a value of the displacement parameter of 0.022.

The convex punches promote larger stress states than flat punches as they approach each other, at constant displacement parameter (figure 6a). Conversely, the flat punches promote more intensive plastic flow compared to concave punches (figure 6b). Thus, convex punches are desirable over concave ones provided that substantial plastic flow is desired (figure 6c).

In the case of convex/convex, concave/concave and convex/flat punches, the von Mises stresses exceed the yielding stress. In the first two cases, the yielding point is located at the core of the disk keeping equal the penetration depth (as shown in figures 4 and 5). However, in the case of convex/flat punches, yielding is achieved at lower values of the displacement parameter and it is not localized in the core of the disk (figure 6a).

7. Conclusions

The net-shape cold forming of γ-TiAl disks by close-die forging is performed via computer modeling. The disks are assumed to behave elasto-plastically while punches and die are assumed to behave rigidly. Prior investigations confirm that the slave surface mesh has to be denser that the master surface one to force convergence and to make the model solution more accurate. Where the punches are assumed to behave as rigid parts (master) the model convergence is improved.

Over the seven proposed disk/punch configurations three of them show net-shape capabilities. The remaining configurations are inadequate for net-shape close-die forging or exhibit difficult convergence even before yielding.

The a) configuration exerts the highest stress state in the punch/die/disk system. The convex surface configuration (for the punch or the disk) is faster to converge compared to flat or concave surface configurations. Conversely, convex punches promote larger stress states than flat punches, whereas flat punches enhance plastic flow.

The c), d), e) and f) configurations are difficult to converge and are less favorable for practical net shape forming, due to the low cold ductility of the material disk or because model limitations under the investigated boundary conditions. In conclusion, from a modeling viewpoint, the optimum net shape capability is shown by a), b) and g) configuration. More quantitative results should be obtained by including in the model friction effects although these may significantly affect the stress state and probably the convergence rate of each configuration.

8. References

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