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Billet Shape Optimization for Minimum Forging Load

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Abstract

The objective of this paper is to obtain an optimal billet shape in the consideration of the influence of the metal flow deformation in closed die forging process. Finite element method in conjunction with optimization algorithm was used to analyze the effect of billet shape on forging load in axisymmetric closed die forging process. Finite element software (ANSYS) was used to simulate closed die forging process and then performing a series of optimization iterations in order to obtain the optimal shape of the billet based on forging load minimization. The material used is aluminium metal matrix composite (AlMgSi matrix with 15% SiC particles). The goal of the simulation and optimization process is to minimize the forging load and produce crack-free forgings. The optimal shape of the billet that gives minimum forging load was obtained after several optimization iterations. The approach used in this study could be extended to the optimization of more complicated forging products.

Keywords: Die Forging, Finite Element Method, Metal Matrix Composites, Optimization.

1. Introduction

Finite element methods and optimization techniques of closed die forging process is still of considerable interest. There are many objectives for these techniques, for example, material flow behaviour, fold-over, improper die filling, excessive forging loads and tool wear, especially with a new materials emerging every day with very attractive properties to automobile and aerospace engineering. It is very important to study the flow behaviour of these materials to produce defect-free closed die forging products.

The optimization of forging process design and forging process plan for various work materials can be based on the maximization of production rate, minimization of production cost, minimization of die cost, maximization of product quality, minimization of forging loads, etc. [1].

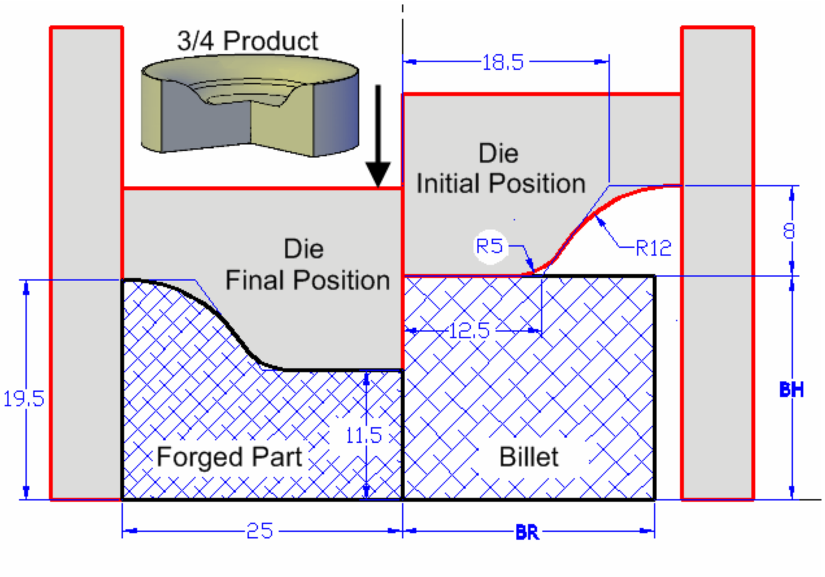
The finite element method provide a prediction of the results of a metal forming process, but still relies on an experienced designer to interpret the results of the analysis and modify the process based on prior knowledge and experience. Current research efforts have sought to use computational resources to enhance and optimize process designs based on a starting design, and improvement of the design is based on the process independent variables, dependent variables and objective function (a dependent variable to be minimized) [2].

The main factors effecting the material flow deformation are die shape, material properties, billet height/diameter ratio, and frictional condition at the billet/die interface [3].

ANSYS parametric design language (APDL) is a scripting language that can be used to build the model in terms of parameters (variables). The APDL is used to build the model in a parametric form to enable changing these parameters during the optimization process, so that the optimal billet shapes is obtained.

The design variable (DV) is as the billet height/diameter ratio shown in Fig 1 The equivalent strain is given as a State Variable (SV). The state variable is working as constrain in the optimization process, forcing the design parameters to be adjusted in order to have a strain not higher than the fractural strain. The Fractural strain is obtained from the literature [4], which is 1.05 at 20^{o}C. The forging load is the objective function, which is going to be minimized by ANSYS optimization module.

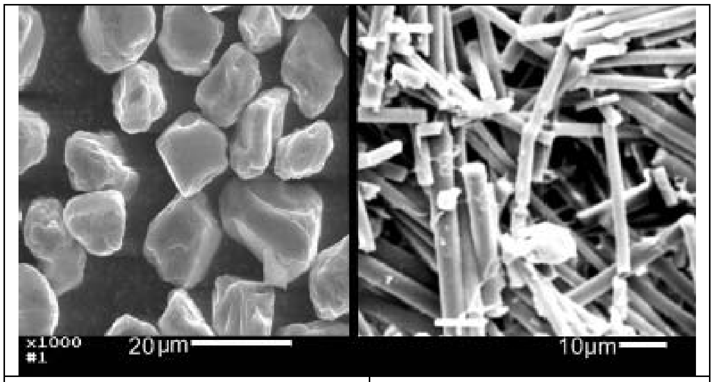
Figure 1: Configuration of billet and die before and after forging



2. Aluminium Metal Matrix Composites

Aluminium is the most popular matrix for metal matrix composites (MMCs). Aluminium alloys are attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electric conductivity, and high damping capacity. Aluminium matrix composites (AMCs) offer a large variety of mechanical properties depending on the chemical composition of the Aluminium matrix. They are usually reinforced by continuous and discontinuous reinforcements. Discontinuous reinforced AMCs are very attractive for their isotropic mechanical properties (higher than their un-reinforced alloys) and their low costs (low prices of some of the discontinuous reinforcement such as SiC particles or Al_2O_3 whiskers) [5, 6].

Figure 2: Discontinuous reinforcement [5].

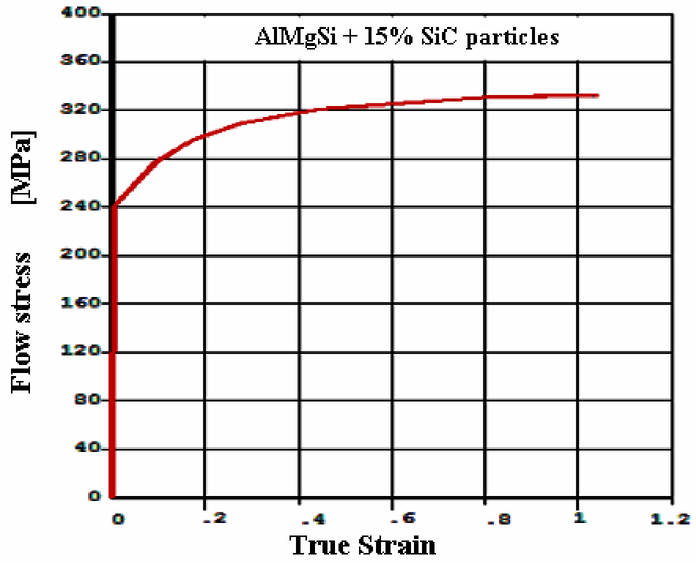


Particulate

Whiskers

Forging MMCs cause particles and whiskers breakage, and normally result in cracks at the outer surface of the billet [4, 7]. To avoid fibres and particles breakage which lead to cracks, the equivalent strain of the material must be kept lower than the fractural strain obtained from the literature shown in Fig. 3, which is $\varepsilon = 1.05$ [4]. The fractural strain is used in the optimization process as a state variable maximum limit.

Figure 3: Flow curve of AlMgSi+15% SiC particles [4].

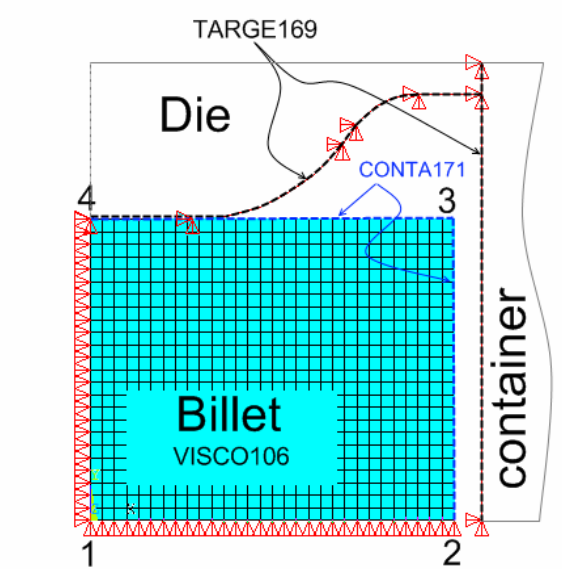


3. Finite Element Model

A cylindrical billet is going to be forged to produce the final forged part shown in Fig. 1 with a minimum load possible by optimizing the billet height/diameter ratio. The billet is represented with initial radius and then the height is calculated based on the volume of the die cavity. The initial billet is represented with geometrical model consisting of assemblage of finite element. Equations relating the distribution of forces and displacements of the metal are established and the boundary condition and die movement are imposed.

The components of the model are shown in Fig. 4. The cylindrical billet is made of AlMgSi reinforced with 15% SiC particles and has an initial radius of 19 mm, just a quarter of the billet and the die being considered for the analysis to reduce computational time and cost. Three types of elements are used in the model. The billet is built up of two dimensional 4-node viscoplastic solid elements (ANSYS type VISCO106). A rigid to flexible contact pair is used to represents die/billet contact. A two dimensional 2-node surface-to-surface contact element (ANSYS type CONTA171) is used to represent friction and sliding contact for the deformable surface of billet and a two dimensional target element (ANSYS type TARGE169) is used to model the rigid surface of the die and the container.

Figure 4: The discretised model showing boundary condition



The axis of symmetry (line 1-4) of the model is constrained in (X) direction. The bottom line of the billet (line 1-2) is constrained in (Y) direction. A displacement load is applied to the target element (TARGE169) associated to the lines representing the die profile in negative (Y) direction. The target element representing the container is constrained in both (X, Y) directions.

Since forging process is associated with large strain, deformation and shape changing, it is hard to obtain a stress distribution, which equilibrates a given set of external load. As a result the total load is applied in a number of increments. During each increment, a linear prediction of nonlinear response is made, and subsequent iterative corrections are performed in order to restore equilibrium by elimination of the residual forces. It is necessary to activate geometrical non-linearity option (NLGEOM) in order to update the geometry in each increment (sub-step). In ANSYS, the non-linear solution is based on the Newton-Raphson procedure [8].

4. Optimization Process

The goal of the optimization process is to find the best solution for the given problem in the design space defined to the optimization algorithm. Optimization model contains of three components: design variable (independent variable), constraints (state variables or dependent variables) and the objective function (dependent variable to be minimized). Specifying the lower and the upper limits of the design variables and identify the design space by specifying the constraints (a dependent variable value that shouldn't be exceeded). After the design space is defined the optimization algorithm will search in design space for the minimum objective function in this case minimum forging load.

The optimization method used in this analysis is called Sub-problem approximation method. The method can be described as an advanced zero-order method which requires only the values of the dependent variables, and not their derivatives. It is based on two concepts, the use of approximations for the objective function and state variables, and the conversion of the constrained optimization problem to an unconstrained problem.

4.1. Design variables (independent variables)

It is assumed that the final shape of the part is given, and nothing much that can be done to modify it. The billet shape can be changed to minimize the forging load and hence the starting shape is cylindrical shape, so diameter of the billet is going to be the design variable. The billet height is then calculated based on the volume of final part and the diameter of the billet.

The optimization algorithm will search for the minimum objective function (Minimum Forging Load) with in the design space specified by the upper and the lower limits of the design and state variable.

In the optimization procedure, ANSYS optimization module performs a series of analysis-evaluation-modification cycles. That is, an analysis of the initial design is performed, the results are evaluated against specified design parameters, and the design is modified as necessary. The process is repeated until all specified criteria are met [8].

4.2. Constraints (dependent variables)

Aluminium metal matrix composites has low ductility compared to traditional forging materials. Therefore, it is very important to specify the fracture strain as a constraint for optimization algorithm to avoid cracked forgings.

4.3. Objective function

In closed die forging, complete die filling with out defects such as cracks, fold-over, wrinkles and with minimum forging load is the main objective. The goal of the simulation is to find out the shape of the billet that leads to a minimum forging load. The load calculated by the FE simulation that is needed to perform the forging process is defined as objective function to the optimization module. The optimizer keeps changing the billet shape until the minimum forging load is obtained.

5. Results and Discussion

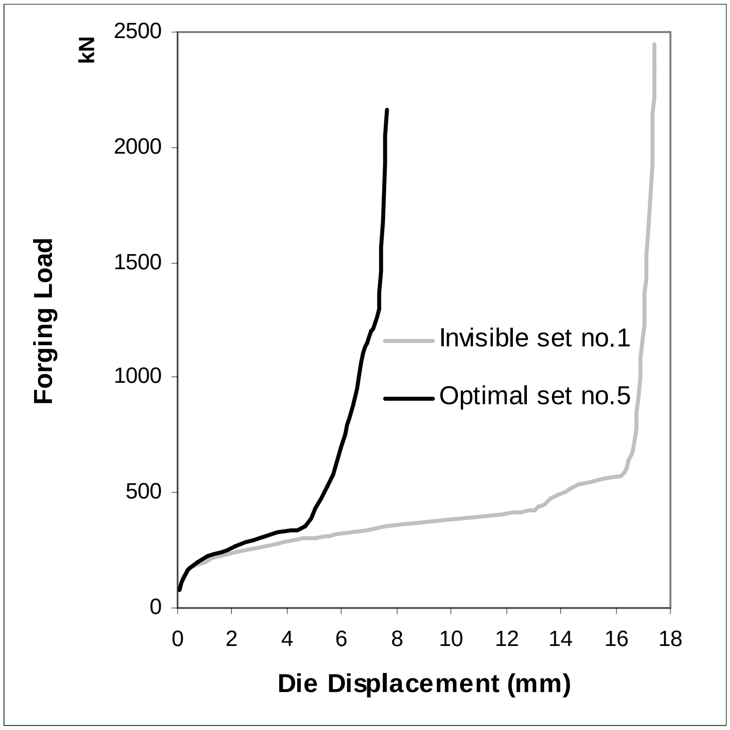
Using the finite element method the forging process was simulated and the forging load was calculated, by the help of the optimization algorithm, a series of the analysis were carried out searching for the minimum load by changing the billet diameter each time. Table I**Table** shows 6 design sets carried out by the optimization algorithm. The fifth set is the optimal one with minimum forging load 2160 kN.

Table I: List of visible and invisible design sets

Optimization Iteration	Equivalent Strain (SV)	Billet Radius (DV)	Forging Load (OBJ)
SET1 (INFEASIBLE)	>1.3551	1.90E-02	2.45E+06
SET2 (FEASIBLE)	0.79773	2.41E-02	2.24E+06
SET3 (INFEASIBLE)	>1.0814	2.17E-02	2.33E+06
SET4 (FEASIBLE)	1.0021	2.48E-02	2.39E+06
***SET5* (FEASIBLE)**	**0.88577**	**2.34E-02**	**2.16E+06**
SET6 (FEASIBLE)	0.90598	2.32E-02	2.18E+06

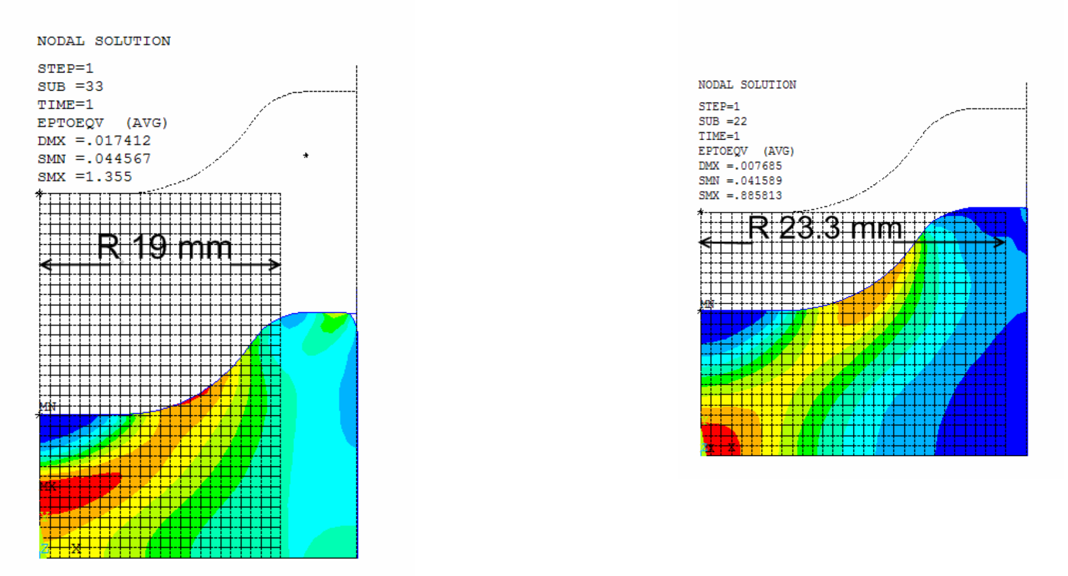
Two load displacement curves are plotted in Fig 5, for the optimal (*SET5* = 2160 kN) and compared to (SET1 = 2450 kN) that has the maximum Forging load. The reduction in load is about 12%.

Figure 5: Load displacement curve for two optimization sets



The strain distribution for optimal (best visible) and the invisible design set is shown in Fig. 6. Their maximum strain values are 0.885 and 1.355 respectively. The maximum strain that the material (AlMgSi + 15% SiC) can sustain with out fracture is equal to (1.05).

Figure 6: Equivalent strain distribution for (a) invisible set (b) optimal set



(a) (b)

Fig. 7 shows the objective function (Forging Load) and billet radius history versus optimization iterations. It can be seen that through 6 optimization iterations, the objective function decreases from the initial value 2450kN to the optimal value 2160 kN in the fifth optimization set.

Figure 7: Forging load and billet radius versus Optimization iteration number

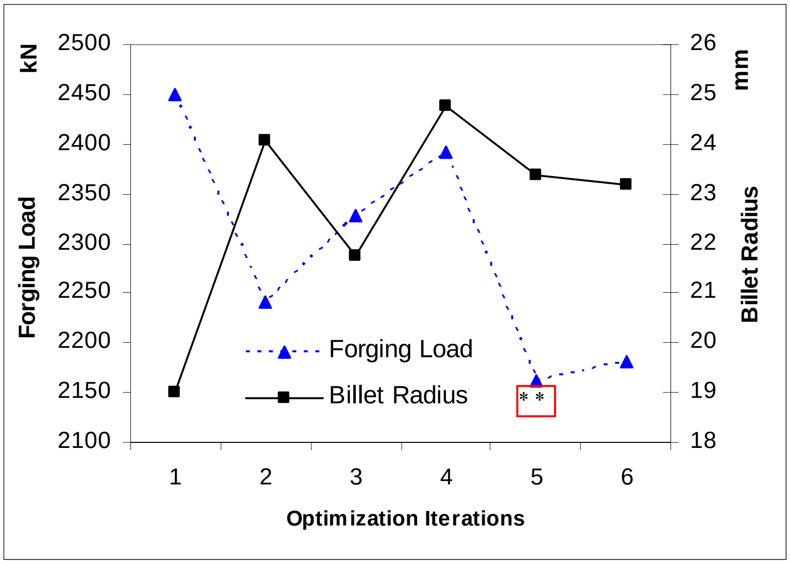
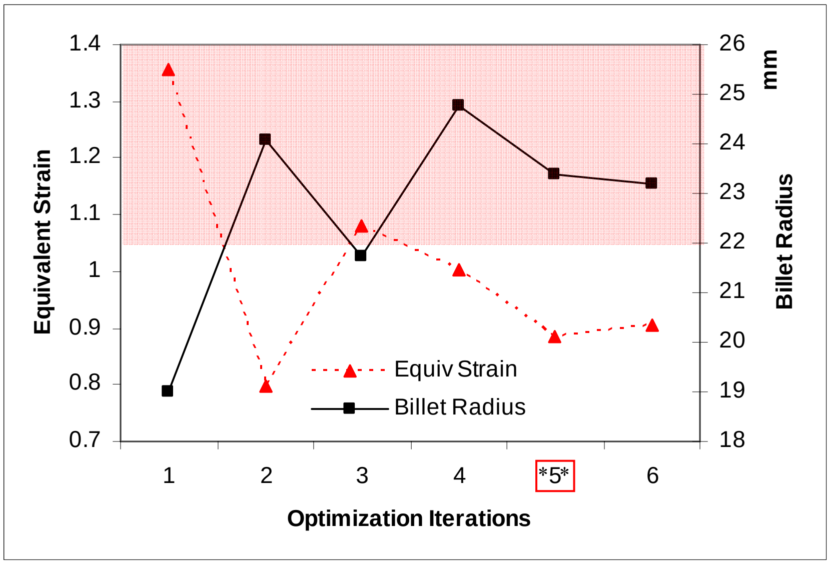


Fig. 8 shows the maximum equivalent strain and billet radius history versus optimization iterations. It can be seen that only two optimization sets (SET1, SET3) are exceeding the fractural strain 1.05, and the optimal set has the second minimum value.

Figure 8: Equivalent strain and billet radius vs. Optimization iteration number



6. Conclusions

In this work, axisymmetric closed die forging process of AlMgSi matrix with 15% SiC particles was simulated using commercial finite element software (ANSYS) to investigate the material flow behaviour and to predict the forging load and the strain distribution. The forging process was optimized using ANSYS optimization module.

Finite element analysis in conjunction with optimization techniques, are used to develop a system for the design of optimal billet height/diameter ratio of closed die forging process. The finite element model was built parametrically using ANSYS Parametric Design Language. The optimization module used the analysis file to search for the minimum objective function (forging load) by changing billet height/diameter ratio. The optimal set is listed in Table I (*set 5*) with billet radius (23.3 mm) and forging load (2160 kN). Performing this task wouldn't be easy with out combining the finite element analysis and the optimization techniques.

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