Evaluation of PROMETAL technique for Application to Dies for Short Run Forgings

By
Kuldeep Agarwal, Deepanker Mathur, Rajiv Shivpuri
Department of Industrial, Welding and Systems Engineering
The Ohio State University, 1971 Neil Avenue, Columbus, Ohio 43210, USA
And
John Lembo
Extrudehone Corporation
1 Industry Blvd., P.O. Box 1000, Irwin, PA. 15642

Abstract

Manufacturing of hot forging dies required several steps such as acquisition of material block, shaping it for machining, rough machining the cavity, heat treating, finish machining, grinding and polishing. This process takes several months. Consequently for limited number of parts often required in aerospace industry, forging is being replaced by direct machining of parts. If the die lead times (administrative and manufacturing) could be reduced to weeks instead of months, forging process will become viable for short run forgings. This paper evaluates the PROMETAL technique for dies in forging of aluminum alloys. This evaluation includes frictional, heat transfer and strength characterization. Isothermal and non-isothermal ring tests together with FEM models are used to determine the interface behavior and its effect on metal flow.

Introduction

A typical forging development procedure involves part design, process and material selection, forging design, die and tooling design, tooling manufacture, set up and production, heat treatment, machining of the forging, testing and assembly. The focus of this study is on forging of aluminum alloys.

Aluminum alloys are forged into a variety of shapes and types of forgings with a broad range of final part forging design criteria based on the intended application [1]. For a given aluminum alloy forging, the pressure requirements in forging vary widely, depending on the chemical composition of the alloy being forged, the forging process being employed, the forging strain rate, the type of forging being manufactured, the lubrication conditions, and the forging and die temperature.

The forging temperatures for most aluminum alloys are in the range of 600-850º F. The flow stress shows a large variation with change in temperature. Thus the forgeability of all aluminum alloys improves with increasing metal temperature. Therefore, unlike some forging processes for carbon and alloy steels, the dies used in virtually all hot-forging processes for aluminum alloys are heated in order to reduce die chill.

The first step in the process of die manufacturing for aluminum forging is to select the die block, which satisfies the press space and cavity sinking requirements. The die block is cast from hot working die steels. The block is machined to the CAD models and cavities machined in the soft condition. Then the dies are heat treated and polished after heat treatment. Alternatively, the forging cavities can be sunk by EDM process in the hard condition in the heat treated blocks. For reasonable die lives the cavities sunk by EDM need considerable post-sinking polishing. In addition, this approach requires the electrodes of the EDM to be machined previously. More recently, the advent of high speed machining has made it possible to directly cut the hardened die blocks. This has reduced die-manufacturing times but increased costs due to enhanced tool wear and high cost of machining centers capable of high spindle speeds.

Forgings are dismissed as useful for short run because of the long lead times involved in the manufacture of tooling. Thus people are forced to revert to machining for short run forgings even when it involved cost and performance penalties. The objective of this study is to develop a rapid tooling design and development system for short run forgings which deploys rapid tool manufacturing techniques together with integrated process and product design approaches. This paper discusses the rapid manufacture of dies.

Rapid prototyping of dies

Popularity of RP techniques has resulted in large number of techniques being developed. However, only a few have found application for tools and dies. For example, Jacobs and Hilton [2] have written about the inserts made by the technique of Direct AIM (ACES injection molding). Xerox Corporation on an SLA-250 built the inserts with Cibatool SL5170 epoxy resin using ACES build style. They were able to injection mold 100 polystyrene parts just 5 days after the CAD design was complete. Karapatis and Glardon(1998) [3] presented the various methods of direct rapid tooling with SLS technique. According to them, direct tooling utilizing SLS is possible with metallic powder; polymer, metal mixture (polymer coated metallic powder) or nickel-bronze-copper phosphide powder. King and Tansey (2000) [4] talked about the rapid steel method used to create steel/copper mold inserts for injection molding. . The powder used is stainless steel powder infiltrated with bronze. Griffith and Ensz [5] evaluated properties in LENS process. Simple sample geometries were chosen where the tensile direction is either parallel (H) or perpendicular (V) to the layers. The stainless steel alloys show the greatest effect of the layered deposition, where the strengths are lower for the vertical samples. This is most likely due to the stress state condition where the layers are perpendicular to the pull direction and any imperfections will initiate fracture. Agarwala and Osborne [6] talk about rapid prototyped pre forms with HIPping . The ceramic performs are generated by RP processes and temperature and pressure is used to fill the cavity with tool steel. RSP tooling technique [7] gives the material properties close to H-13, but has only been evaluated on injection molds and die casting tools. In this process spray forming of thick deposit of tool steel is done on a pattern to capture the desired shape and texture.

Prometal technique

One of the promising rapid prototyping techniques which can be used for forging dies is the 3D printing technique developed by MIT. It has been commercialized by Extrudehone/Prometal. The main technique of making the prototypes is as follows –

(a) The CAD file is sliced into layers and a STL file is generated.
(b) Each layer begins with a thin distribution of powder spread over the surface of a powder bed.
(c) Using a technology similar to ink-jet printing, a binder material selectively joins particles where the object is to be formed.
(d) A piston that supports the powder bed and the part-in-progress lowers so that the next powder layer can be spread and selectively joined.

This layer-by-layer process repeats until the part is completed. Following a heat treatment, unbound powder is removed, the metal powder is sintered together. This sintered metal powder is then infiltrated with bronze to impart the strength and fill up the pores. The process is shown in fig. 1.

Material properties

The material properties obtained by the Prometal process are shown and compared with conventional tool steel in table – 1. There are 2 phases in the material – 420 Stainless steel and bronze. This can be seen from the fig. 5.

To find out the variation of the hardness in the material in different orientations, a microhardness test was conducted on the sample. A section was cut from the sample and the hardness values (Rockwell C) were taken both along and perpendicular to the orientation. The results are shown in Fig. 6.

Initial experiments

A short run forging tool was fabricated within nine business days from receipt of the file. This forging die for Aluminum Precision Products was manufactured with 420 stainless steel metal powder and infiltrated with bronze. The resultant material composition is 60% steel and 40% bronze. The die was used in an isothermal forging application with the forged material being 2XXX series aluminum (fig. 2). The part produced is shown in fig. 3. This proof of concept trial clearly demonstrated the ability to produce a near net shape tool in a rapid time frame.

Material characterization

The first step in the development of dies by 3D printing method is the characterization of material produced by the technique. The issues that come in the study are the friction and heat transfer between the die and workpeice.

Friction in metal working

In metal deformation processes, frictional forces are generated at the interface between the tools and deforming materials by virtue of the workpiece surface extension [9]. These frictional forces have the following modifying effects –

(a) The total deformation loads are increased.
(b) The internal structure and surface characteristics (surface finish and surface defects) of the product are influenced.
(c) Wear is produced on the tooling material, thus reducing its useful life.
(d) Dimensional variations are produced in the processed material.

Because of these effects, friction is considered to be a major variable in metal working operations and must be adequately controlled to optimize processing procedures for economically producing material with the desired geometry and internal structure. For effective friction control, quantitative data on the effects of lubrication and other processing variables, such as temperature, speed and pressure, are essential.

Of the many laboratory tests utilized for friction studies the ring test technique originated by Kunogi [10] and further developed by Male and Cockcroft [11] has the greatest capability for quantitatively measuring friction under normal processing conditions.

The ring test technique involves a simple forging operation performed on a flat ring-shaped specimen, the change in diameter produced by a given amount of compression in the thickness direction is related to the interfacial friction conditions. If friction were equal to zero, the ring would deform in the same way as a solid disk, with each element flowing radially outwards at a rate proportional to its distance from the center. With a small but finite interfacial frictional force, outward flow takes place at a lower rate and, for the same degree of compression, the outside diameter is smaller than with zero friction.

Measurement of the final internal diameter of compressed rings provides a particular sensitive means for studying interface friction. Correlation of changes in internal diameter with numerical values of friction can be obtained either by independent calibration or by simulations.

Ring compression test

The ring compression test was conducted at OSU. The rings taken were of the standard geometry (6:3:2) –Outer dia – 1", Inner dia – ½" , Height – 1/3"

The platens used to compress the rings were made from Prometal technique and had the orientations of 0˚, 30˚, 60˚, 90˚. The test was also conducted with die made of H-13. The compressed rings obtained by the test are shown in fig. 7.

First, the test was conducted with keeping the dies at room temperature and heating the rings to 800˚F. The friction factor obtained was verified by DEFORM simulations and is shown in table – 2. The test was conducted with and without the use of lubricant (graphite in colloidal solution of water and oil).

Because of the steep change in the flow stress of aluminum with change of temperature, the test was conducted again by heating the dies to about 450˚F. The results of this test are shown in table – 2.

The final series of test was conducted by polishing the die to a surface roughness of 23 microinches. The results of the friction factor obtained are shown in table – 3.

After the ring compression test was completed, the cross section of the ring was taken and its microstructure was evaluated. The microstructures are shown in fig 8.

Discussions

The ring compression test was performed with rings of standard geometry (6:3:2). The die samples used were of the Prometal material (with 4 different orientations – fig. 4) and H-13. The tests were conducted with and without the use of lubricant and with and without heating the dies. The different orientations of the dies did not show much variation in the friction factor. The friction factor of the material was found to be 0.75 when the dies are at room temperature. This factor reduced to 0.55 when the dies were heated to 450˚F. Also, this factor reduced to 0.27 (0 degree) and 0.30 (90 degree) when the dies were polished to a surface roughness of 23 or 33µin respectively.

The microhardness test shows that the hardness values are different for all orientations and are almost the same along different directions in the same orientation. 0 degree orientation showed the lowest average hardness while 90 degree orientation showed the maximum hardness.

The microstructures reveal that with H-13 dies there is a zone of recystallization at the corner while with Prometal dies there is rapid quenching and the aluminum microstructure is homogenous throughout. Thus it can be deduced that the Prometal dies have a much higher heat transfer coefficient than H-13.

A universal scale down die was designed with the rib-web dimensions and the draft angles that represent a typical aluminum forging (fig. 9). It has been planned to do forging tests on this scale down die and the simulation showing the filling is shown in Fig. 10. The forgings will be done on 0 degree and 90 degree orientation.

Conclusions

The ring compression test showed that the friction at the interface between the die and aluminum under forging conditions is quite high. As mentioned earlier, this can result in problems while actual forging. So, it is necessary to perform some kind of surface treatment on the die made by such a process so that the friction can be reduced which might be suitable for forging applications.

The results of the microhardness tests show that the difference in values along a layer are sometimes quite high. This might be due to the different phases in the material (bronze and SS 420). Thus, the material has different properties in different directions and is thus anisotropic.

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Property	**Conventional tool steel**	**316 + Bronze**	**420 + Bronze**
Hardness	51-55 HRC	60 HRB	26-30 HRC
Ultimate Strength, Ksi	150	59	99
Yield Strength, Ksi	115	34	66
Young's Modulus, Mpsi	30	21.5	21.4
Elongation	9 %	8 %	2.30 %
Thermal Conductivity Btu.in/ft^2.h.F	169	51	57
Density, lb/in^3	0.282	0.29	0.289

Table – 1 Material properties of Prometal technique and conventional tool steel

S.No.	**Die material**	**Friction factor (m) (without lubricant)**		**Friction factor (m) (with lubricant)**		**Surface Roughness (Ra µin)**
		68 ˚ F	**450 ˚ F**	**68 ˚ F**	**450 ˚ F**	
1	H-13	0.80	0.55	0.61	0.21	45
2	Prometal , 0 degree	0.80	0.68	0.75	0.55	96
3	Prometal , 30 degree	0.81	0.69	0.76	0.56	97
4	Prometal , 60 degree	0.80	0.68	0.77	0.56	99
5	Prometal , 90 degree	0.79	0.69	0.75	0.55	94

Table – 2 Ring test results (Aluminum rings at 800˚ F)

S.No.	Die material	Friction factor (m) (without lubricant)	Friction factor (m) (with lubricant)	Surface Roughness (Ra µin)
1	H-13	0.37	0.18	18
2	Prometal , 0 degree	0.43	0.27	23
3	Prometal , 30 degree	0.44	0.28	26
4	Prometal , 60 degree	0.44	0.28	25
5	Prometal , 90 degree	0.45	0.30	33

Table – 3 Ring test results (die at 450˚ F, aluminum rings at 800˚ F)

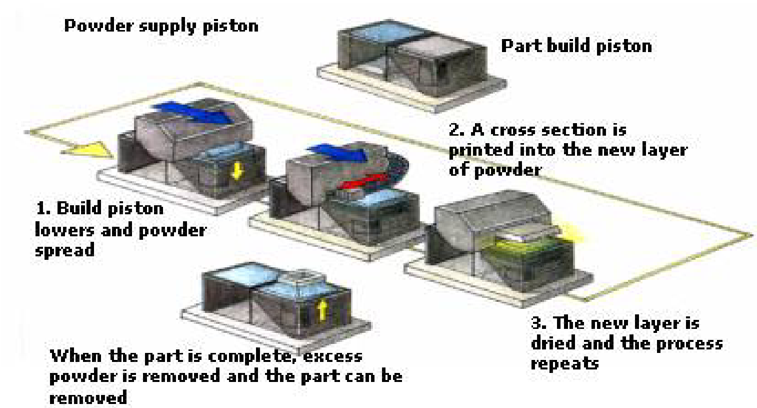

Fig.1 Prometal process

Fig. 2 Die made from Prometal technique

Fig. 3 Part used for initial trial of the die

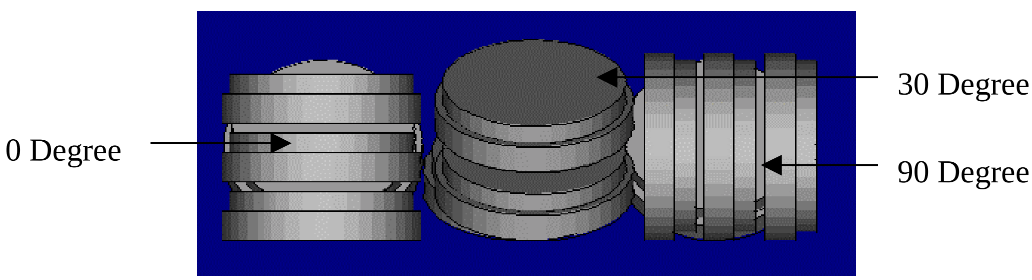

Fig. 4 Ring compression dies build direction

0 Degree *90 Degree*

Fig. 5 Microstructure of the samples (50 X)

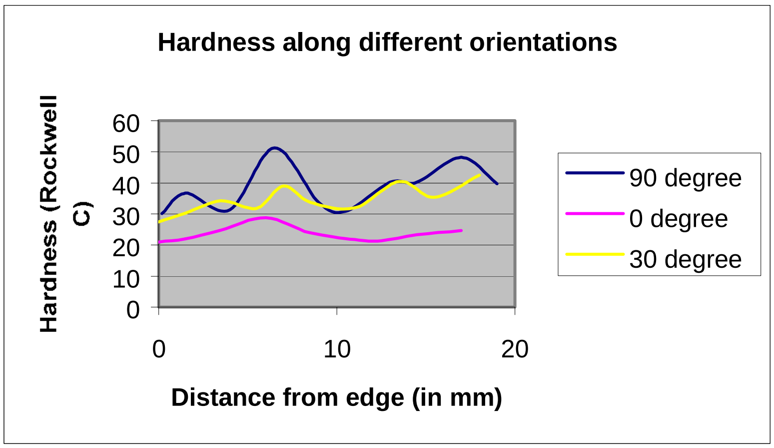

Fig. 6 Microhardness test results

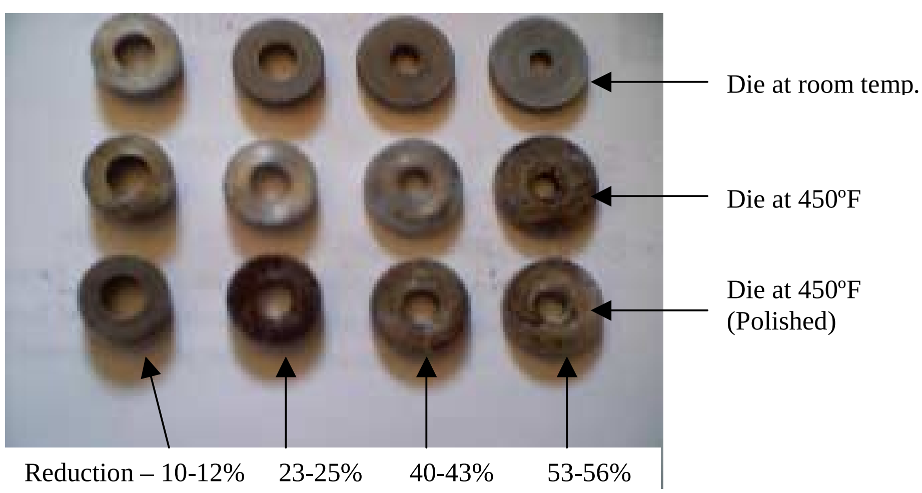

Fig. 7 Ring compression test – Prometal die

10 X With H-13 Dies showing recrystallization

10 X With Prometal Dies showing friction and grain flow

200 X With Prometal dies showing rapid quenching

Fig. 8 Microstructures from ring compression samples

Fig. 9 Scale Down Die

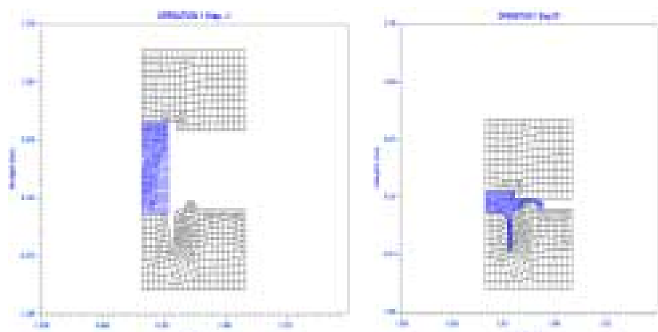

Fig. 10 Simulation for filling of scale down part

Note –

The above problem was modeled as axisymmetric and taking the dies as rigid and the material (Al-7075) at 800 F. The dies are at 450 F.

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