Modern Methods of Preforming Titanium Alloys for Forging Aero Engine Vanes

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Abstract

Intermediate forming aimed at distributing the material volume contributes towards better utilization of the material, reducing the amount of energy necessary for heating and improving quality by near-net-shape geometries. A range of different forming operations exists for realizing material distribution.

This paper gives an overview of the process technologies used for distributing the material in an intermediate forming stage in the closed die forging of aero engine vanes and also illustrates their application areas. The development of a single cross wedge rolling operation will save two upsetting operations and one extrusion operation. A considerable reduction in cycle times and in manufacturing costs is the result of the shortened process chain. Additionally, the number of ancillary processes, such as heating, adjustment and lubricant application are reduced as well.

Introduction

Product developments within the aircraft industry have previously had a significant effect on the development of the closed die forging technology. These new developments - and also the need to reduce costs – are increasingly pointing the way to lightweight construction.

Components forged in the die are especially meeting the stringent requirements on dynamically stressed parts in relation to strength and safety [1].

Due to the general trends in world economy, following a long period of relatively low raw materials prices during the 1990s and following the turn of the century, the market for raw materials and metals underwent an upturn from around 2003 onwards. As a result of these changes, raw material prices reached an all-time high during the first half of 2006. The Federal Institute for Geosciences and Raw Materials price index for metal-based raw materials (BGR-MPI) rose by 240 base points between the start of 2000 and the end of 2007 [2]. The current trend of prices on the raw material markets is not attributable to any shortfall in the supply of the individual raw materials, but is instead linked with a fundamental structural change on the demand side which is closely associated with the progressive globalization of the world economy.

The trend of prices in energy markets over the past few years is continually increasing. The price for electrical energy has doubled and the price for gas has risen by 80% based on the comparison ratios issued by the European Forging Industry Federation [3].

The resulting implications for the further development of production technology in the area of bulk metal forming are - in addition to increasing productivity - primarily to reduce the energy consumption and to improve material utilization.

Closed Die Forging

Closed die forging is a forming process under pressure carried out at temperatures above the re-crystallization temperature of the billet material using forming cavity that transfers its dimensions and forms to the workpiece and which encloses the workpiece either totally or to a considerable extent. The cavity is split into two halves so that, once the forming process has been completed, the dies can be opened and the workpiece can be removed. Presses or forging hammers are used as machines for the forming process. For closed die forging of undercuts or for upsetting rods, multi-component tools are required. Triple component dies are used, for example, in horizontal upsetting machines. The tools are made up of the horizontal-operation upsetting die and two clamping jaws separated horizontally, the top set of jaws can be moved for opening the cavity.

The use of closed die forging enables a high degree of material utilization, generates a improvement of the original material characteristics and reduces subsequent machining work. Due to the relatively high cost of the dies, adequate production quantities are an essential pre-requisite for the use of closed die forging on a commercial basis. In case of exceptionally high demands on material strength and component reliability manufacturing by forming is essential.

Standard Alloy TI-6AI-4V

Titanium, which is 40% lighter than steel, features a higher level of strength when it is alloyed with elements such as aluminum or vanadium. Ti-6Al-4V is the most used titanium alloy and can be found in more than 45% of all titanium based industrial products. Its economic value derives from a advantageous combination of the mechanical characteristics of the alloy with manufacturing expertise and commercial availability.

The alloy consists of a hexagonal structure (α-phase) and a body-centered cubic lattice structure (β-phase). The problems in relation to hot forming of the (α+β) mixed crystal alloys are encountered in heating and maintaining the forming temperature. The temperature lies in the range above the re-crystallization of the (α+β) phase, between 900° and 950°C [4]. During heating, due to the high affinity of titanium with oxygen, nitrogen and hydrogen, a thick layer of scale is generated and diffusion into the surface layers of the workpieces takes place.

Material Distribution in Closed Die Forging

The manufacture of a component with oblong shape and complex geometry can not be realized in a single forming operation. Frequently, the initial material consists of a geometry with a constant cross-section. In order to reduce the amount of waste, it is advantageous to distribute the volume of the billet along its axis to correspond precisely with the finished forging. The shape of the preform is to a considerable extent dependent on the finished forging on the one hand and, on the other, on the cross-sectional area resulting from the intermediate forming shape. The aims of preforming are summarized as follows: (a) to distribute the material along the longitudinal axis of the workpiece, (b) to ensure complete cavity filling with smallest amount of material loss, (c) to avoid forging defects, (d) to reduce the amount of deformation work in finish forging, (e) to keep loads and wear of the dies low and (f) to save material.

The distribution of the material along the main axis can be realized either by displacement or by accumulation. Free upsetting and upsetting in the die are conventional production processes for material accumulation. Material displacement can be achieved by applying a range of manufacturing methods. Appropriate forming processes include stretch forming, extrusion, reducer rolling and cross wedge rolling. In manufacturing the selection of the process is made based on the following criteria:

- geometric shape and absolute dimensions of semi-finished and finished product,
- quantities to be manufactured – costs of the die,
- available plant technology,
- requirements on the component characteristics, for instance grain structure and
- the complexity of the entire process chain.

Material Accumulation by Upsetting

In the upsetting process the cross-section of a forging is increased while the length is reduced. Basic upsetting is carried out using plain flat tools. The process limit is characterized by the failure mechanisms of outward bending and buckling of the length of the billet. The characteristic value is the upset ratio which is the relationship between the initial length l_0 and the initial diameter d_0. In order to achieve the maximum upset ratios, the process is carried out by applying dies or employing partial heating. The l_0/d_0 ratio ranges from 2 (for upsetting between flat upsetting surfaces) to 6 (for upsetting in partial dies) [5]. When higher degrees of upsetting are required, several operations of upsetting are necessary, for which the above rules apply to each single operation.

Material Displacement using Cross Wedge Rolling

Cross wedge rolling is rotating pressure forming using tool elements that rotate in the same direction or tool elements driven in a straight line from opposite directions which make rolling contact with the workpiece, thus forcing it into a rotational movement. The forming elements are wedge-shaped so that they displace the material in the direction of the axis. Depending on the machine principle, the workpiece may be produced by means of a straight movement or a rotating tool movement.

The diameter of the billet corresponds to the maximum diameter of the rolled part. Cross rolling is an incremental forming process with open groove and partial force exposure. Due to the varying degrees of freedom, the layout of the cross rolled shape and the design of the tools have special significance. One fundamental characteristic value for the assessment of the material displacement process is the specific reduction in diameter ε_d. This value specifies the relative relationship of the change in diameter Δ_d in relation to the initial diameter d_0. In a series of studies on the forming behavior of titanium alloys in cross wedge rolling, specific values for the lower and upper limit of diameter reduction were determined [6].

Material Distribution Diagram

A useful aid for designing the intermediate forging shape is the material distribution diagram. The diagram is based on the final shape of the forging. A number of vertical cross-sections are calculated along the imaginary main axis of the forging. These cross-sections are depicted in a diagram, taking into account flash and other losses, along the complete length of the forging. By converting the cross-sections into simple circular cross-sections the material displacement intermediate forging design can be subsequently calculated.

Basic Form Design of Aero Engine Vanes

Forged vanes made from the standard alloy Ti-6Al-4V are applied in engine turbines subjected to working temperatures up to 315°C [1]. Closed die forging is used to form the basic shape on which the entire manufacturing process of the vanes is based. The starting point for planning the process chain is the final formed shape of the aero engine vane as illustrated in Fig. 1.

Fig. 1: Precision forged aero engine vane

A basic sequence of six operations is required, from the semi-finished rod to the forged part: 1 – Sawing, 2 – Heating, 3 – Material distribution, 4 – Preforming, 5 – Closed die forging and 6 – Trimming.

The individual forming stages are specified within the framework of on-going planning of the operational process. In die forging on presses the possibilities of material distribution are limited due to the kinematics of the machine, i.e. large scale material distribution operations have to be carried out using a suitable process external to the press. Due to the importance of temperature in the hot forming of the titanium alloy, a heating operation has to be included for each intermediate forming stage. In order to improve the material flow during forming, lubricants are applied between the workpiece and the die. In the presented project the work is carried out using glass dispersion which is dissipated in each forming process. For this reason each forming operation is preceded by an operation step “Apply Lubricant“. During

heating, a layer of scale builds up as a result of the chemical reactions with the gases diffused in from the air. This layer is detrimental in the finished product and must therefore be removed by means of an additional adjusting operation after each forming stage. The straightforward sequence of the six operation steps has thus already been extended considerably.
A material distribution diagram is used to specify the forming stages. The aero engine vane can be divided up into the shroud, airfoil and foot sections. In Fig. 2 the cross-sectional areas are displayed across the length of aero engine vane.

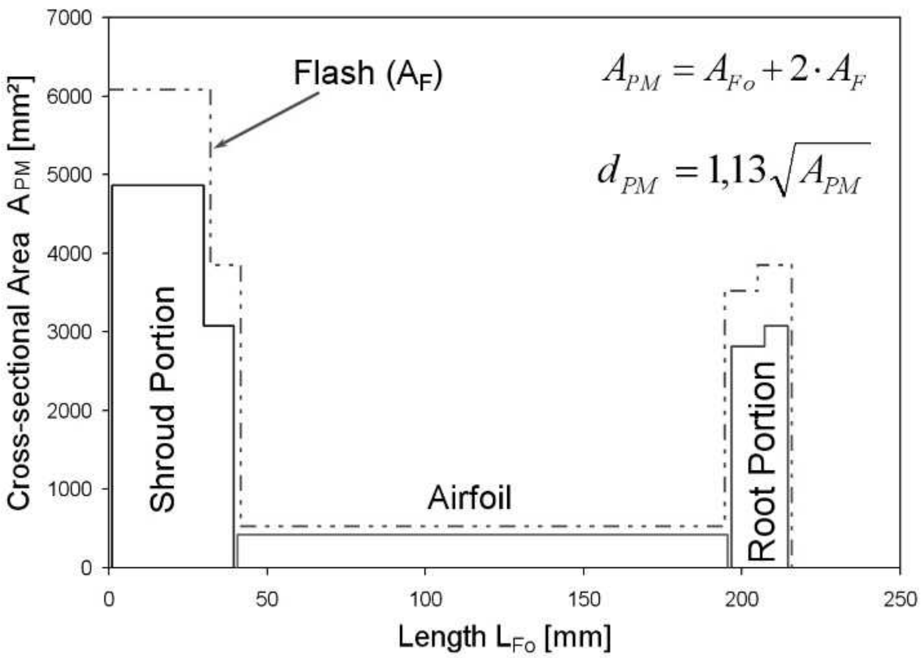

Fig. 2: Material distribution diagram for aero engine vane

The necessity of material distribution can be derived from the progression of the curve. Significantly less material is needed for filling the die in the airfoil section by comparison to the foot and shroud section. The conventional production process is based on accumulating material from a billet with a very small diameter. The minimum diameter d_{PM} is derived by calculating the cross-sectional area in the airfoil section. In the particular example this diameter is 26 mm. Based on this diameter and the constant volume law the length of the billet can be calculated. For the shroud area, the length is 416 mm with an upsetting ratio of 16. In the foot area, the length is 125 mm and the upsetting ratio is 4.8. Due to the large upsetting ratios the conventional upsetting process requires several upsetting and extrusion operations. On the other hand it would be possible to increase the initial diameter of the billet. Both options will have a negative effect on the objectives specified above. The large number of upsetting operations generates additional costs for each individual forming stage and the second option adversely affects material utilization in the area of the airfoil. Due to the high length/diameter ratio, traditional production methods call for repeat upsetting in a tapered die on an upsetter.

In order to solve this unsatisfying manufacturing process chain a new approach has been developed. By way of an alternative production process, the possibilities offered by cross wedge rolling were examined. By calculating the maximum diameter reduction and taking into account the semi-finished part geometry an initial diameter of 60 mm was selected for the billet which is to be formed by cross wedge rolling. Based on the law of constant volume, the section length of the shroud area is calculated at 78 mm and the section of the foot is 24 mm. For both sections, due to the low upsetting ratios of 1.3 and 0.4, only one upsetting operation is required for creating the specific preform shape.

Cross wedge rolling enables double workpieces to be manufactured in a single stroke. Thus the proportion of tool costs per forging can be halved and the potential offered by cross rolling can be fully utilized. The shortening of the process chain using this production variant is illustrated in Fig. 3.

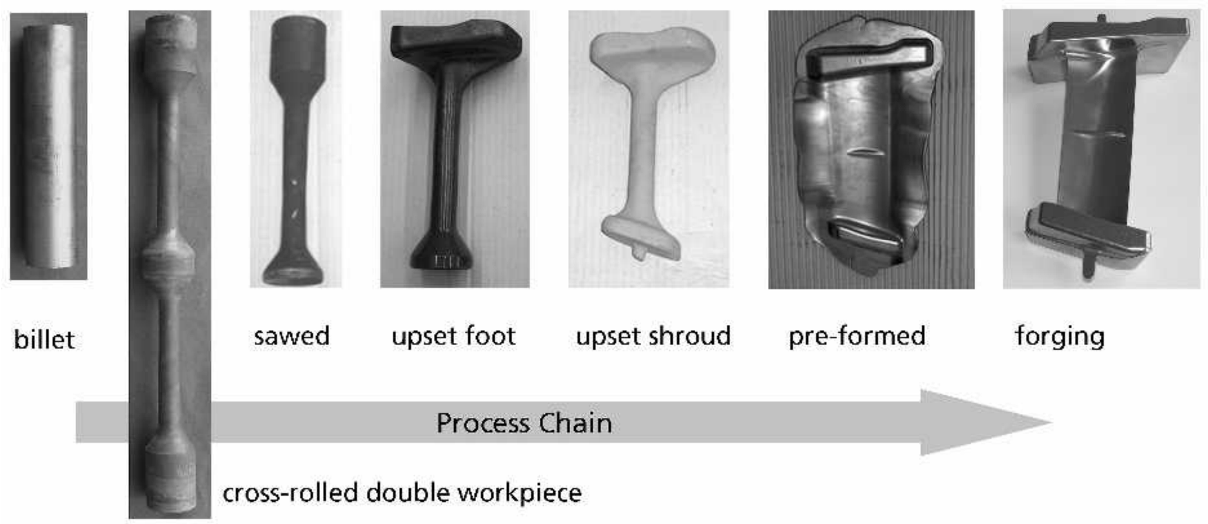

Fig. 3: Process Chain for Basic Forming of Aero Engine Vanes

Because no application of lubricant is required for cross wedge rolling, this operation is additionally eliminated. Due to the high forming strength of the titanium alloy and the wear of the tool, the hot shearing step at the end of the rolling process within the cross rolling machine was omitted in favor of sawing.

Summary

The challenge of reducing material consumption and energy costs related to closed die forging of titanium alloys has led to an alternative manufacturing chain integrating cross wedge rolling.

The cross wedge rolling method enables the use of low-flash closed die forging, based on the economical production of preforms with precise material distribution. It has been shown that, by using cross wedge rolling, it is possible to reduce the number of forming stages necessary for material distribution in closed die forging of aero engine vanes made from titanium alloys. The elimination of preparatory operations such as heating, lubricant application and interim adjustment resulted in a considerable shortening of the process chain. By saving intermediate heating and by improved material utilization, it has been possible to reduce the amount of energy required for hot forming. Cross wedge rolling of double instead of single workpieces represents an additional increase in productivity of the manufacturing process.

Bibliography

[1] Peters, M.; Leyens, C.: Titan und Titanlegierungen. Verlag Wiley-VCH, Weinheim: 2002

[2] Hrsg. Bundesanstalt für Geowissenschaften und Rohstoffe: Rohstoffsituation 2006, Hannover, 2007

[3] Hrsg. EUROFORGE: Energy Benchmarking, Hagen, 2007

[4] Hegazy, A-A.: Untersuchung zur Warmumformbarkeit der Titanlegierung TiAl6V4. Aluminium 59 (1983) 6, pp. 451-455

[5] Lange, K.; Meyer-Nolkemper, H.: Gesenkschmieden. Springer-Verlag, Berlin/Heidelberg, 1977

[6] Lorenz, B.; Bachmann, K.; Steger, J.: Umformverhalten von Titanlegierungen beim Querkeilwalzen. unveröffentlichter Bericht, Fraunhofer-IWU Chemnitz, 2004