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Technical Paper

Design, simulation and manufacturing of a connecting rod from ultra-fine grained material and isothermal forging

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ABSTRACT

In this research work, a study on the mechanical properties of isothermal forging for connecting rods is made from previously ECAP (Equal Channel Angular Pressing)-processed AA1050 and AA5083 aluminium alloys. This severe plastic deformation (SPD) process is used in order to achieve a starting material with a submicrometric structure, thus improving the mechanical properties of the part. In this study, the design and the experimentation process is shown, where this involves the design stage by finite element simulations, the experimental tests and the use of metallographic techniques for the required properties to be analysed. It is observed that there is an improvement in the mechanical properties when the starting material is ECAP-processed before carrying out the isothermal forging. This improvement consists in an increase of 20% in the hardness of the final connecting rod which also possesses a microstructure grain size of 500 nm. To come to these conclusions, the results obtained with the connecting rods manufactured by isothermal forging from previously ECAP-processed material are compared with those conventionally manufactured. Therefore, the feasibility and the advantages of the industrial manufacturing of mechanical components by isothermal forging from ECAP-processed material are demonstrated here as mechanical properties are achieved, as well as a better flow of the material and at a lower forging temperature. In the existing bibliography, there are no research works dealing with the manufacturing of connecting rods from ultra-fine grained material and that is the reason why this present study is considered to be of scientific and technological interest, and therefore, it may be considered to be at the frontline of current knowledge.

1. Introduction

The Equal Channel Angular Pressing (ECAP) process was first proposed by Segal et al. [1] in 1972 in the former Soviet Union in order to obtain ultra-fine grained materials by severe plastic deformation (SPD). Nevertheless, it is over these past few years when a great deal of scientific and technological interest has come about from the development and application of these materials. It consists in a discontinuous severe plastic deformation process in which a material is extruded through a die with two channels of the same cross-section that intersect at an angle between 80° and 135°. The material may be processed several times in order to accumulate a higher plastic strain value inside it [2]. In comparison with other severe plastic deformation processes, this process is the one which introduces the most homogeneous strain values and allows parts with higher size to be processed [3]. Over the last decade, the ECAP process has become a manufacturing process of ultrafine grain size metals and alloys used to improve their mechanical properties. In spite of the great interest in these materials, few elaborations exist that attempt to exploit these above-mentioned advantages.

Although the number of research works which analyse the ECAP properties over the materials thus-processed is numerous, the number of practical applications of these materials is scant. As examples of manufactured parts, it is interesting to mention the research work by Luis et al. [4], in which the design and subsequent manufacturing of rings are carried out from ECAP ultra-fine

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grained material. The manufacturing of these is designed by means of finite element simulations with two forging strokes or stages and both the mechanical properties and the microstructure are studied. A comparison is made between the results obtained at different forging temperatures [4]. Puertas et al. [5] study the design of a Francis turbine blade from ECAP-processed AA1050 and then subjected to isothermal forging. It is observed that there is a noticeable improvement in the mechanical properties as a consequence of the submicrometric structure gained by ECAP and which allows parts with better mechanical properties to be manufactured from ultra-fine grained material.

In the existing bibliography, several research works related to the design, analysis and manufacturing of connecting rods are found. Nevertheless, none of them is related to the manufacturing of this mechanical component from ultra-fine grained material, as has been proposed as an innovation in this present research work.

Finite element studies have been improved more and more with the passing of the years. In the one by Takemasu et al. [6], the objective is to design the forging process of a connecting rod with no flash in order to save costs. To this end, it is necessary to finely control the volume and geometry of the preform in order to avoid both the flash appearance and the incomplete die filling. The optimization of this process is carried out by finite element simulations and the authors divide the preform into three different parts which are separately simulated. As a further advancement to this research work, Vazquez and Altan [7] make a design for hot forging of connecting rods by finite element with the aim of saving material costs as the amount of flash is reduced. They also make a comparison between these results and other results experimentally obtained. The die and preform design is iterative in order to reach a part with no flash which is the best adjusted to the final geometry. The results obtained achieve a flash saving of between 20% and 40%, in relation to conventional forging, where the final flash percentage is 5% with respect to the part.

As is the case for this present study, most of the existing research works use the finite element analysis as a tool for the forging design. There are research works such as that by Grass et al. [8] in which the thermo-mechanical manufacturing process of a connecting rod is analysed by FEM, where it is composed of several rolling and forging stages. In this study, it is observed that the precision of the FEM simulations is very high if it is compared to the experimental tests. Moreover, it is seen that it is possible to study the material flow by following several points throughout the simulation. In another FEM study by Grass et al. [9], these authors study not only the temperature influence on the strain introduced in the material but also the grain size prediction during the forming process at temperature with the help of recrystallization models defined. The results are very similar in comparison to those experimentally obtained.

There are other studies in which finite element method is used in order to evaluate the viability of other methods for manufacturing parts [10]. Furthermore, it is very important to accurately predict springback when working with sheet metal [11]. In the research by Yin et al. [12], these authors study the forging process of an aluminium connecting rod for an air compressor. They substitute the manufacturing process by casting or hot forging for a liquid die forging, thus avoiding the appearance of defects produced by pores or non-metallic inclusions. Thanks to this manufacturing process, the product quality is improved and it is observed that this plastic forming technique is very useful. The research work by Wang and He [13] reviews the developments that have been applied to the manufacturing of connecting rods. These are based on the addition of a central feeding system for the billet and a temperature control system, the use of 3D CAD/CAM tools so as to optimise the rolling and transversal rolling processes, the improvement in accuracy thanks to better equipment such as hydraulic presses and transversal rolling machinery and an improvement in quality due to the use of dies which allows trimming, punching and calibrating operations to be combined. Along this line, it is also very important to model and to simulate the shaping/forming machinery and equipment, above all in relation to its dynamic behaviour [14]. There also exist studies related to the forging of connecting rods from dust material such as the one by Qiu et al. [15]. The starting material is metallic dust from a Ti-1.5Fe-2.25Mo (wt%) alloy and FEM simulations are employed to analyse the process. It is observed that the mechanical strength at the end of the piston rivet of the part is the lowest, whereas it is homogeneous for the rest.

The use of finite element modelling is not only related to the process design but to the study of the material behaviour as is the case of the research work by Chen et al. [16], in which the mechanical properties of a connecting rod are intended to be improved by a modification to the manufacturing process which consists in changing the liquid used for quenching the part. Oil is changed into aqueous polymer or water. These authors compare the results obtained from the connecting rods quenched in the new fluid with the original ones and it is observed that that the mechanical properties are better and no cracks appear. Finite element analysis is used so as to simulate the quenching process and it is found that there is a good correlation between the results simulated and those experimentally obtained. Another study on the behaviour of a material is that by Khare et al. [17], where the causes for the cracks that occur are studied by finite element simulations in the case of the connecting rods for a gasoline engine. Once the critical zones of the part are analysed, a redesign is made in order to avoid the connecting rod failure to fatigue. This new redesign is also analysed by finite element and it is experimentally validated in order to check the reliability of the FEM simulations, which are in good agreement with experimental results.

In a preliminary research to this present study, Luri et al. [18] shows the design process of a set of forging dies to manufacture a connecting rod from ultra-fine grained material. The forging process is designed with two strokes and is simulated both by finite volume and finite element modelling in the case of an AA5083 aluminium alloy.

As was previously mentioned, in this present study connecting rods are manufactured from nanostructured starting material. In order to achieve this submicrometric structure, the material is previously ECAP-processed.

In the existing bibliography, there are numerous and different studies on the ECAP process, depending on the type of metal or alloy employed. Some of these research works are outlined below, where they are focused on the parameters which influence the mechanical properties and on the microstructure of the material, such as the number of passages, the ECAP route employed and the intersection angle.

In relation to the ECAP processing, there are several research studies in which compression tests are performed in order to add a new variable for improvement in the mechanical properties.

Another of the important parameters to be analysed is the number of ECAP passages the billet is subjected to. In the study by Alhajeri et al. [19], AA1050 billets are ECAP-processed at room temperature up to six passages in order to analyse the mechanical properties of the material by means of taking microhardness measurements along the longitudinal and transversal axes. It is observed that after the first ECAP passage, the increase in strain is the highest in relation to the others. The highest strain value is located at the centre after the first passage but when the number of ECAP passages is increased, the strain distribution becomes more homogeneous.

One of the most important aspects to be taken into consideration in relation to the microstructure of ECAP-processed materials is the heat treatment that these materials are subjected to. In the research work by Luis et al. [20], an improvement both in the mechanical