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A study of direct forging process for powder superalloys

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ABSTRACT

Powder metallurgy (PM) processing of nickel-based superalloys has been used for a wide range of near net-shape fine grained products. In this paper a novel forming process, i.e. direct forging of unconsolidated powder superalloys is proposed. In this process, encapsulated and vacuumed powder particles are heated up to a forming temperature and forged directly at high speed to the final shape, by using a high forming load. Experiments of direct powder forging have been conducted on an upsetting tool-set. Microstructure, relative density and hardness of the formed specimen have been investigated. A finite element model of the direct powder forging process has been established in DEFORM and validated by the comparisons of experimental with simulation results of load variation with stroke as well as relative density distribution. The stress state and the relative density variation have been obtained from FE simulation. The correlation between the stress and consolidation condition has been rationalised. The developed FE model can provide a guide to design the geometry and thickness of preform for direct powder forging.

1. Introduction

Powder superalloys have been widely used to produce high performance components [1]. Four typical powder metallurgy methods for superalloys are hot isostatic pressing [2], hot isostatic pressing + hot isothermal forging [3,4], hot isostatic pressing or hot unidirectional pressing + hot extrusion + hot isothermal forging [5]. Hot isostatic pressing (HIPing), as an important near net-shape forming process, allows dense, precisely-shaped components to be formed from metal powders. However, HIPing is extremely costly. During a HIPing process, the powder, which is packed into an evacuated sheet metal preform container, is degassed and sealed under vacuum, and then the container with powder is heated and simultaneously subjected to a gas pressure (usually argon) in a pressure vessel for a long time [6,7], resulting in high cost and low productivity. Furthermore, an intrinsic problem is that prior particle boundary (PPB) precipitate networks can occur in the HIPing process [8]. PPB precipitation has been the major issue that largely limits the application of net-shaped HIPing to nickel-based superalloys. It is generally believed that PPBs are caused by particle contamination and atomic segregation during the long heating time. Both result in precipitation at PPBs, either as carbides, oxides, oxy-carbides, or possibly as oxy-carbonitrides [9]. Since PPB precipitates are brittle and thus provide an easy fracture path, the undesirable PPB networks are detrimental to mechanical properties of HIPed nickel alloy components. In order to break up the PPB networks and restore mechanical properties, post-HIPing deformation, e.g. hot extrusion and hot isothermal forging, is needed, which increases cost.

With regard to powders of other metal alloys, sintered powder forging of steel now is widely used commercially to produce load bearing components, particularly in drive trains of automobiles [10]. Some studies have been carried out on aluminium powder forging [11–13]. Dashwood and Schaffer [11] carried out a hot forging test on a sintered specimen of aluminium alloy and found that the porosity was effectively removed due to compression strain. However due to the fragility of nickel-based superalloy green compacts, it is difficult to use sinter-forge technology for them. In order to reduce the oxidation during heating and soaking of the powder, Das et al. [14] poured Fe–P powder into an cylinder metal container with two open ends, used dry hydrogen flowing through to remove the oxide layer from the powder surface, and heated the powder and the container in a furnace simultaneously. The powder was then hot forged to achieve the final shape. However the best relative density they could obtain was 0.976 in the forged slabs, which may be due to the trapped hydrogen gas between the powders. Using a degassed and sealed metal container can reduce the gas trapped between powders as well as prevent powders from oxidation.

With regard to superalloy compaction techniques, Kelsey Hayes ROC developed a rapid omnidirectional compaction (i.e. fluid die process) in 1979 [15], which does not require a costly HIPing unit for consolidation. In this method, recyclable 'fluid' dies consisting

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of a nickel-copper alloy have been used. At high temperature, the die softens and pressure applied to the die is transmitted to the powder. However the geometry of the 'fluid' die cavity is changed after hot compaction due to the shrinkage of the superalloy powder and therefore it is necessary to produce another die each time after deformation. Crucible Industries developed ceramic mould for HIPing process in 1987 [16], in which superalloy powder is filled into a porous ceramic container. The ceramic container is inserted into a larger steel container which is subsequently filled with a pressure-transmitting bed of fine Al_2O_3 powder, and degased and sealed. In the HIPing process, the steel container is subject to a gas pressure, and the pressure is then transmitted to the ceramic container via Al_2O_3 powder to obtain extremely complex shapes. However HIPing process results in high cost and low productivity. Meeks and Fleming [17] developed a ceramic consolidation (Ceracon) process, which involves taking a heated preform and consolidating the material by pressure against a granular ceramic medium using a conventional forging press [18].

Many researchers have been working on the relationship between pressure and time to process completion, during HIPing [19–21]. Arzt and Ashby [7] studied the effect of pressure and time on relative density for superalloys. As shown in Fig. 1(a), they found that the deformation mechanisms changed from diffusion at a low-pressure to power-law creep at an intermediate pressure and then to yield at a high-pressure. As HIPing pressure is increased, less time is needed to achieve full density of the powder. Based on their research, a diagram was generated as shown in Fig. 1(b). The symbols indicate the relationship between pressure and time when the relative density reaches 1.0, which are obtained from Fig. 1(a). Therefore if the pressure is increased, the time for obtaining a fully dense material could be reduced following a logarithmic form.

In this paper a novel forming process, i.e. direct powder forging of powdered nickel-based superalloys is proposed. In this process, the encapsulated and vacuumed powder is heated up to a forming temperature and forged directly to the final shape, by using a high forming load for a very short time. Direct powder forging is a low-cost and energy-saving process compared to conventional PM processes. Also readily available conventional forging press machines can be used for direct powder forging. A shorter heating time results in fewer PPB precipitates, and due to a large amount of plastic deformation, the existing PPB networks are broken up and thus the detrimental effect of PPBs is weakened. In this paper an up-setting test was conducted to investigate the direct powder forging process. Microstructure, relative density and hardness have been investigated. A finite element model of direct powder forging has been developed in DEFORM-3D.

2. Experimental setup and method

Argon atomised superalloy FGH96 powder, supplied by Beijing Institute of Aeronautical Materials (BIAM), was used as the starting powder. Its chemical composition is given in Table 1. Laser diffraction particle size analyser Malvern Mastersizer 2000 was used to measure the size of the powder. The size of powder particles followed a standard normal distribution, and the average size was 35 μm based on a number distribution. The gamma prime solvus of this alloy is around 1120 °C.

Due to its good weldability and high stiffness and strength at room temperature and its high ductility at elevated temperature, stainless steel is normally chosen as a container, which is strong enough to maintain shape and dimensional control but soft and malleable at the forming temperature [22]. In this study, powder particles were poured into a cylinder container of stainless steel 304, and then the container was vacuumed to 1.0×10^{-5} Pa in order to reduce the amount of air and thus reduce the oxidation of powder at high temperature. The dimension of the container is shown in Fig. 2(a). The outer diameter of the stainless steel container was 20 mm, the thickness was 2.0 mm and the outer height was 20 mm. The container was coated with glass lubricant to reduce friction during hot forging, as shown in Fig. 2(b).

Upsetting can generate a complex 3-D stress distribution due to contact friction between the test-piece and the tools. In order to study the effect of stress on consolidation in the powder forging process, upsetting test was adopted. The test setup is shown in Fig. 2(c). Two flat dies were mounted on a pillar toolset mounted on a 250 kN ESH single shot high rate testing machine. This high

Table 1
Chemical composition of the FGH96 nickel-based superalloy (wt%) [1].

Cr	Co	Mo	W	Ti	Al	Nb	Zr	C	B	Ni
16	13	4	4	3.7	2.2	0.8	0.036	0.03	0.011	Balance

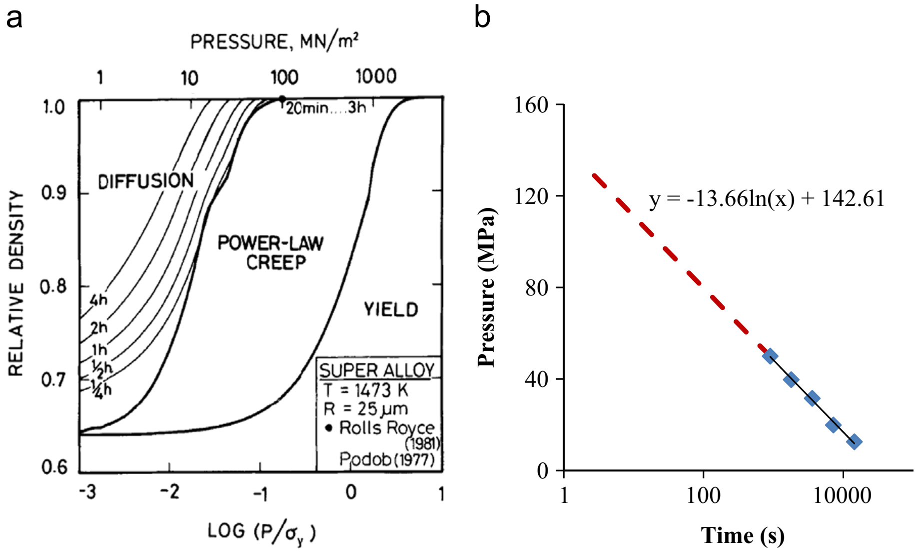

Fig. 1. Concept of direct powder forging: (a) a density/pressure map at $T=1200$ °C for a superalloy with a particle diameter of 50 μm. [7]; (b) relationship between time and pressure for diffusion bonding, at a certain temperature.