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Experimental studies and modelling of high-velocity loaded iron-powder compacts

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ABSTRACT

A production technique with the capacity to significantly improve the mechanical properties of powder metallurgy (PM) parts is high-velocity compaction (HVC). To extend the usage of the HVC method, detailed knowledge of the HVC process is important. To facilitate the development of production processes, numerical simulations can be utilised. In the development of high-precision simulation models, constitutive data of HVC specimens at high strain rates are required. In this study, the dynamic compressive properties of cylindrical specimens made by HVC were measured using a split Hopkinson pressure bar (Kolsky bar) assembly. For this technique, a specimen is placed between two elastic bars. The impact loading is achieved by a projectile accelerating inside an air gun, which impacts the end of the input bar and generates elastic-wave propagation.

The powder material used for the experiments is a press-ready iron-based premix. Among specimens made by HVC and conventional compaction (CC), the effects of the specimen density and the strain rate on the compressive properties, such as failure stress, Young's modulus and failure behaviour, are investigated. During dynamic compression, the failure behaviour of the specimens was also recorded using a high-speed video camera. The difference in the mechanical behaviour between HVC-pressed specimens and conventionally pressed specimens are also investigated. The stress–strain curves of HVC-pressed specimens are identical to those of conventionally pressed specimens, but the failure behaviour differs are concluded.

A well-established numerical method for forming simulations also conducted for powder compaction is the finite element method (FEM). The impact loading of the powder is modelled and simulated using nonlinear three-dimensional FEM. To model the impact process, a constitutive relation for the powder behaviour is proposed, taking into account the strain rate and density variations. To capture the global response caused by cracking during impact, a damage model is implemented. The numerical results in terms of the stress and strain history in the specimen during impact are compared with the experimental measurements. In conclusion, the proposed material model captures the increase in the yield stress due to the higher strain rates and the decrease in stress due to cracking.

1. Introduction

Powder metallurgy (PM) is a rapidly developing technology. To compete with alternative methods, a low production cost is important. If the manufacturer can control production routes and exploit the specific advantages of powder materials, new markets and opportunities will arise. A better understanding of the complex material behaviour will give advantages to alternative methods and possibilities. A key to increase the use of PM material in various applications is to use computer simulations more extensively. Both time and money can be saved if the manufacturing processes of new components and ideas can be exploited virtually. Economic advantages, such as high materials utilisation (95% of the raw material can be used in the final product, in comparison with as little as 50% in other forming processes) and low energy consumption, make it a particularly attractive forming process. The PM process can also produce the unique microstructures and compositions required for cemented carbides and other hard materials, refractory metals, magnets, and composite materials. Powder materials are pressure sensitive and density dependent, which induces complex material behaviour. To numerically reproduce this behaviour, the choice of constitutive model and material parameters is critical. A better understanding of the materials behaviour will provide advantages to other production methods and will allow more extensive computer simulations. Numerical analysis of tool kinematics, tool force, tool stresses, tool design, density distribution, strain-rate sensitivity, green strength, residual stresses, crack initiation, etc., might reduce the time consuming trial-and-error methods currently in use.

High velocity compaction (HVC) of particulate materials or powder systems is a relatively new mass-production technique with the capacity to significantly improve the mechanical properties and hence

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expand the applications of powder-materials parts. With fast hydraulic valves governed by computer systems, the compaction energy can be controlled, and multiple strokes can be used with rapid repetition. A punch impacting into a powder compact in a die will generate elastic and plastic waves of deformation propagating through the compact, causing impacts between particles and the consolidation of the compact. A number of investigations into the HVC process have been published in recent years. All publications indicate that high-density components can be obtained using HVC [1–6]. Other characteristics are low spring back, low ejection forces and uniform densities.

To attain fundamental knowledge of the compaction process, it is necessary to conduct numerical simulations, e.g., using the finite element method. Therefore, a good knowledge of the powder behaviour during high-speed loading is required. This paper reports an experimental investigation and numerical modelling of the behaviour of an iron-based powder premix using the split Hopkinson pressure bar (SHPB) assembly. The global objective of this research is to improve the fundamental understanding of the mechanics of high-velocity compaction and to establish a constitutive model that captures the behaviour of a high-velocity loaded powder. For all materials, densification occurs as a result of contact interactions between the particles. The details of these interactions are, however, different for each individual powder mix. To capture the interactions between particles one possibility is to model the individual particles using a discrete modelling approach. In this work, the constitutive modelling follows a continuum approach which is favourable in a computational point of view. The effect of high strain rate on the interaction of the particles is indirectly incorporated in the continuum based model in the choice of material parameters.

2. Experimental method

The powder material used in the experiments is a press-ready premix consisting of Distaloy AE, 0.5% graphite (uf-4) and 0.6% Kenolube. Distaloy AE is a pre-alloyed water-atomised iron powder from Höganäs AB, Sweden. Kenolube is a lubricant from the same supplier. The theoretical pore-free density of this mix is 7.52 g/cm^3. The behaviour in the compression state of powder mixes (green strength) was characterised by static and dynamic tests. The static tests were performed in a standard static-testing machine. The dynamic tests were performed using the SHPB method.

Cylindrical specimens were manufactured with a height of 20 mm and a diameter of 25 mm with six different densities: 6.9, 7.2 and 7.4 g/cm^3 using an HVC machine and 6.0, 6.5 and 6.9 g/cm^3 using the conventional die-compaction method (conventional compression: CC). Both types of specimens were made by single-action pressing. Hereafter, they are referred to as the HVC specimens and CC specimens, respectively. A photograph of one of the specimens is shown in Fig. 1. The specimens were compressed in the height direction. (Hereafter, this is referred to as the longitudinal direction.) The HVC specimens were manufactured using an HVC-machine with a hydraulic-driven hammer (HYP35-02) from Hydropulsor AB, Sweden.

In the manufacture of powder specimens, the compacting pressure significantly increases with increasing density. The relationship between the compacting pressure and the relative density is shown in Fig. 2. When the density is 6.9 g/cm^3, the compacting pressure of HVC specimens is almost the same as that of CC specimens.

2.1. High-velocity compaction

The manufacture of HVC specimens was performed using a laboratory HVC machine with a hydraulic-driven hammer. This machine has a maximum capacity of 4 kJ. The hydraulic hammer consists of two parts: the hydraulic piston and a weight, which is connected to the piston rod. The hydraulic oil pressure applied on the hydraulic piston is constant and thereby also the force accelerating the piston and the weight. The total mass accelerated was 31 kg. See Fig. 3 for a schematic view.

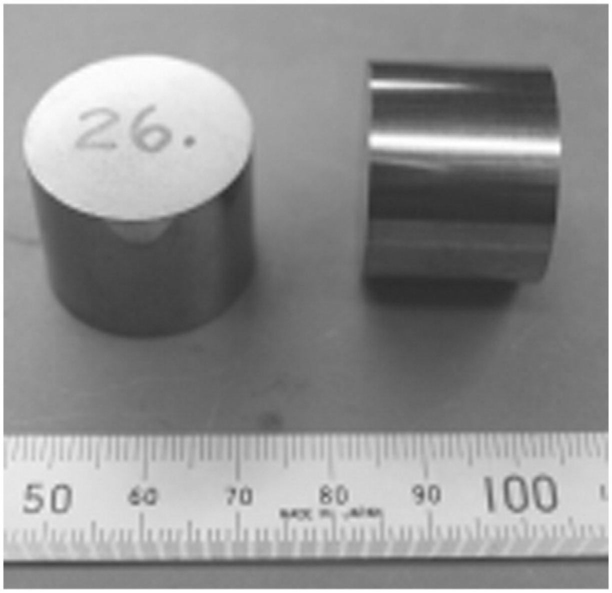

Fig. 1. Photograph of a cylindrical specimen (HVC specimen, 7.4 g/cm^3).

Due to the constantly acting force, the energy level is easily adjustable by varying the acceleration distance of the hammer, i.e., the distance between the start position and the impact position. The level of energy can be calculated by multiplying the accelerating force and the distance. The HVC process typically starts with a pre-compaction, during which the powder is compacted from its apparent density to a density of approximately 5 g/cm^3, and thereby, the majority of the air is evacuated from the cavities. During the HVC compaction, the die was mechanically fixed, i.e., the die was not floating.

The impact-compaction force curve was measured during each HVC compaction. A single HVC compaction results in several force peaks; see Fig. 4. This is because the hydraulic hammer bounces on the top punch until the impact energy dissipates. The hammer impacts the upper punch with its mass and the residual oil pressure in the accumulator until the stress is largely stabilised. The maximum compaction pressure occurs in the first and highest force peak. The experiment shown in Fig. 4 has an impact velocity of 13.2 m/s, corresponding to impact energy of 2.7 kJ and a peak force of 776 kN with a maximum compaction pressure of 1581 MPa. The resultant density for this test is 7.4 g/cm^3. The maximum overall strain rate is of the order 10^2 s^{-1} for the compactions performed.

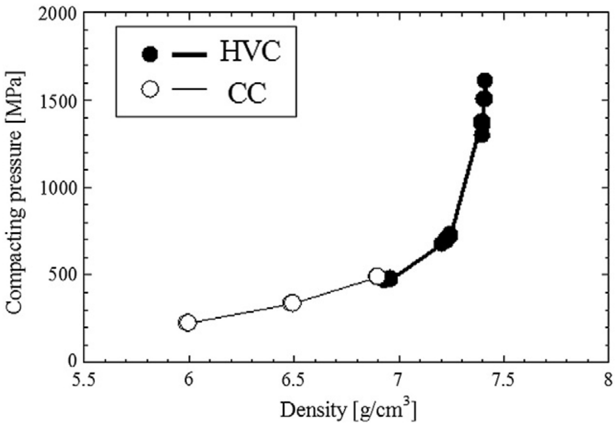

Fig. 2. Relationship between the compacting pressure and density.