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Experimental and numerical investigation of temperature evolution during electromagnetic pulsed compaction of powders

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ABSTRACT

The transient temperature evolution during electromagnetic pulsed compaction of powders is an important concern to densification mechanism, and a homogenous temperature field is beneficial for compaction densification. An experimental and numerical investigation of temperature evolution during electromagnetic pulsed compaction has been completed. Based on the thermodynamics of temperature evolution during electromagnetic pulsed compaction, a numerical model using multi-particle finite element method was developed to provide more detailed information of the temperature evolution. It has been found that the temperature rise during electromagnetic pulsed compaction is mainly induced by the plastic deformation work, while the temperature gradient within the powders is greatly caused by the frictional work. With the die wall/powder friction increasing, the radial temperature gradient becomes greater. With the inter-particle friction increasing, the axial temperature gradient becomes greater and it is strongly correlated to the non-uniform densification within the powders. More external work combined with greater compacting velocity leads to greater temperature rise in powders, and the axial temperature gradient is elevated because of the limited heat conduction in the shorter time.

1. Introduction

Electromagnetic pulsed compaction is a high energy rate forming technique. It is completed by the repulsive force generated by the opposite magnetic fields in the adjacent conductors during a very short time (less than tens of milliseconds). The primary magnetic field is caused by the time-varying discharge current in the coil, and the second magnetic field is induced by the eddy current in the adjacent metallic conductor. Intensive research on electromagnetic forming process [1–4] has been presented and the electromagnetic pulsed compaction has been further developed in recent twenty years due to the great interests from automotive, aviatic and electronic industries [5–7]. The near-net shaped parts by electromagnetic pulsed compaction have relative density as high as more than 0.95. Owning to the advantages of high forming precision, high relative density, high mechanical performance [8,9], the electromagnetic pulsed compaction has been widely accepted as an advanced manufacturing method for various complex-shaped parts of conventional metals or new-type composite materials at room temperature or elevated temperature [10,11], especially for the brittle or stiff materials.

During the electromagnetic pulsed compacting process, the frictions between particle and particle, particle and die walls produce great heat at the contact surfaces, and part of the mechanical energy expended during plastic deformation of particles is also converted into heat, especially in cases of highly localized plastic deformation. The accumulated heats cause a noticeable temperature rise of the powders in a short time of milliseconds. For the temperature-dependent materials of powders, the transient temperature rise during powder compaction can result in material's thermal softening or inter-particle welding [12,13]. What's more, a homogenous temperature field is beneficial to compaction densification [14,15]. Some thermodynamic equations were presented to determine the heat and external work during powder compaction process [16,17,18], and validated to predict the temperature evolution during powder compaction by several tests [19,20]. From the viewpoint of energy conversion mechanism during powder compaction, it was revealed that plastic deformation work is the main cause for the temperature rise of powders, and the residual internal energy after compaction is less than 10% of the total energy [7,19,21]. Numerical approaches were presented by Zavaliangos for predicting transient temperature evolution during tableting [22,23]. The transient temperature field within the tablet was successfully estimated by the thermo-mechanical analysis with a calibrated Drucker-Prager Cap model. Krok [24] concluded in the numerical simulation that the punch shape, compacting speed and die wall/powder friction significantly affected the thermo-mechanical behavior during tableting, and the degree of deformation had more dominant impact on temperature rise than the die wall/powder friction. The inter-particle interaction is key role for heat transfer and energy dissipation during powder compaction, Wu [25] analyzed the two major energy dissipation

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mechanisms(stress wave propagation and plastic deformation) during normal impact of elastic and elastic-plastic spheres. Rusinek [26] and Chaudhuri [27] presented different inter-particle heat conduction algorithms in numerical studies of temperature distribution, and the simulated results had reasonable agreement with experimental results. However, up to now, few research on the coupling interactions between the micro-dynamics of particle and the temperature evolution can be found. The effects of particle size, inter-particle friction and compacting velocity on the temperature evolution during powder compaction need to be evaluated.

A unique insight into the temperature evolution inside the powders in the close die is not accessible due to the inherent experimental limitations. Numerical modeling, which can provide more detailed information than physical test, has been widely used to study the compaction densification behavior. Two numerical procedures, the continuum approach and the discrete element approach, were adopted in previous numerical studies about densification behaviors [28,29]. Continuum approach, hypothesizing that the powders is a continuous homogeneous medium with changeable volume under external loading, was extensively used in densification studies of metal powder compaction. It can handle many macroscopic problems, but the particle-level information is lacking. Discrete element approach, assuming that each particle is a rigid body and the inter-particle interaction forces determine the translational, rotational or sliding motion of particle assembly, gives an effective way to study the mass flow at particle level during compaction, but the stresses and strains inside the particles are lacking. In recent years, the multi-particle finite element method (MPFEM) has been developed based on the improvements on both continuum approach and discrete element approach, and successfully employed by many researchers in high-velocity compaction studies [30,31,32]. It is fundamentally performing classical finite element simulations on an assembly of discrete particles, and ensures the great flexibility in terms of particle rearrangement, sliding, rotating and local contact deformation [33]. Hence, MPFEM is more effective to study the densification behavior that involves the transmission from deformation of an individual particle to continuous bulk behavior of powders.

In this study, an experimental and numerical investigation of the temperature evolution during electromagnetic pulsed compaction are completed. The electromagnetic pulsed compacting test is carried out with a self-developed WG-IV electromagnetic pulse forming machine. Based on the thermodynamics of temperature evolution during electromagnetic pulsed compaction, a numerical model using multi-particle finite element method is presented and validated to study the transient temperature evolution during electromagnetic pulsed compaction. The influence of friction and compacting velocity on the temperature evolution is studied by this numerical model.

2. Electromagnetic pulsed compacting test

The electromagnetic pulsed compacting test was carried out with a self-developed WG-IV electromagnetic pulse forming machine at Wuhan University of Technology (China), as shown in Fig. 1. The maximum energy of this electromagnetic pulse forming machine is 60 kJ. The capacitance of the capacitor bank is 1100 μF, and the voltage limit is 11 kV.

The electromagnetic pulse energy can be calculated by the following equation,

$$E = 0.5cU^2 \tag{1}$$

where c, U are the capacitance and voltage of capacitor bank, respectively. Different electromagnetic pulse energy output can be realized by presetting corresponding voltage value on the microcomputer control panel. Firstly, the typical LRC circuits is switched on as soon as the voltage in capacitor bank reaches the desired value. Then a pulsed current is discharged from the capacitor bank and flows through the panel coil, and a time-varying magnetic field is generated. With this time-varying magnetic field, an eddy current is induced in driving board. The opposing forces between the magnetic field and induced currents are applied on the driving board. The driving board pushes the tapered amplifier and upper punch to compact the powders in the die. The compaction tools are shown in Fig. 2. The pressure in powders can rise to as high as hundreds of MPa within few milliseconds.

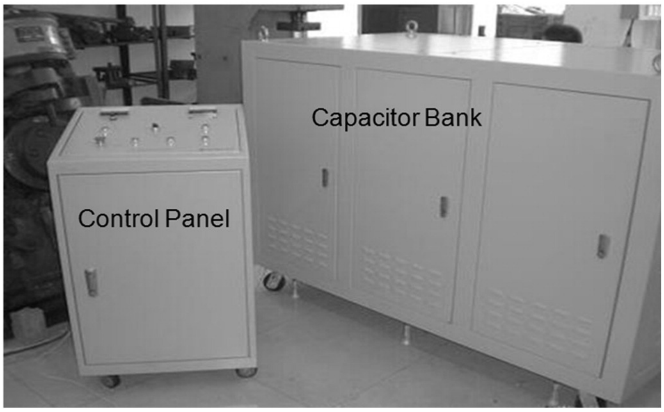

Fig. 1. WG-IV electromagnetic pulse forming machine.

The initial velocity of driving board together with tapered amplifier and upper punch can be deduced by the following equation,

$$V_0 = \sqrt{2\eta_t E / m} \tag{2}$$

where η_t is the energy efficiency coefficient of the electromagnetic field [34], and m is the total mass of driving board, tapered amplifier and upper punch. The die, upper punch and lower punch are made of tool steel (TC70 in ISO4957) with the HRC of 65 after heat treatment. The density is 7750 kg/m^3, the specific heat capacity is 477 J/kg·K, and the thermal conductivity is 53 W/m·K.

As shown in Fig. 3, two holes with the diameter of 5 mm were drilled in the die body at 1/3 and 1/4 height, respectively. The bottom surface of the two holes is 2 mm far from the internal surface of the die body. The thermal sensors were placed at the bottom surface of the holes to measure the temperature rise of die body during electromagnetic pulsed compaction. The DH5922N system was used for temperature measuring with sampling frequency of 100 kHz. The Fe powders were prepared by gas atomization in Beijing Shougang company, and the average diameter is 250 μm, as shown in Fig. 4. The electromagnetic compaction test was carried out at room temperature of 23 °C.

3. Numerical modeling of powder compaction

3.1. Mesh and boundary conditions

To simplify the finite element model, the initial powder particle is assumed to be a 2D sphere with average diameter of 250 μm. On the sphere edge, the refined elements were used to guarantee the accuracy in describing the inter-particle interactions. Inside the particle, the coarse elements were adopted to avoid additional computational costs. Each particle was discreted into 144 quadrilateral elements with the node number of 169. For the assembly of particles, four types of initial packing structures (random packing, tetragonal packing, hexagonal close packing and honeycomb packing) were commonly suggested [31,33,35]. Both the random packing and hexagonal close packing show good agreement with the experimental results of compacting tests. The random packing structure represents higher accuracy for describing inter-particle frictional mechanism, so random packing in 2D is