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A density-dependent modified Drucker-Prager Cap model for die compaction of Ag57.6-Cu22.4-Sn10-In10 mixed metal powders

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ABSTRACT

Due to the bad plastic workability, silver based brazing filler metals with high proportions of additional elements such as Zn, Sn, In, Ga, are very brittle and difficult to be made into thin sheets using conventional manufacturing processes. A novel process method that combine powder compaction and sintering, can fabricate thin sheets of the fragile silver based filler metals. In this work, the densification mechanism of Ag57.6-Cu22.4-Sn10-In10 (wt.%) mixed metal powders was investigated, and a modified density-dependent Drucker-Prager Cap (DPC) model was introduced to describe its compaction behavior based on the equivalent density method. The powder compact was considered as a continuum, and a linear elasticity law as a function of relative density was then used to express the elastic behavior of the powders. An instrumented die with force transducers has been designed to determine the material parameters of the modified DPC model. The elastic and plastic material parameters such as E, υ, β, d, p_a, R and p_b were then determined experimentally. The friction coefficient between the powders and the die wall with a lubricated die was determined based on the Janssen–Walker theory in the instrumented die experiments. Furthermore, the modified DPC model with the linear elasticity law was validated using finite element simulation method in ABAQUS with a user subroutine (USDFLD). A good agreement between the simulations and experimental results was obtained, indicating the feasibility and applicability of the introduced modified models to describe the die compaction behavior of the mixed metal powders.

1. Introduction

Silver(Ag) based filler metals have been widely used as candidates for joining ferrous and non-ferrous materials, and alloys in aerospace, power electronic and household appliances industry due to their excellent performance [1,2]. Usually, high proportions of Zn, Sn, In, Ga and other rare earth elements are added into the silver based filler metals to reduce the solidus temperature and the melting range and also improve the fluidity of alloys [3–9]. However, the additional Zn, Sn, In, Ga, would react with Ag and Cu, and form hard and brittle intermetallic compounds in the filler metals, which would weaken the ductility and plastic workability of the alloys [4,10,11] and make them brittle and difficult to be processed into thin sheets. In industry applications, the filler metals are commonly used in the form of thin strips, foils and sheets, for the sake of easy handling and controlling of interlayer thickness between welding seams. Previous studies have shown that several kinds of silver based filler metal strips with thicknesses of the order of 100 μm to several millimeters could be fabricated by using conventional manufacturing processes, such as melting, alloying, casting, heating treatment and rolling [11–13]. Since these processes were usually complicated and time-consuming, the rate of finished product was unsatisfactory and was only about 60% [13]. On the other hand, the continuous casting methods [14–18] have also been adopted to manufacture the silver based filler metal strips. However, the alloy strips were very fragile and easily broken during the continuous casting processes [16], limiting the practical applications of continuous casting methods. In addition, powder metallurgy and mechanical alloying method [19–23] have been recently used to obtain silver based filler metal. Ring parts of the Ag-Cu-Sn filler metal were produced by Wu [23] through powder mechanical alloying, cold compaction and hot treatment processes. Thin Ag-Cu-Ti sheets were made by ball milling and subsequently cold pressing the mixtures of pure TiH_2 and Ag-Cu braze powder [24]. Mixtures of pure powders of Ag, Cu and Ti were ball-milled homogenized and cold pressed under 200 MPa into the small rods and then heated, and sintered under pure argon atmosphere to produce the Ag-Cu-Ti alloy [25]. The process combining powder compaction and sintering is therefore viewed as a promising approach to fabricate thin sheets of brittle silver based filler metals. In this way, the silver based filler metals with high proportions of Zn, Sn, In, and Ga, which are brittle and processing difficult, could be easily fabricated into sheets with different thicknesses and shapes. The combined method is superior to the

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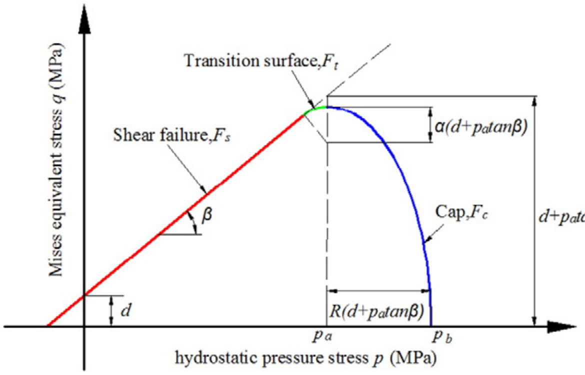

Fig. 1. Yield surfaces of the modified Drucker-Prager Cap model [53,54].

conventional processes due to the simplified production process, shortened production cycle, and the reduced energy consumption, capital cost, operating cost, and scrap rate.

The quality of the filler metal sheet is vital when using the powder compaction and sintering method. It requires the powder mixture under a pressure sufficiently high to bind the particles together, and the sheet density must be sufficiently high to avoid weld porosity in welding seams. Meanwhile, the filler metal sheet must not only be free of visible defects and physically strong to withstand subsequent sintering, packaging and transportation steps, but also be able to be fabricated at a high speed with an suitably low compaction force so as not to damage the expensive moulds, and machine. As such, it is of great importance to optimize the proper process parameters, compaction force and moulds design when using the abovementioned combined method. Generally, trial and error method is used in industry applications to optimize the process parameters and tooling design through extensive experiments. While compared with the costly and time-consuming trial and error method, computational simulation of powder compaction process based on finite element modeling (FEM) is an alternative approach. It assists to understand the effects of the tooling properties, the lubrication, and the process parameters, (i.e., the compaction speed, compaction sequences, and the punch force) on the distribution of stresses, strains and density in the powder compact, thereby providing a guideline in the optimization of tooling design and the process parameters.

The numerical modeling of the powder compaction process requires a proper constitutive model and a thorough knowledge of friction between die and powder. The simulations of powder compaction were typically carried out using two different approaches: the discrete model method [26] and the continuum model method [27,28]. Individual particle behavior was modeled and the contact interaction and deformation of particles were analyzed in discrete model method, while the powder bed were considered as a continuous media in the continuum model method which was more suitable for engineering applications. So far, most of the research on powder compaction has been mainly focused on densification of pure powders due to the complexity in densification of mixed powders. While in this work, the modeled powder material was Ag57.6-Cu22.4-Sn10-In10 mixed metal powders which were used to produce thin sheets of filler metal by powder compaction. Thus a proper constitutive model for mixed metal powders is of significant importance in modeling the densification behavior. For densification of mixed powders, Lange [29], Turner [30] and Kim [31] experimentally studied the densification behavior of mixed powders under various types of powders and experimental conditions. Bouvard [32] and Storåkers [33] proposed theoretical models based on the model of Arzt [34]. However, the calculated results from these models may be useful only for global densification behavior such as the variations of relative density with pressure, but not for local deformation and density distribution into powder compact [35]. Cho and Kim [36] analyzed the densification behaviors of mixed powder under high temperature processes with the proposed mixed creep potentials in terms of the volume fractions of copper and tool steel powders. By mixing the yield functions proposed by Fleck et al. [37] and by Gurson [38] for pure powder in terms of volume fractions of Cu powder and the fraction of contact, Kim [35] proposed a mixed yield function to characterize the densification behavior of mixed cooper and tool steel powder under cold compaction. But these models are complicated and cannot be directly used for densification of mixed powders under a general loading condition. Recently, many researchers have adopted a modified Drucker-Prager Cap model, which was originally developed for geological or soil materials, to describe the densification behavior of metal powders [39–44], cosmetic products [45], pharmaceutical powders [46–50] and ceramic powders [51,52] based on the continuum model method. Due to the addition of an elliptical cap to a shear yield surface, the modified DPC model is able to well characterize the densification mechanisms of the powders during the loading, unloading and ejection steps. And the parameters of the model could be determined expediently by several standard calibration experiments. Herein, the modified DPC model was introduced to model the densification behavior of the mixed metal powders. Based on the equivalent density method, the mixed metal powders were treated as a pure powder and its theoretical density was calculated in terms of the mass fraction of each powder.

In this work, the powder compacts of Ag57.6-Cu22.4-Sn10-In10 filler metal were produced by powder compaction, and the densification mechanism was investigated as well. The modified DPC plasticity model and a linear elasticity law as a function of the relative density were employed to describe the compaction behavior of Ag57.6-Cu22.4-Sn10-In10 mixed metal powders. An instrumented die with force transducers has been designed to determine the material parameters. The finite element method based on a user subroutine (USDFLD) was used to validate the constitutive model. The detailed analyses and findings provided in this work are expected to provide a proper method for modeling the densification behavior of mixed metal powders, and can be guidelines in implementing process simulations and optimizing tooling design and the process parameters.

2. Constitutive model and methods of parameter identification

2.1. Constitutive model

The modified DPC model used in this study is implemented in the finite element analysis software ABAQUS/Standard [53,54], which is derived by adding a cap yield surface to the conventional Drucker–Prager model as shown in Fig. 1. The model is assumed to be isotropic and its yield surface consists of a Drucker-Prager shear failure surface (F_s), a cap yield surface (F_c), and a transition region (F_t) between them.

The shear surface F_s in the DPC model is determined by the friction angle β and the cohesion d, which provides a criterion for shearing

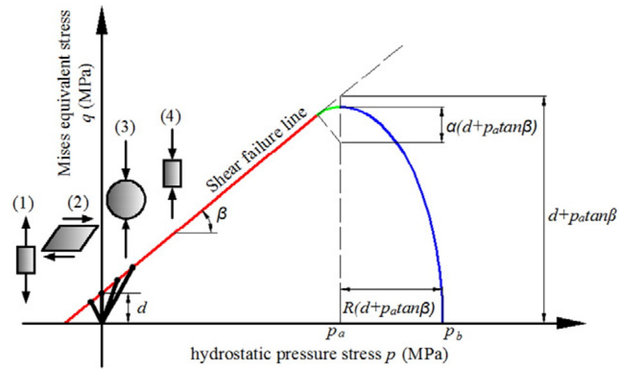

Fig. 2. Determination of the shear failure line from (1) uniaxial tension, (2) pure shear, (3) diametrical compression, and (4) uniaxial compression test. [54].