Journal of Computational and Applied Mathematics 246 (2013) 301–311

Contents lists available at SciVerse ScienceDirect

Journal of Computational and Applied Mathematics

journal homepage: www.elsevier.com/locate/cam

A new method of intelligent control for system stabilization in process-integrated powder coating by radial axial rolling of rings[☆]

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A R T I C L E   I N F O

Article history:
Received 2 January 2012
Received in revised form 14 May 2012

Keywords:
Finite element simulation
Ring rolling
Apollonian circles
Control mechanism

A B S T R A C T

Process-integrated powder coating by radial axial rolling of rings represents a novel hybrid production process to apply powder metallurgical coatings on large ring-shaped parts. The goal is to noticeably improve resistance against abrasive wear. To investigate important quantities such as e.g. the residual porosity in the layer and the stress states in the rolling zone, the versatile use of the finite element method (FEM) is crucial. Therefore, a parameterized FE model is developed on the basis of a finite strain viscoplastic material formulation. Reasonably controlling the movement of the guide rollers is an important task. It will be shown that the development of a mathematical formulation for the analytical design of such a control system based on Apollonian mutually orthogonal circles is necessary. The paper will be concluded by simulation results of the ring rolling process and comparisons with experimental results.

1. Introduction

One of the important branches of metal forming processes that evolved over 150 years is ring rolling. Fundamental scientific work regarding ring rolling processes is presented by Harbord and Hall [1] and Weber [2]. General overviews of ring rolling processes are given by Beseler [3] as well as Johnson and Needham [4]. The ring rolling process is used to manufacture seamless rings [5]. These are precisely dimensioned for applications in aerospace and automotive industries, as well as for railway wheels and tires [6,7]. A comprehensive historical background related to solid ring rolling processes can be found in [8,9].

In many applications, it is advantageous to equip the rolled ring with a wear resistant smart functional layer [10,11]. See e.g. rollers in crushing and briquetting mills used in mineral industry. Moll et al. [12] and Frischkorn and Reese [13] focused on new techniques for the application of such coatings. Modern techniques can be classified into hot-isostatic pressing (HIP), flame spraying and buildup welding. The main investigations in these fields are carried out by Haefer [14] and German [15] as well as Kuroda et al. [16].

Although the HIP process is the most common way to apply such a coating, it has some disadvantages [17]. The size of available HIP plants can only house rings with a diameter up to 1.5 m. In contrast to that, the largest ring rolling plants can produce rings with a diameter up to 10 m. Since only a few large HIP plants are available, one has to deal with the disadvantage of long manufacturing times. Flame spraying and buildup welding require the application of high temperature and several hours process time. In flame spraying, the volume of hard phases in the MMC layer increases due to diffusion. This reduces the compound hardness. In build-up welding, the dissolution of the hard phases leads to a decrease of the hard

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[☆] This document is a collaborative effort.

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doi:10.1016/j.cam.2012.06.040

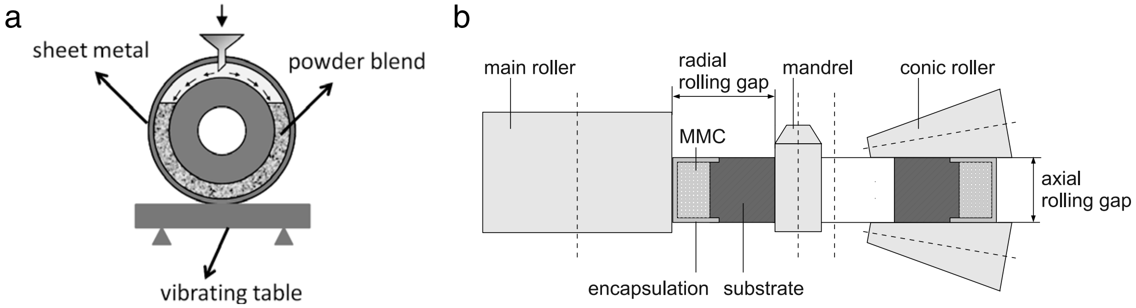

Fig. 1. Pre-compaction process, vibration of the ring on a vibrating machine in order to fill the chamber and to pre-compact the powder blend (a), radial and axial rolling passes with integrated powder chamber (b) [18].

phase content in the matrix. This results into an unwanted alloying of the matrix and thus the elimination of eutectic hard phases. A comprehensive description of these aspects can be found in [18].

In the new approach, the integration of the compaction process into the rolling stage is thought to break the limitations that come along with the HIP process [18]. The most effective concepts for coatings that reduce abrasive wear are based on powder metallurgically produced metal matrix composites (MMCs) consisting of a high alloyed steel matrix with embedded hard phases (e.g. borides and carbides) [12,11].

The material investigated in the present work consists of hard particles with low reactivity towards iron-like titanium carbide (TiC). It can be processed in the same way as a material including hard particles with high reactivity, e.g. fused tungsten carbide (WC/W2C) [19]. Hard phases crystallize during the cooling of high-alloyed casts and obstruct grooving by minerals as employed in thermal sprayed layers and build-up weldings. To overcome the restrictions of these processes, we aim at the development of a new production process based on the integration of powder metallurgy (PM) into radial axial ring rolling.

In order to investigate the influence of several geometry and process parameters on the residual porosity of the layer, parameterized FE models are developed. The control of such complex systems cannot be achieved by currently available standard approaches [20]. A new technique to control and stabilize the process is necessary to reach stable processes for different combinations of parameters. In this paper, different models including a large variety of geometries, are successfully used to carry out the ring rolling process. We demonstrate the influences of the layer material and various roller geometries as well as well-defined ring relocations on the compaction behavior.

The paper is structured as follows. In Section 2 the principles of powder metallurgical coatings are discussed. After that the material model which describes the sintering and compaction of the metal powder is introduced. In Section 4, the crucial issues of the FE simulation are explained. Section 5 explains the control mechanism and its significant effects on ring roundness and ring rolling stability. Finally Section 6 is devoted to a discussion of the results. The paper will be finished by some concluding remarks.

2. Design and manufacturing of the powder coating process

In order to produce a ring-shaped part with a powder coating by radial axial ring rolling it is necessary to first create a rolling blank. As is illustrated in Fig. 1a the rolling blank consists of a substrate ring and a powder chamber which is welded circumferentially to the ring. The powder chamber's cross section has a rectangular shape that is embedded in the ring (see Fig. 1b).

The filling process is carried out on a vibration table to reach an optimum state of powder pre-compaction and a high density of the powder volume in the chamber before sintering (see Fig. 1a). Vibratory compaction depends on several parameters such as the mechanical properties of the powder particle, the hard phase size, the particle size distribution, the particle morphology, the flow ability, the vibration intensity and the capsule shape. Most satisfactory results in pre-compaction are obtained by applying very low amplitudes of less than 1 mm and high frequencies of 70 Hz or above. The heating of the ring to the rolling temperature is used to trigger the sintering of the layer material which results in the formation of sintering necks between the powder particles. A large spectrum of sintering tests is carried out using different matrix powders with and without hard particle additions in combination with various sintering temperatures (950, 1000, 1050, 1100, 1150 °C) and dwell times (2, 4 and 6 h). These experiments show that a temperature of about 1150 °C is necessary to achieve a sufficiently high density of the sintered powder inside the capsule [18].

Finally the prepared ring is brought onto the rolling plant. After that the ring rolling process can be started which leads to a noticeable increase of the ring's diameter and further compaction of the powder material inside the capsule.

3. Rate dependent material model for sintering and compaction of a porous solid

The material behavior of the compressible layer is described by a model of finite strain viscoplasticity. Due to the high temperature, the rate dependency of the material has to be taken into account. A comprehensive description of a