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Numerical modelling of powder metallurgical coatings on ring-shaped parts integrated with ring rolling

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ABSTRACT

Today's demands for flexible and economic production of ring-shaped work pieces coated by functional layers can only be met by new manufacturing techniques. These are suitably based on precise process modelling and high-performance control systems. The process-integrated powder coating by radial axial rolling of rings introduces a new hybrid production technique. It takes advantage of the high temperatures and high forces of the ring rolling process. This is not only to increase the ring's diameter, but also to integrate powder metallurgical multi-functional coatings within the same process. To improve the feasibility assessment of the proposed geometries and material combinations as well as to investigate important quantities such as the stress state in the rolling gaps and the residual porosity of the powder metallurgically produced layer, the versatile application of the finite element method (FEM) is crucial. Therefore, parameterized two-dimensional and three-dimensional finite element (FE) models are created. It will be shown that the implementation of a new control mechanism based on Apollonian mutually orthogonal circles and bipolar coordinates allows an efficient stabilization of the proposed systems. The paper is concluded by a detailed description of the process simulation and a comparison of its results with experimental data.

1. Introduction

Ring rolling represents an incremental forming process which is used to manufacture precisely dimensioned seamless rings. Its first scientific developments were made in the 20th century (Harbord and Hall, 1923; Weber, 1959). Typical applications can be found in aerospace, automotive and railroad industries (Johnson et al., 1968), e.g. rings for railway wheels and tires (Tiedemann et al., 2007). Additionally, the potential of a novel incremental ring rolling process which allows a flexible near-net-shape forming of both hot and cold rings is presented by Allwood et al. (2007).

In many applications, it is advantageous to equip the rolled ring with a wear resistant smart functional layer (German, 2005; Moll et al., 2007). Examples are the rolls in crushing and briquetting mills used in mineral industries. There are several techniques available to manufacture these coatings. One example is thermal spraying studied, e.g. by Haefer (1987) and Kuroda et al. (2008). This coating process has several variations such as plasma spraying proposed by Bach et al. (2004), flame spraying presented by Bach et al. (2000) and detonation spraying investigated and utilized by Haefer (1987), in which melted materials are sprayed onto the proposed surface. However, the created coatings are not thick enough to be applied in briquetting machines used in mining and mineral industries. Additionally, long process times and high process cost are disadvantages of these methods (Berns et al., 1993).

Another famous technique related to wear resistant coating is hot isostatic pressing (HIP) which is performed by Helle et al. (1985). This manufacturing process is used to produce near-net-shape devices from metal powder that exhibit almost no residual porosity (Tanaka et al., 1989). In comparison to cold compaction of metal powder, which is usually followed by pressureless sintering, the risk of cracks caused by residual stresses is much lower within the HIP process. However, the size of available HIP plants can only house rings with a diameter up to 1.6 m and a height up to 2.5 m (German, 2005). Due to the poor availability of large HIP plants, long process times and high logistic costs have to be taken into account.

Hence, there is a need for a novel and innovative production technique to overcome these disadvantages. Kopp et al. (2004a) study the joining of functional steel parts with a steel component during thixoforming in one process step. In another paper, Kopp et al. (2004b) propose forming of metals in the semi-solid state and investigate the mechanical properties for three groups of materials as, e.g. thin film deposited by physical vapor deposition, plasma

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assisted chemical vapour deposition and bulk ceramic materials. Following these ideas, a new ring rolling technology is developed by Meier et al. (2007) and Theisen et al. (2007).

In this new process, the integration of the compaction process into the rolling stage is thought to break the limitations that come along with the mentioned coating processes. The created products can have a diameter up to 12 m and a height up to 2.8 m. Although this novel process is reasonably efficient with respect to energy, process time and costs, there exists some difficulties. The encapsulation has to maintain vacuum conditions and conventional rolling strategies are not applicable. Furthermore, the geometrical design (influence of chamber's design on the rolling and compaction behavior), constructional aspects (type and position of welding seams to ensure the required mechanical strength and stability under load and filling solution) and processing aspects (surface processing parameters, cleanliness of all surfaces and quality of the welding seams) are additional difficulties which have to be overcome.

To support the design of this new process and to predict the influence of several geometry and process parameters on the residual porosity in the layer, parameterized FE models are developed. High computational run time is a well known problem in the simulation of the ring rolling process (Davey and Ward, 2002a). To reduce the computational effort, Hu and Liu (1992) study the consequences of working with a 2D plane strain model. Additionally, the use of hybrid meshes (Hellmann et al., 2000) in combination with arbitrary Lagrangian–Eulerian (ALE) techniques are investigated by Davey and Ward (2000) and Davey and Ward (2002b). By applying the ALE formulation the mesh distortion is independent of the material flow. In this way, a fine mesh needs to be only maintained in the rolling gap.

An important issue of ring rolling research is concerned with system stabilization. An analysis of the guide roll forces is presented by Johnson and Needham (1968). Kopp et al. (1984) introduce a control algorithm based on geometrical and kinematical relations of rolls and the ring in the process. This control mechanism is applied experimentally. The kinematical relations between the deformation and the ring's geometry in order to control the process with respect to the feed speed of the rolls are presented by Koppers and Kopp (1992). A comprehensive overview of applicable strategies for controlling the ring rolling process is demonstrated by Allwood et al. (2005). Additionally, there are several studies which are published by Guo et al. (2004), Hawkyard et al. (2007) and Li et al. (2008) related to the control of the guide roll movement.

These mechanisms work well for the systems including a solid ring. However, they are not well applicable for rings coated by multi-functional surfaces with non-isochoric plastic deformation. The basic ideas related to the analysis of the guide roll forces for the rings coated with porous materials are presented by Kebriaei et al. (2013). In that study only a 2D plane strain model is investigated. Therefore, this control mechanism is now improved to be applicable to 3D simulations and practical investigations. In contrast to the previously mentioned authors our control algorithm is combined with a FE model. Additionally, we introduce a special technique to control and to stabilize the process based on information of the current stroke of the hydraulic cylinders that actuate the guide rolls.

In the paper we study different models including a large variety of geometries for the simulation of the ring rolling process. We demonstrate the influences of the layer material as well as various roll geometries and well-defined ring relocations on the compaction behavior.

The paper is structured as follows. In Section 2 the principles of the process-integrated powder coating are discussed. After that in Section 3, the material model which describes the sintering and compaction of the metal powder will be introduced. In Section 4, the setup of the FE model is discussed. Section 5 is devoted to the development of a novel control mechanism for the guide roll movement in order to reach a stable ring position throughout the process. The significant effect of the applied control mechanism on the ring roundness and the ring rolling stability is then subject of the first part of Section 6. This is followed by an investigation which mesh density is required to obtain converged results. Additionally, we study the influence of working with the assumption of plane strain instead of a fully three-dimensional model. Moreover, the effect of different ring and roll geometries as well as the well-defined relocation of the ring on the residual porosity in the layer is presented in this section. The paper closes with some concluding remarks.

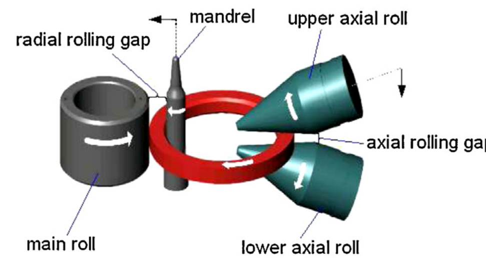

Fig. 1. Principle of ring rolling.

2. Process-integrated powder coating

The principle of the rolling process is sketched in Fig. 1. The mandrel pushes the ring towards the main roll which is driven by an angular velocity. Friction between the ring and the main roll as well as between the ring and the mandrel lead to a rotation of the ring. By decreasing the radial rolling gap the ring growths in tangential and in axial direction. In the opposing axial rolling gap the height of the ring is controlled and reduced by the axial rolls.

In the new process, a sheet metal is welded circumferentially around the outside of an unrolled ring blank. Powder layer material (metal matrix composite, MMC) is placed inside the resulting chamber (see Kebriaei et al., 2013). The powder chamber is exposed to nitrogen atmosphere and is evacuated afterwards. Then the ring is heated up to approximately 1150 °C. This temperature is maintained for 4–6 h in order to perform sintering of the metal powder. In this way the powder particles are connected to each other by sinter bridges. Next, the rolling of the ring is performed. This starts at temperatures of about 1100 °C. The encapsulation has to maintain the vacuum conditions until the compaction of the layer has reached the point of closed porosity, i.e. that the pores are separated from each other. Otherwise oxidation of the layer material may occur.

3. Constitutive modelling of metal powder

3.1. A pressure sensitive model of viscoplasticity

The model used to describe the compressible layer material is based on a finite strain elasto-plastic material formulation. Since the process takes place at high temperatures rate dependence has to be taken into account. The kinematic framework is based on the multiplicative split of the deformation gradient $\boldsymbol{F}$ into elastic ($\boldsymbol{F}_e$) and plastic ($\boldsymbol{F}_p$) parts. The free energy per mass ψ is additively decomposed into the two parts ψ_s and ψ_p. The energy stored in the solid skeleton is considered by ψ_s while ψ_p accounts for the free surface energy due to the porosity of the material. The presence of ψ_p is important to model sintering effects, i.e. a temperature driven densification under the absence of an external load. Specific forms of ψ_p are introduced, e.g. by Mähler and Runesson (2000) and