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# Study on the progress of solidification, deformation and densification during semi-solid powder rolling

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ABSTRACT

Semi-solid powder rolling (SSPR) is a novel strip manufacturing process, which combines the features of semi-solid rolling and powder rolling. High-performance metallic strips can be successfully prepared by semi-solid powder rolling. Based on its features, solidification, deformation and densification occur simultaneously and collaboratively during rolling. Progresses of them during semi-solid powder rolling were investigated via temperature, rolling force and density. By using numerical and experimental methods, the factor of progress remarkability (*F*) was proposed and calculated to discuss their progress remarkabilities during the whole procedure. A modified calculation methodology was adopted to calculate the rolling force and finite difference technique was used to calculate the temperature change. The calculated results agree well with the experimental data. The results show that an appropriate roller temperature gives a suitable cooling rate and it decreases as the time increases. According to the factor of progress remarkability (*F*), solidification occurs quickly and is significant in the material supplying region and drag-in region while densification and deformation are remarkable in the densification region resulting in a good strip with a high density.



## 1. Introduction

High strength aluminum alloys such as AA7050 are used extensively for aerospace applications. Plate or strip products are usually manufactured by conventional ingot metallurgy (I/M) process. Subsequently, the materials are further processed (e.g. heat treatment, hot rolling, and cold rolling) to meet the required properties and so the procedure is complex and energy wasting. The aluminum alloys strips prepared by semi-solid rolling such as rheo-rolling have cracks, pores and liquid segregation easily [1–5]. Powder rolling may need binder during forming and then green strips need sintering for further consolidation. Wu et al. studied semi-solid powder forming (SPF) and discussed various processing routes [6–11]. Until now, SPF is mainly applied in the extrusion and compaction tests to prepare bulk materials. Therefore, a novel strip manufacturing process, termed “semi-solid powder rolling” (SSPR), was proposed by the authors. This new process is mainly used to prepare strips with high quality, especially for alloys that have a wide freezing range and low melting point such as aluminum alloy (AA7050, 2124 etc.). The general concept of semi-solid powder rolling is from the possible combination of semi-solid forming and powder rolling. Semi-solid powder rolling consists of semi-solid powder preparation under an inert atmosphere, semi-solid powder rolling under a suitable temperature change condition, and post-treatment procedures if necessary. Semi-solid powders are rolled and consolidated into a strip when they are still in a semi-solid and highly formable state. While still in the early stage of research, SSPR shows a promise for reducing strip manufacturing costs and saving energy as well as improving quality. The inherent rapid solidification effect, easily controllable process conditions and solid solubility extension may also provide a new choice of process for the development for alloys.

Consequently, semi-solid powder rolling has many different features compared with powder rolling and semi-solid rolling. Based on the results of microstructure evolution, it infers that solidification, deformation and densification occur simultaneously and collaboratively during rolling [12]. They affect the procedure of SSPR and have an important effect on the quality of strip. Each one of them has different significances in the different sections (the whole procedure is divided into four sections as shown in Fig. 1). The objective of this study is to provide an insight into the progresses of solidification, deformation and densification, respectively during SSPR. The mathematical model was established and experiments were carried out. The factor of progress remarkability (*F*) was proposed and calculated and then the quality of strip and the process can be optimized by using *F*.

## 2. Mathematical model and experiments

### 2.1. Experimental

A schematic of the approach and the actual experimental apparatus are shown in Fig. 1. The powders used in this work are the gas atomized 7050 aluminum alloy powders (Al–6.43Zn–2.26Mg–2.02Cu) with a

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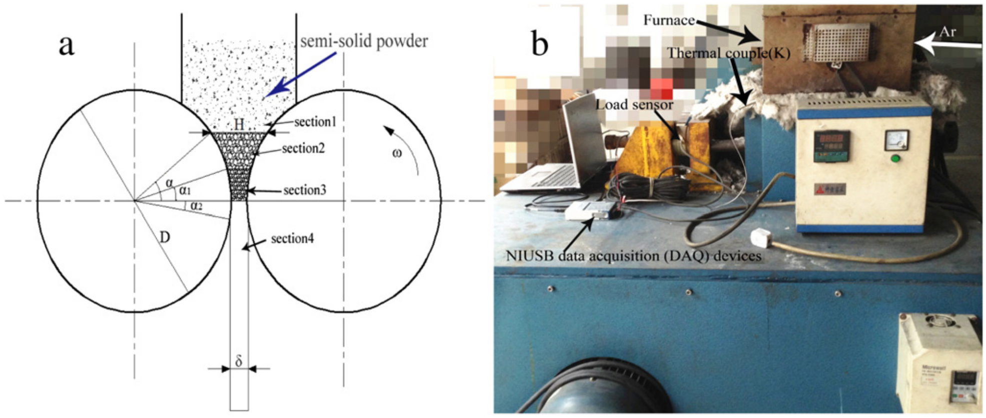


**Fig. 1.** Schematic of semi-solid powder rolling process (a) and the experimental apparatus (b).

nearly spherical morphology and the mean particle diameter of 75 μm. The experiments were carried out on a powder rolling machine with rollers pre-heated to 300 °C. The diameter of roller is 150 mm with a width of 100 mm, rolling gap of 0.1 mm and a rotating speed of 0.4 rad/s. Fig. 2 shows the liquid fraction of 7050 aluminum alloy as a function of temperature. Actually, it is a fit to the data calculated by MATLAB using the Scheil equation. The powders were firstly heated to the range of 625 °C–640 °C at an interval of 5 °C in the furnace (the corresponding liquid fraction ranges from 45% to 65%), and the holding time was 30 min. And then the semi-solid powders were fed into the gap to consolidate dense strips with a width of 100 mm and a thickness of 1.5 mm to 2 mm. The whole procedure from heating to rolling was carried out under an argon atmosphere. In order to measure the temperature change and rolling force during SSPR, the NI USB data acquisition (DAQ) devices (800392c-01) NI-9317 that come from National Instruments were used (the corresponding NI application software are LabVIEW 8.x, LabWindows/CVI 8.x, Measurement Studio 8.x and LabVIEW SignalExpress LE 3.x). The location of load sensor is shown in Fig. 1b. Thermocouples (K) were put into the semi-solid powders and then were rolled out with these powders. In order to measure the density, the rollers stopped abruptly during rolling and a resulting wedge revealing four sections was obtained (Fig. 1a). Afterward, the relative density of each section was tested by using Archimedes' principle. Due to the difficulty of stress measurement for semi-solid powders, dense semi-solid AA7050 alloy was used to test stress–strain. The compression tests, within the scope of semi-solid temperature on 7050 alloy, were carried out by using a Gleeble-3500 material thermo-simulation machine under the strain rate from 0.1 $s^{-1}$ to 10 $s^{-1}$.

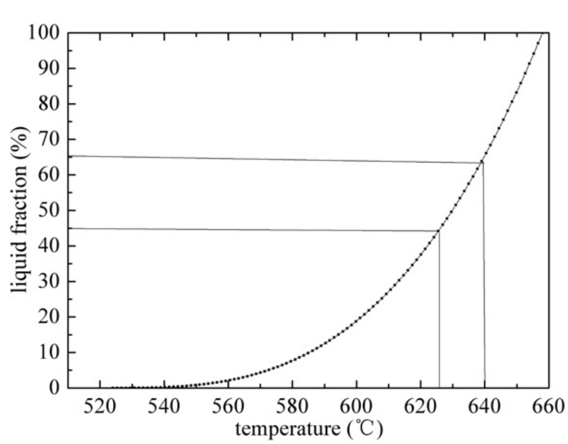


**Fig. 2.** Effect of temperature on liquid fraction of 7050 aluminum alloy powders.

### 2.2. Mathematical formulations

#### 2.2.1. Temperature calculation

The mathematical model was developed by using a finite difference method. It was developed under a set of physical assumptions as listed below.

(1) The rollers are not deformable and rotate at the same speed.
(2) The heat flow and the semi-solid material flow are considered to be two dimensional.
(3) The heat and momentum transfer are neglected in the direction along the width direction of a strip.
(4) The relationship between solidification rate and temperature is that the lower the temperature is, the faster the solidification rate is during solidification.
(5) There is no relative slip between the rollers and the formed strip during rolling.
(6) Thermo-physical parameters of aluminum alloy are only the function of temperature.

The conductive heat transfer between semi-solid powders and rollers results in a rapid solidification and the material/roller heat-transfer coefficient ($h_{\rm int}$) is given by [13]:

$$h_{\rm int} = 169.25 \cdot f_s + 90 \cdot f_l = 169.25 \cdot \left[1 - \left(\frac{T - T_s}{T_l - T_s}\right)^{\frac{1}{1-k_e}}\right] + 90 \cdot \left(\frac{T - T_s}{T_l - T_s}\right)^{\frac{1}{1-k_e}}$$

$$T_s < T < T_l \tag{1a}$$

$$h_{\rm int} = 169.25 + 0.00836T \quad T < T_s \tag{1b}$$

where $f_s$ is the fraction of solid, $f_l$ is the fraction of liquid and $k_e$ is the equilibrium partition coefficient. The cooling rate between semi-solid powders and rollers can be calculated by

$$v_{cooling} = \frac{\partial f(T)}{\partial t}. \tag{2}$$

The inflow conditions (Fig. 3) of the temperature of the semi-solid powders at the inlet are:

$$T = T_0 \quad v_y = 0 \quad v_x = \left(r + \frac{H}{2}\right)\omega$$

where the $v_x$ and $v_y$ are the components of velocity in the $x$ and $y$ directions, respectively and ω is the rotational speed of the rollers.