

Constitutive Modeling for Thixoforming of 9Cr18 Semi-solid Alloy and 3D Forecast Mapping

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Abstract: Thixotropic compression tests were carried out on 9Cr18 semi-solid alloy through Gleeble-1500 thermal simulation machine. According to the experiment analysis, macro separation occurred during thixoforming. The liquid film was extruded outside to the surface and solidified to form eutectic structure. The solid particles were connected with each other and underwent plastic deformation. According to the comparison between Zhou-Guan model and modified Zhou-Guan model, it could be observed that the adding of thixotropic factor played an important role in the regression and the latter one was more credible. The modified Zhou-Guan model could well describe the thixoforming behavior. 3D forecast mapping was built for 9Cr18 semi-solid alloy in thixoforming temperature range. It would provide valuable information for selecting process parameters during thixoforming in the manufacture process.

Key words: thixoforming; constitutive model; liquid fraction; thixotropic factor; 3D forecast

Over the last four decades, semi-solid forming (SSF) has attracted increasing research interest due to its higher performance as compared with conventional casting and forging^[1,2]. Plenty of researchers are focusing on semi-solid forming due to its obvious advantages such as near-net-shape forming, fewer forming steps and smaller resistance, etc.^[3]. As one method of SSF, three steps are required for thixoforming: semi-solid billet preparation, reheating and forming^[4].

The specific microstructure characterization of semi-solid billet that spheroidal solid particles are suspended in the liquid matrix needs to be clarified. A number of researchers have reported on clarifying the behavior of the semi-solid microstructure. Koeune and Ponthot^[5] proposed a one phase thermomechanical model for simulation of semi-solid thixoforming, considering the concept cohesion degree of solid particles. An adjustment micro-macro model was later proposed to consider free solid suspensions^[6]. Qin and Wallach^[7] used phase field to predict the non-dendritic structure. Moumni et al.^[8] discussed the phase transformation by phenomenological modeling. The researches aimed at investiga-

ting the material model. However, the material model should be transformed into constitutive model before being used for numerical simulation. Currently, many of the constitutive models are proposed for hot deformation behavior^[9-11]. Yang et al.^[12] studied constitutive model for 2524 aluminum alloy in creep age forming. Ren et al.^[13] investigated constitutive model for martensitic stainless steel when considering the strain effect. There are few researchers attempting to combine semi-solid property and constitutive model, and the deformation behavior during thixoforming needs to be clarified^[14].

The present study aimed at proposing a constitutive model for thixoforming of semi-solid alloy and forecasting the deformation behavior in thixoforming temperature range. Thixotropic behavior during thixoforming was considered and a modified constitutive model was proposed based on thixotropic behavior.

1 Experimental Procedures

1.1 Materials

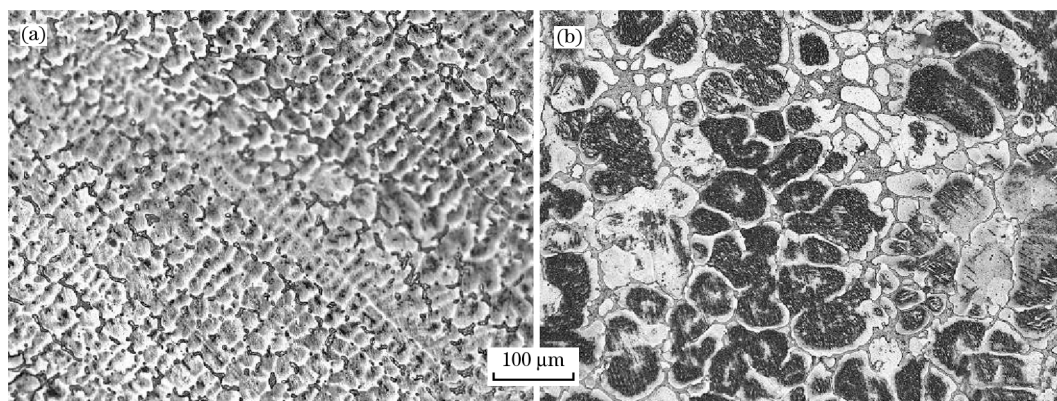
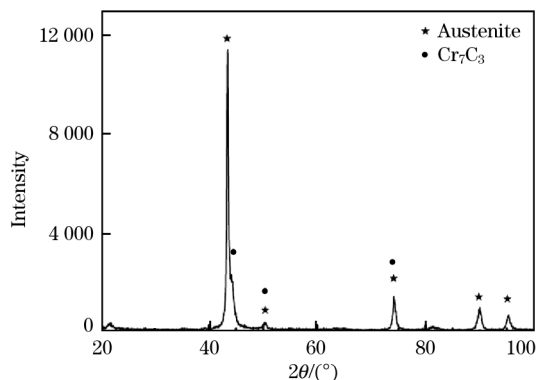
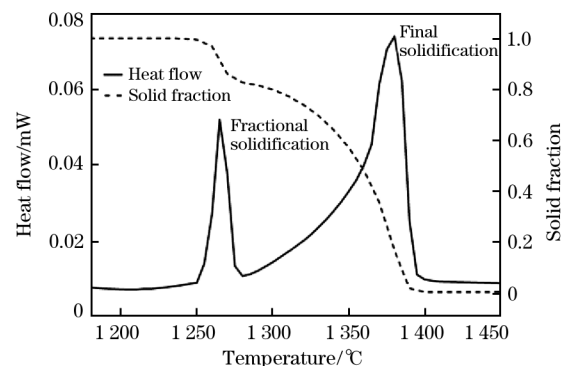
The feedstock material was 9Cr18 stainless steel and the chemical composition is shown in Table 1. The

Table 1 Composition of experimental 9Cr18 stainless steel
mass%

C	Cr	Si	P	S	Al	Ni	Co	Fe
0.97	17.33	0.52	0.02	0.005	0.10	0.16	0.12	Balance

semi-solid billet was prepared by wavelike sloping plate method^[15]. The microstructure of semi-solid billet is different from the dendrite structure of traditional casting specimen (Fig. 1(a)). As shown in Fig. 1(b), two phases coexist in the specimen; the globular solid grains are suspended in the solidified liquid matrix. The average equivalent diameter of the

globular austenite grains is about $(94.4 \pm 10) \mu\text{m}$ and the shape factor of the globular grains is about 0.80. According to X-ray diffraction (XRD) result in Fig. 2, the main phases include austenite and chromium carbide (Cr_7C_3), which is different from the martensite structure of conventional 9Cr18 steel^[16]. Previous research also reported that the alloying elements in the semi-solid range would stabilize the austenite during cooling^[17]. The semi-solid temperature range is determined by using differential scanning calorimetry (DSC) with a heating rate of $10^\circ\text{C}/\text{min}$ and the solid fraction curve is shown in Fig. 3^[18]. The solidus and liquidus temperatures of 9Cr18 steel are ap-

**Fig. 1** Microstructure of casting ingot (a) and semi-solid billet (b) of 9Cr18 steel**Fig. 2** XRD spectra of 9Cr18 semi-solid billet**Fig. 3** DSC results and solid fraction curves of 9Cr18 semi-solid billet

proximately 1263°C and 1384°C , respectively^[18].

1.2 Thixotropic compression tests

Small cylindrical compression samples of 15 mm in height and 8 mm in diameter were fabricated from the semi-solid billet. Thixotropic compression tests were conducted by using Gleeble-1500 thermal simulation machine. In order to carry out experiments in the semi-solid temperature range, two tantalum pieces daubed with lubricant (MoS_2) were placed between the indenters and samples to reduce friction and avoid

welding. The heating process was divided into two stages. The samples were heated to $1200\text{--}1250^\circ\text{C}$ at a speed of $20^\circ\text{C}/\text{s}$, then to 1250°C , 1275°C , and 1300°C at $2^\circ\text{C}/\text{s}$, respectively, and held for 5 s to homogenize the temperature. According to previous study, the holding time was enough to homogenize the temperature of the specimen^[18]. Then, the compression tests were conducted under various strain rates of 0.1, 1.0 and 5.0 s^{-1} with compression rate of 60%. Finally, the samples were quenched in wa-

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