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Effects of liquid fraction on the microstructure and mechanical properties in forge solidifying 12Cr1MoV steel

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ABSTRACT

A method called forging solidifying metal (FSM), developed to establish an energy-efficient process chain for ferrous alloys, was proposed based on the semi-solid forming (SSF) technology. The microstructure of the 12Cr1MoV steel investigated was inhomogeneous when deformed by the FSM process under conditions of 70% and 50% liquid fractions (F_L). A circle-like macrosegregation band, which was enriched in C, Cr, Mo and V, appeared in the forging. What is significantly different from that is, a uniform, dense microstructure characterized by fine grains (30 μm) was obtained when the FSM process was conducted at the F_L of 30%. With decreasing F_L, the mechanical properties of the forgings gradually homogenized.

1. Introduction

Ferrous alloys are widely used in industrial components such as metallurgical rollers (9Cr2MoV), molds (SKD 61), heat pipes (12Cr1MoV), etc. Superior mechanical properties such as high hardness, toughness and strength, are essential performance evaluation criteria for metals. Meng et al. (2014) noted that the conventional ferrous alloy manufacturing route is rather complex. The route generally involves ingot casting, annealing, reheating, and multipass forging or rolling, followed by heat treatment. A long soaking time is required before deformation to reduce segregation. Large strains, induced by multipass hot forging or rolling, are needed for recrystallization to achieve grain refinement (Barani et al., 2007). Microstructural strengthening can also be achieved through heat treatment to obtain a refined microstructure with uniformly distributed precipitates. The conventional route, while being effective for guaranteeing the quality of final products, has a few disadvantages, such as high -cost and long manufacturing cycle time. Several researchers have attempted to find solutions for eliminating primary metallurgical defects such as coarse dendrites, shrinkage porosity, and segregation in heavy ingots. For example, Wei and Lu (2012) reported on microstructural refinement via multiple normalizing processes. Xu et al. (2014) and Qian et al. (2015) investigated the effects of risers (size and shape) on shrinkage and segregation in heavy ingots. Manikandan et al. (2016) reduced the segregation in alloy 718 by using an enhanced cooling method. These examples highlight that previous studies have mainly focused on the conventional route, despite its high -cost and long production circles. Therefore, a more efficient process for producing good-quality ferrous alloys is highly desirable.

The SSF technology was invented after the discovery of the rheological properties of Sn-15Pb alloy by Spencer et al. (1972). A characteristic fine microstructure (solid particles surrounded by a liquid matrix) can be obtained by several methods (Flemings, 1991). Kiuchi and Kopp (2002) demonstrated that the SSF process has several advantages. Compared to conventional forging, the SSF process is highly-effective and consumes lower energy, due to certain material properties in the semi-solid state. Meng et al. systematically studied the experimental parameters of the SSF process, such as the liquid fraction (Meng et al., 2012), predeformation (Meng et al., 2013), and heat treatment (Meng et al., 2014), for SKD 61 steel on a laboratory scale. Their findings suggested that the SSF process can potentially replace the multipass forging process for manufacturing ferrous alloy products.

A number of methods have been proposed for fabricating ferrous alloy billets in the semi-solid state. These billet preparation methods include strain-induced melt activation (SIMA) (Young et al., 1983), the recrystallization and partial melting (RAP) (Kirkwood et al., 1992), electromagnetic stirring (Griffiths and Mccartney, 1996), and the cooling slope process (Adachi et al., 2005). Due to the ultra-high temperature, which leads to the degradation of tools in direct contact with the molten metal and severe oxidation of the billet also occurs (Atkinson and Rassili, 2010). Most of these methods are adopted mainly in the production of low melting alloys, such as aluminum and

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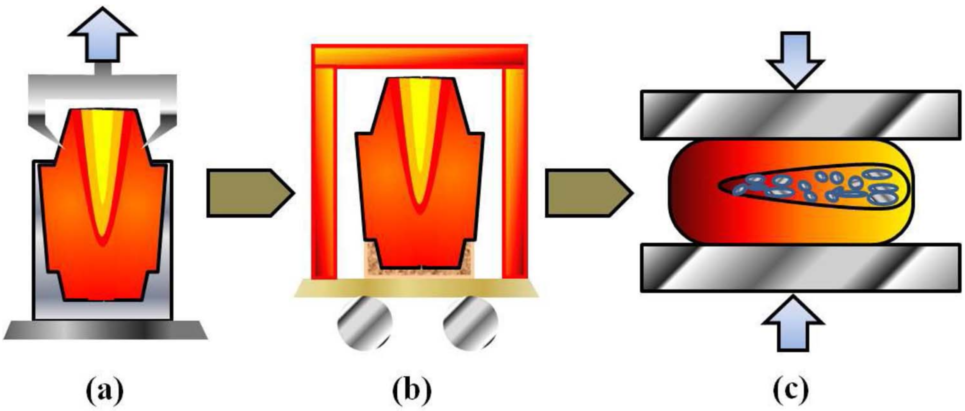

Fig. 1. Schematic diagram of the FSM process developed in this study. The ingot is (a) demolded, (b) transfered, and (c) forged with the mushy core.

magnesium. However, there has only been limited research on the application of the SSF process to ferrous alloys (Kirkwood et al., 2010).

As a more efficient process for manufacturing good-quality ferrous alloys, a route coined as FSM is proposed based on the SSF technology. The FSM process is described as follows: during cooling, the surface of a cast ingot becomes a hard shell, while the core remains in the mushy zone state (Fig. 1a). The ingot, with the mushy core, is demolded and transferred to a press (Fig. 1a and b). The ingot is then forged with the mush core beyond the conventional forging temperature range. The large deformation is used to break down the solidifying coarse dendrites of the ferrous alloy, as shown in Fig. 1c. A few semi-solid deformation tests were designed and carried out. In current study, in order to verify the effectiveness of FSM process, the effects of F_L on the microstructure and mechanical properties of a widely used 12Cr1MoV steel were investigated through a series of pilot-test studies.

2. Experimental procedures

2.1. Material

12Cr1MoV steel is a commonly utilized high temperature material for components such as heat pipes in fired power plants. Inhomogeneous microstructures and porosity are the primary problems during its manufacture. The chemical composition of the material used in this study is shown in Table 1.

2.2. Experimental design and implementation

A series of pilot-test studies were designed. To simulate the industrial practice, a few iron boxes (50-mm thickness) were fabricated. The size of each box was 300 mm × 300 mm × 600 mm. The iron boxes were used as molds, and molten 12Cr1MoV steel was poured from a ladle, as shown in Fig. 2a. The specimen was then allowed to stand in air for a period of time (Fig. 2b) and transferred to a press for deformation. In this study, the pilot specimens with different F_L based on the numerical simulations below were deformed with a 50% reduction along the 300-mm direction, and then air cooled to room temperature (Fig. 2c). An un-deformed specimen, cooled in air until being completely solidified, was defined as being in the as-cast state. Macrostructural inspections, microstructural analyses, and mechanical testing under different conditions, were conducted.

Before the semi-solid experiments were performed, its F_L evolution

Table 1
Chemical composition of the 12Cr1MoV steel used in this study (wt%).

C	Si	Cr	Mn	Mo	V	Fe
0.15	0.25	1.00	0.60	0.30	0.22	Balance

feature during solidification had been firstly calculated using commercial software PROCAST. In the calculations of the temperature and flow fields, some assumptions had to be made in the finite elements method as follows: (1) the free surface rises steadily with the top pouring liquid evenly distributed to simulate the smooth filling process; (2) only the thermal field is simulated and the flow is ignored after filling. The detailed conservation equations including the continuity, Navier-Stokes and heat transfer equations during solidification of steel ingots were described in our previous publications (Wang et al., 2012; Qian et al., 2015).

The total finite element mesh of the mold and ingot consisted 61,292 nodes and 313,577 tetrahedral elements (as shown in Supplementary Fig. 1). The main thermo-physical parameters used in the current simulations were listed in Table 2. The liquidus and solidus temperatures of 12CrMo1V steel were 1518 and 1480 °C respectively. The initial temperatures of the pouring melt and the iron mold were 1550 and 80 °C, respectively. A natural air cooling convection was set over the mold. The interfacial heat transfer coefficient between metal and mold was set as 1000 W/m^2/K. Fig. 3 illustrates the distribution features of retained liquid fractions of 70%, 50% and 30% respectively, and their corresponding solidification time was approximately 10, 15 and 20 min respectively. And hence, to elucidate the differences of microstructure and mechanical properties as the initial F_L varies, three experimental ingots with the above solidification time had been deformed, respectively.

2.3. Microstructural characterization and mechanical testing

After the FSM process, the fogings were cut along the stretching direction. The cutting planes were then polished, and etched with a 20% nitric acid/H_2O solution, to observe the macrostructure (Fig. 2d). For microstructural analyses, metallographic samples were selected from characteristic regions of the forgings. After grinding and polishing, these samples were etched in a 5% nitric acid/alcohol solution. The sample microstructures were observed using a Zeiss MC63 optical microscope (as-etched condition). The segregation was studied through a mapping analysis (as-polished condition), using an electron probe micro-analyzer (EPMA-1610 made by SHIMADZU company). The area fraction of pearlite (F_p) was statistically calculated using Image J software, with 20 images being selected for each sample. Specimen chemical analyses were conducted by optical emission spectrometry (Optima 8300 made by PerkinElmer company). The specimen fracture surfaces were observed by an FEI INSPECT F50 scanning-electron microscope (SEM). Carbides were identified by an energy dispersive X-ray spectrometer (EDS) analysis in the SEM.

Room-temperature tensile experiments were conducted using a Shimadzu AG-X 250 kN tensile tester at crosshead speed of 1 mm/s. Standard samples with a diameter of 5 mm were adopted. To ensure accuracy, at least three samples were tested for each condition. The