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Study of the processing map and hot deformation behavior of a Cu-bearing 317LN austenitic stainless steel

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ABSTRACT

The hot-working behavior of a Cu-bearing 317LN austenitic stainless steel (317LN–Cu) was investigated in the 950–1150 °C temperature and 0.01–10 s^{-1} strain rate range, respectively. The effects of different deformation parameters and optimum hot-working window were respectively characterized through analyzing flow stress curves, constitutive equations, processing maps and microstructures. The critical strain for dynamic recrystallization (DRX) was determined by the inflection point on θ-σ and $-\partial\theta/\partial\sigma$-$\sigma$ curves. The peak stress was found to increase with decrease in temperature and increase in strain rate. Typical signs of DRX over a wide range of temperatures and strain rates were observed on the flow stress curves. The power dissipation maps in the strain range of 0.1–0.4 were basically similar, indicating the insignificant effect of strain on the power dissipation maps of 317LN–Cu. However, the instability maps showed strong strain sensitivity with increasing strain, which was attributed to the flow localization. The optimum hot-working window for 317LN–Cu was obtained in the temperature range 1100–1120 °C and strain rate range 0.01–0.018 s^{-1}, with a peak efficiency of 38%. Microstructural analysis revealed fine and homogenized recrystallized grains in this domain.

1. Introduction

As a kind of surgical implant material, 317LN austenitic stainless steel has been widely used in clinical applications because of its excellent combination of mechanical properties, pitting and crevice corrosion resistance ability [1–3]. However, the surgical implants and medical devices are prone to induce bacterial adhesion, which can often cause post-surgical implant and/or device related bacterial infections leading to high risk of implant failures hence posing serious health risks to patients and massive financial burden to healthcare systems. Researchers have been trying to solve the problem of bacterial infections from the materials point of view and have proposed an effective way to develop a new type of antibacterial functional stainless steel that can indigenously provide sustained antibacterial agents to kill pathogenic bacteria to deter or mitigate risk of bacterial infections. Owing to inherent antibacterial ability of Cu ions, a novel class of antibacterial stainless steels could be designed by adding proper amount of Cu into conventional stainless steels during the metallurgical process providing them strong antibacterial ability through the precipitation of a certain amount of rich-Cu phase in the steel matrix, which can continuously release trace amount of Cu ions in the biological environment [4,5]. Based on this design principle, a Cu-bearing 317LN antibacterial stainless steel (317LN–Cu) was successfully developed in recent years [5,6]. The reported experimental results have proved the strong antibacterial performance of Cu-bearing 317L stainless steel against both *Escherichia coli* and *Staphylococcus aureus* bacteria, and owing to the release of trace amounts of Cu ions from the steel surface, bacterial bio-film formation on the surface was effectively inhibited [4,7]. However, from the material design point of view, an excess Cu addition may lead to copper brittleness during the hot working process such as forging and hot rolling [8,9]. Meanwhile, only a few studies have reported on the favorable parameters for the hot working process of higher level Cu content stainless steel. Hence, the study of hot deformation behavior of 317LN–Cu Cu-bearing stainless steel is highly needed for the optimization of hot-working process and microstructure control.

The optimum hot-working window is one of the important parameters that denote the plastic deformation capabilities of stainless steel and it can be predicted by many methods. The constitutive model is usually used as a mathematical representation for the description of correlation between flow stresses and working parameters. In addition, the process map (PM), which is based on the dynamic materials model (DMM) [10], is a powerful tool for the evaluation of deformation mechanism and optimization of processing parameters. Moreover, the PM can precisely identify the instability and the workability regions in combination with the microstructure analysis.

Recently, the deformation behaviors in combination with the constitutive model and PM of high alloyed austenitic stainless steels have attracted great attention. Several researches have dealt with the

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relationship between PM and hot-working parameters for stainless steel especially austenitic grades such as 304, 316 and 317 stainless steel, and some others have validated the deformation mechanisms such as DRX, dynamic recovery (DRV), static recrystallization (SRX) and static recovery (SRV) under different deformation conditions for austenitic steel [11–15]. Besides, the effects of initial grain size and the alloying additions such as Cr, N, Ni and Mo on the recrystallization characteristic during hot deformation were also investigated through the analysis of the PM and constitutive equations. Hitherto, the PM and constitutive equations have been widely used to characterize the deformation behavior for different kinds of alloys [16–18]. However, the hot deformation behavior of stainless steel with high copper content addition has not been reported in the literature. Therefore, a hot deformation study combined with the PM analysis on the newly developed 317LN–Cu stainless steel is essentially important.

In this study, the hot deformation characteristics of 317LN–Cu stainless steel have been investigated. The effects of hot working parameters such as strain, strain rate and temperature on the mechanical properties and microstructure were also analyzed. Flow stress–strain curves, work hardening curves, constitutive equations and microstructure analysis were adopted to examine the hot deformation behaviors of 317LN–Cu. In addition, the processing maps based on the DMM model were derived at different true strains in order to predict the hot working ability of 317LN–Cu. It is believed that the results of this study could provide solid technological basis for the hot working procedure of 317LN-Cu stainless steel.

2. Experimental procedure

An experimental 317LN–Cu stainless steel was melted in a 25 kg vacuum induction melting furnace. The chemical composition (wt.%) of the 317LN-Cu is as follows: 0.023C, 0.06Si, 0.02Mn, 0.009P, 0.007S, 18.9Cr, 14.46Ni, 3.52Mo, 0.15N, 4.28Cu, and Fe in balance. The ingot was forged and then machined into hot compression specimens of Φ 8 × 12 mm.

To investigate the effects of deformation temperature and flow stress, the uni-axial compression tests were performed on a Gleeble-3800 tester at the temperatures range of 950–1150 °C with interval of 50 °C and strain rate range of 0.01–10 s^{-1} with interval of an order of magnitude, respectively. Graphite foil and MoS_2 paste were used between the specimens and the platen to minimize the friction during deformation. A chromel–alumel type thermocouple was embedded in the middle of the specimens to monitor the temperature during hot compression. The experimental data of flow stress curve as a function of strain at each deformation temperature and strain rate was automatically obtained by computer software. Deformation conditions such as temperature and displacement velocity were also automatically recorded by computer system. To keep uniform microstructure, each specimen was heated at 1200 °C for 5 min and then cooled down to the desired deformation temperature at a rate of 10 °C/s. All the specimens were deformed with the highest reduction of 40% and quenched immediately in water to reserve the deformation microstructure. The initial microstructure of the experimental steel both in the cross-section (TD) and vertical direction (ND) are shown in Fig. 1(a) and (b), which reveals that the microstructure is composed of complete austenite features and some annealing twins. For comparison, the initial optical microstructure after soaking at 1200 °C for 5 min is shown in Fig. 1(c) and (d), showing the coarse austenite grains.

The hot deformed specimens were cut along the longitudinal direction using an electric-spark cutting machine. The surface of the specimens was ground and polished. Thereafter, electrolytic etching in a solution of 30% nitric acid was employed to reveal the austenite microstructure. The microstructures in the maximum deformation zone were examined by an optical microscope (Axiovert 200 MAT) and transmission electron microscope (FEI Tecnai G^2 Spirit 120 kV), respectively.

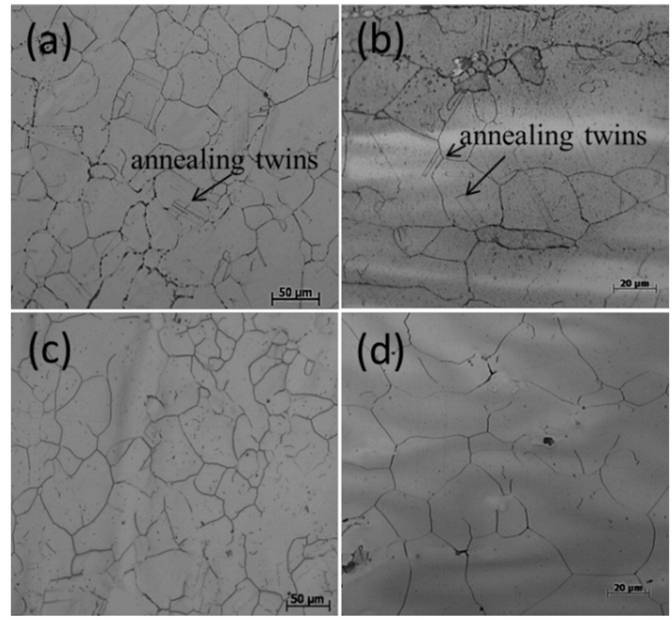

Fig. 1. Microstructure of initial state: (a) TD; (b) ND and solution state: (a) TD; (b) ND of the experimental 317LN–Cu stainless steel.

3. Results and discussions

3.1. Flow behavior

The flow curves of experimental 317LN–Cu stainless steel at temperature range 950–1150 °C and strain rates of 0.01–10 s^{-1} are shown in Fig. 2. As expected, the flow stress is sensitively dependent on both the deformation temperature and strain rate. Meanwhile, the flow stress increased with increase of the strain rate and decreased with increase of the temperature. For instance, the flow stress decreases rapidly with the increase of deformation temperature at the same strain rate, as shown in Fig. 2(f), and increases with the decrease of strain rate at the same deformation temperature, as shown in Fig. 2(a). Furthermore, all the flow stress curves increased significantly at the initial stage of hot deformation, attributed to the work hardening, and then followed by a relatively steady state, but only some of the curves showed a distinct peak such as at 1150 °C and 0.1 s^{-1}, which indicates the occurrence of DRX.

It is noteworthy that the curves at the higher temperature range of 1050–1150 °C and higher strain rates of 10 s^{-1} even exhibited the feature of multi-peaks. Generally, this phenomenon is regarded as the interactive mode of hardening and softening, where the softening mode may include DRX and DRV. With the increase in temperature and decrease in strain rate (decrease of the *Z* parameter), the peak became broad and even disappeared, as shown Fig. 2(f), which exhibited a “flat-top” type flow curve without a clear peak. This “flat-top” type curve often reflects the occurrence of DRV. However, some studies proved that the DRX simultaneously existed with DRV in the “flat-top” type curves [19,20]. Thus, combining the microstructure observation in the later section and the work hardening curves depicted in Fig. 3, the softening mechanism during hot deformation could be attributed to a synergistic effect of DRV and DRX softening mechanisms.

It is worth mentioning that at low strain rates (<1 s^{-1}), the flow stress curves also showed a “flat-top” type as the temperature increased. In other words, a flat-top curve could be easily obtained when the steel was deformed at higher temperature and lower strain rate. This is easy to understand because the mobilities of grain boundary and dislocation could be accelerated or improved at a higher temperature, while a longer time, i.e., 0.1 s^{-1}, at a lower strain rate, could be