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Influence of processing parameters on hot workability and microstructural evolution in a carbon–manganese–silicon steel

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ABSTRACT

In this work, the influence of processing variables such as strain, strain rate, temperature and cooling medium, on workability, microstructural evolution and mechanical properties of a carbon–manganese–silicon (C–Mn–Si) steel have been studied. Hot deformation of the C–Mn–Si steel has been carried out using compression testing over a domain 1223–1473 K and 0.001–10 s^{-1} where the steel is in austenitic phase field. The effect of cooling medium on the microstructural evolution has been studied by carrying out post-deformation cooling of the specimens in air and water media. Influence of the cooling medium on properties of the steel has been evaluated by comparing the hardness and Charpy impact test results. Based on the flow behavior analysis and microstructural examinations the optimum domain for the hot deformation of C–Mn–Si steel is found to be in the ranges of 1273–1350 K and 3–10 s^{-1}. Flow instability in C–Mn–Si steel is manifested in the form of deformation bands in the microstructure. The signature of instability is not influenced by the phase transformation. The hardness of the material is dependent on the temperature of deformation and influenced by cooling medium. However, it does not show any correlation with deformation strain rate.

1. Introduction

Over the past few decades, C–Mn–Si steels have generated considerable interest in scientific arena as these materials find wide application in thermal power sectors, nuclear industries [1], and automobile industry [2,3]. In these industries, the steel is used in various forms in functional requirements. Depending on the usage, various hot working routes such as rolling, forging and extrusion are used to manufacture different industrial components. It is needless to say that thick-plates and forgings used in these industries require being free from microstructural defects, not only to ensure the optimal mechanical properties of the component, but also to sustain those properties for the entire design life of the component. Presence of any flaws in the microstructure minimizes the load bearing capacity of the plates or forgings and also acts as an initiation point of cracks. These in turn enhance the chances of failure of the components before the design life. To avoid these consequences, it is necessary to take advance measures to manufacture defect-free plates and forgings of C–Mn–Si steel, which require a proper design of the manufacturing process. In a broader perspective, efficient design of any manufacturing process that involves metal forming operations is primarily based on the analysis of flow behavior of the material [4,5]. For a material, flow behavior is an inherent characteristic, which along with microstructure, defines its workability. Therefore, during design of the manufacturing process, response of the material and its microstructural condition must be taken into account. In usual practice, after hot deformation, the products are cooled to room temperature in different cooling media, such as air [6], molten salt [7], water [8] and oil, etc. The cooling medium has a pronounced effect on the microstructural evolution as it changes the rate of heat transfer from the product [7]. If the material under consideration is a carbon steel, significant changes in both microstructure and properties can be expected as this material undergoes phase transformation during heating to elevated temperatures. Likewise, during cooling to room temperature, substantial changes in the microstructure are possible depending on the processing temperature [9] and cooling rate [7]. Since majority of the manufacturing processes consist of various stages, such as heating to hot working domain, deformation and subsequent cooling [10], it is a practical necessity to study the combined effect of deformation and cooling media on workability. A cursory inspection of the available literatures indicates that abundant results are available on similar materials. However, these results are either on phase transformation without deformation or on study of flow behavior without considering the effect of cooling media. From the available studies on deformation behavior, majority are concentrated in cold [11,12] or warm [7,13–17] working regions. Amongst the studies available on the optimization of processing parameters of similar grade steels a notable recent studies on 29MnSiCrAlNiMo steel [18] indicates optimum domain for hot working

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Table 1
Chemical Composition of C–Mn–Si steel.

Element	C	Mn	Si	P	S	Cr	Ni	Mo	Fe
Wt.%	0.22	0.8–1.5	0.4	0.035	0.012	0.2	0.3	0.1	Bal

occurs in the temperature range 1203–1253 K and strain rate range 0.001–0.014 s^{-1}. Another study by Liu et al. [19] on 22 SiMn2Tib shows an optimum domain at 1113-1213 K and 0.001–1 s^{-1}. A study by El et al. [20] on 0.34C–1.52Mn–0.72Si suggests a domain centered at 1423 K and 10 s^{-1} and the material does not show any instability. Similarly, another study by Lin et al. [4] on 0.45C–0.63Mn–0.28Si shows an optimum processing domain at 1323–1423 K and strain rate range of 0.01–3 s^{-1}. All these results clearly show a wide variation in optimum strain rate as well as temperature domain even after using similar optimization technique. This suggests that the flow behavior is sensitive to chemical composition. A smaller variation in the alloying element significantly affects the working domain as it influences flow behavior. The evidence of variation in flow behavior and microstructural evolution in carbon steel due to the variation in carbon [15], manganese [21] and silicon [22] are well documented. The above review of the literatures indicates that the necessity of the study on the high temperature workability of the C–Mn–Si steel persists. To fill up the gaps in literature, the present study has been carried out.

The objectives of the present work include characterization of the workability of C–Mn–Si steel over a wide range of strain rate and temperature and studying the effect of cooling medium on microstructural development after deformation. For this purpose, isothermal hot compression tests were carried out in the temperature range 1223–1473 K and strain rate range of 0.001–10 s^{-1} on two sets of specimens. While one set of specimens was water-quenched after deformation, the other set was air-cooled. Using this experimental data, processing map based on Dynamic Materials Model (DMM) has been developed. The processing map has also been validated using the results obtained from microstructural investigations of both air-cooled and water-quenched specimens. The effect of cooling medium has been analyzed by comparing the toughness and hardness of the air-cooled specimens with those of water-quenched specimens.

2. Experimental details

The chemical composition of the C–Mn–Si steel used in the present study is given in Table 1, and its microstructure in the as-received condition is given in Fig. 1. Specimens of 10 mm diameter and 15 mm height were machined from this steel. Concentric grooves of 0.5 mm depth were made on the top and bottom faces of the specimens to facilitate the retention of lubricant during testing. The edges of the top and bottom faces of the specimen were chamfered to avoid fold-over during the initial stages of compression. A small hole of 0.8 mm diameter and 5 mm depth was drilled at mid-height of the specimen to insert thermocouples. These thermocouples were used to record the actual temperature of the specimen as well as adiabatic temperature rise, if any, during testing.

Hot compression tests at constant true strain rates were carried out in temperature range of 1223–1473 K at interval of 50 K using a computer-controlled servo-hydraulic testing machine of 100 kN capacity as per ASTM standard E209 [23]. Before keeping the specimens between the platens, they were coated with borosilicate glass paste to prevent the surface from oxidation at elevated temperatures. Prior to deformation, the specimens were heated to the desired temperature for deformation in a resistance-heating split-furnace equipped with the machine. Each specimen was soaked at the test temperature for 5 min to ensure uniform spatial temperature distribution throughout the specimen. At the chosen temperature range, specimens were deformed with constant true strain rates (ε) of 0.001, 0.01, 0.1, 1 and 10 s^{-1}, up to a nominal strain of 50%. To study the effect of cooling rate on microstructural development, two sets of specimens were tested under similar conditions, with one set of the specimens being water-quenched and the other set air-cooled after the deformation.

Load deformation data obtained from these experiments were converted to true stress–true strain data using standard equations after removal of the machine compliances. The elastic region was subtracted from the true stress–strain curve to get true stress-true plastic strain data [24]. The flow stress data obtained at different processing conditions were corrected for adiabatic temperature rise, if any, by linear interpolation between $\ln\sigma$ and $1/T$, where σ is the flow stress and T is the absolute test temperature.

The hot deformed specimens were bisected along the longitudinal direction using a precision cut-off machine. One of the bisected specimens was diamond polished using standard procedures and subsequently chemically etched in 2% nitric acid and ethanol solution. The microstructures of the etched specimens were examined optically in the maximum deformation zone of the samples.

To evaluate the combined effect of deformation and cooling rate on mechanical properties, hardness values of the tested specimens were measured using a Vickers hardness testing machine at 10 kgf load with dwell time of 15 s. For measuring hardness value, at each condition two specimens were used and 15 data points were collected from each specimen. To evaluate the effect of cooling rate on fracture mode and fracture toughness, Charpy V-notch impact tests were carried out on full-size ($10 \times 10 \times 60$ mm^3) specimens as per ASTM E23 [25]. At each condition, three specimens were used for the Charpy impact test.

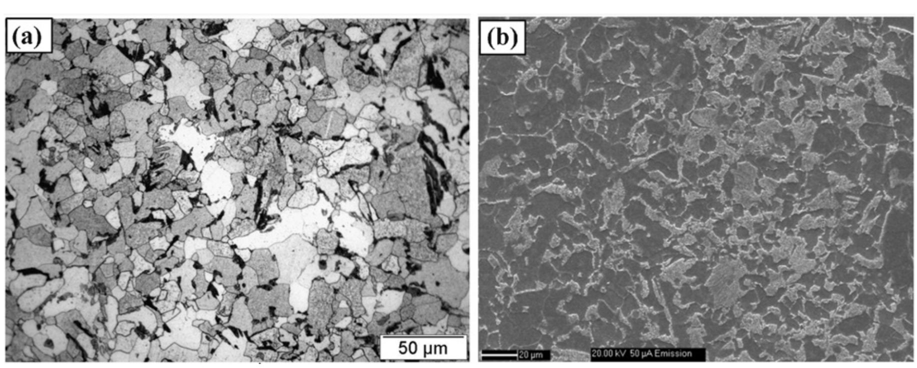

Fig. 1. As-received microstructure of C–Mn–Si steel. (a) Optical micrograph (b) SEM image.