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Development of ultrafine grains in C–Mn steel plates through hot-rolling and air-cooling

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ABSTRACT

Ultrafine grained steel (grain size 2–3 μm) that has a numerous futuristic applications in automobile and engineering industry has been developed in laboratory scale with plain C–Mn and C–Mn–Nb, C–Mn–V compositions. Three heats (25 kg each) of different chemistries were made in a laboratory induction furnace and hot-rolled into 20 mm thick plates initially in a 2 high/4 high experimental rolling mill. Dilatometry was carried out to determine the transformation temperatures. Subsequently, hot-compression tests were performed in a thermo-mechanical simulator with designed parameters and optimum processing window for obtaining fine and uniform through-thickness ferrite grains. The experimental steels were further hot-rolled to 4 mm plates in 3 passes and then air-cooled. Optical microscopy, SEM and TEM studies confirmed the presence of uniform through-thickness ultrafine ferrite grains in the range of 2.5–3.5 μm in the experimental steels. Both tensile and Charpy impact toughness properties were found to be good in these steels. Yield strength of 422 MPa, 472 MPa and 594 MPa with 22–23% elongation could be achieved in plain C–Mn, C–Mn–Nb and C–Mn–V steels respectively. Charpy V-notch energies of these steels were 44 J, 68 J and 44 J at −20 °C respectively. Uniform through-thickness ultrafine grains resulted in the substantial improvement of strength and toughness of the experimental steels.

1. Introduction

Steels with ultrafine grains are known to have better strength, toughness and weldability. Over past two decades, there has been a lot of research works worldwide to achieve more and more fine grains in microalloyed as well as plain C–Mn steels [1–35]. The main reasons behind such efforts are to produce high strength steels with less alloying elements, avoid extra processing steps like annealing, quenching, tempering, etc. and to enhance weldability by lowering carbon equivalent [11]. The fineness achieved by thermo-mechanical controlled processing in microalloyed steels is limited to 4–5 μm. For plain C–Mn steels, however thermo-mechanical controlled processing is not very effective, because in these steels grain coarsening is unavoidable in the austenite recrystallization and non-recrystallization zones. However, the technique of deformation induced ferrite transformation (DIFT) is very effective for plain C–Mn steels to achieve grain sizes up to 2–3 μm [1].

The alternative names given to this technique by other researchers are Dynamic Transformation (DT), Strain Induced Dynamic Transformation (SIDT), etc. [2]. In these techniques, transformation occurs dynamically during deformation contrary to the earlier approach where grain refinement used to occur statically, i.e., after deformation. Here, essentially heavily deformed austenite grains are transformed into fine ferrite grains. Therefore, strain and strain rates are important parameters in these techniques. Similarly, the prior austenite grain sizes, deformation temperatures, and cooling rates are also important parameters which are to be regulated properly to achieve ultrafine grained steels [1,2,9,12,16,35].

From literature, it could be gathered that there are a few techniques by which ultrafine grains can be produced industrially in plain carbon steels up to the level of 3–5 μm in flat as well as long products [1]. However, ultrafine grains are achieved in these steels to a limited extent of thickness. Variation in the microstructure as well as grain sizes is observed in these steels in through-thickness direction. The steel structure at the center is found to be different and the grain size is coarser compared to the surface [3–5,16–18]. This sort of structural inhomogeneity leads to a wide scatter in mechanical properties and the benefits of ultrafine grains produced at the surface layers get restricted. Therefore, challenge lied in getting uniform structure and

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Table 1
Chemical composition of the experimental steels (wt%).

Steel	C	Si	Mn	S	P	Nb	V	Al
1	0.27	0.40	1.22	0.010	0.006	–	–	0.048
2	0.29	0.37	1.19	0.013	0.008	0.032	–	0.023
3	0.29	0.40	1.24	0.010	0.006	–	0.21	0.039

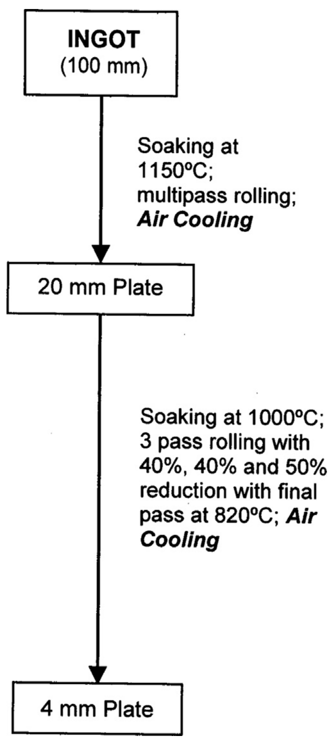

Fig. 1. The schematic diagram showing the hot rolling schedule of experimental steels.

through-thickness grain size to the desired level in the experimental steel. The present work aims toward the development of a process by which, a uniform through-thickness grain size in the order of 2–3 μm can be achieved in hot-rolled steel plate up to 4 mm thickness.

2. Experimental methods

Three laboratory heats of different chemistries (with plain C–Mn, C–Mn–Nb and C–Mn–V compositions) were made in 100 kg vacuum induction furnace and cast into 100 mm diameter cylindrical ingots. The chemical analyses of the steels are shown in Table 1. The defective portion of the ingots comprising about 10% of the height from bottom and 25% from top were discarded. The remaining portion of the ingots of both the steels were soaked at 1150 °C for 3 h and rolled in a HILLE, UK make 'HILLE-100' model 2 high/4 high experimental rolling mill into 20 mm thick plates. Samples were prepared from the as-rolled plates for dilatometry and hot-compression studies. After determining the optimum processing window for obtaining fine ferrite grains, the plates were further rolled into 4 mm plate in 3 passes with finish rolling temperature 820 °C and cooled in air. The schematic diagram showing the rolling schedule is depicted in Fig. 1.

Dilatometry studies for all the steels were carried out using a DSI, USA make 'Gleeble 3500C' model dynamic thermomechanical simulator. Specimens were electrically heated, and subsequently cooled at various rates ranging from 1 to 50 °C s^{-1}. The specimens used in the study were 6 mm in diameter and 85 mm in length. The experiments were conducted at 4 cooling rates, namely, 1, 10, 20 and 50 °C s^{-1} to obtain the transformation start and finish temperatures and consequently, to assess the nature of phase transformation occurring at various cooling rates. The transformation temperatures calculated from the dilation plots are provided in Table 2. The schematic diagram showing hot-compression schedule is exhibited in Fig. 2.

Hot-compression studies were carried out in a 'Gleeble 3500C' model dynamic thermo-mechanical simulator with designed parameters (strain: 0.5, strain rate: 5 s^{-1} and finish rolling temperature

Table 2
Transformation temperatures calculated from the dilation plots.

Steel	Cooling rate (°C/s)	Ar_3 (°C)	Ar_1 (°C)	B_s (°C)	B_f (°C)	M_s (°C)	M_f (°C)
1	1	757	680	648	566	–	–
1	10	–	–	521	407		
1	20	–	–	–	–	383	367
1	50	–	–	–	–	431	408
2	1	784	640	619	577	–	–
2	10	–	–	655	494	–	–
2	20	–	–	–	–	352	291
2	50	–	–	–	–	348	332
3	1	–	–	677	499	–	–
3	10	–	–	531	412	362	320
3	20	–	–	–	–	369	274
3	50	–	–	–	–	393	298

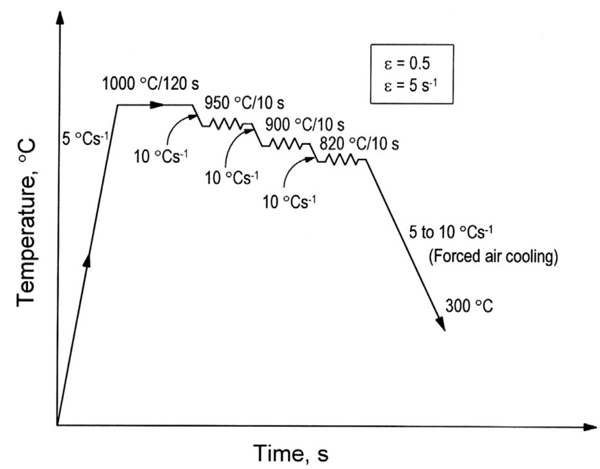

Fig. 2. The schematic diagram showing the hot-compression schedule of experimental steels in Gleeble thermo-mechanical simulator.

Table 3
Grain sizes of the hot-rolled steels.

Steel	Condition	Location	Grain size (μm)			
			Min.	Max.	Mean	Avg.
1	As rolled and air cooled	Surface	0.71	12.78	3.22	3.46
		Quarter	0.71	15.39	3.48	
		Center	0.71	12.09	3.70	
2	-Do-	Surface	0.71	12.26	2.94	2.92
		Quarter	0.71	10.25	3.06	
		Center	0.71	11.80	3.07	
3	-Do-	Surface	0.71	11.16	2.50	2.84
		Quarter	0.71	9.89	2.91	
		Center	0.71	10.87	3.11	