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Materials

Effects of C and Mn elements on deformation-enhanced ferrite transformation in low carbon (Mn) steels

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Abstract: Effects of C and Mn contents on the deformation-enhanced ferrite transformation (DEFT) in low carbon (Mn) steels have been investigated by hot compression. The microstructures of 2-4μm ultra-fine equiaxed ferrite grains with minors distributed homogeneously can be obtained by DEFT in all the tested steels. The more pronounced refinement is achieved as the C or Mn content increasing because of the higher-density nucleating sites and lower growth rate. The effectiveness of C on the level of refinement is more obvious than that of Mn.

Key words: deformation-enhanced transformation; ferrite grain refinement; low carbon steel; manganese steel

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1 Introduction

Grain refinement is an effective way of increasing the strength and ductility of metallic materials simultaneously. Despite a tremendous expenditure of effort, the refinement of ferrite in low carbon steels without the use of micro-alloying elements remains a difficult scientific and technological task. Conventional thermo-mechanical controlled processes (TMCP) are not available in this case. Differing from the 'deformation induced transformation' [1-5] mechanism, a novel process has been proposed [6-10], based instead on a 'deformation-enhanced ferrite transformation (DEFT)', referring to the transformation of austenite to ferrite under conditions of both undercooling and straining. Both the driving forces of the transformation and the nucleation rate will be significantly increased under such a condition. Based on a systematic investigation in low carbon steels our work has confirmed that through the use of such a novel process, a 2-3 *μm* ultra-fine grain size of ferrite can be achieved by a single rolling process [6-10], and thereby, the strength of the material dramatically increased.

In this paper, the effects of C and Mn on the production and nature of ultra-fine ferrite grains in steels of plain low carbon grades, and whether the chemical composition of the steels has any impact on the transformation kinetics and grain size formed were investigated.

2 Experimental

The chemical composition, together with critical points without strain (such as A_3 and A_{r3} based on dilatation experiments) of four grades low carbon (Mn) steels used, is listed in **table 1.** Steel S1, S2 and S3 were used to study the effect of Mn, and steel S1 and S4 to study the effect of C. Their ingots were produced by vacuum induction melting and hot-forged, beginning at 1100°C and ending at 850°C, to round bars in a diameter of 11 mm. Cylindrical hot compression samples, 6 mm in gauge diameter and 15 mm in gauge length, were machined out of the raw bars. The single pass hot deformation process of DEFT, between A_3 and A_{r3}, was conducted on a Gleeble 1500 thermal simulation machine. The details of the process schedule, including the parameters such as the austenitizing temperature (T_A, the austenite grain size is 35-45 m in all steels) and the cooling rate (V_c), are illustrated in **figure 1** and table 1, respectively. According to A_{r3} in table 1, the transformation from austenite to ferrite before deformation at 760°C did not occur in all steels. All the samples were sectioned parallel to the deformation axis and prepared by polishing and etching in 3vol%-4vol% nital solution for optical microscope

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and scanning electron microscope (SEM).

Table 1 Austenitizing temperature (T_A), cooling rate (V_c), critical points without strain A_3, A_{r3} and chemical composition of the steels wt%

Steel	T_A /°C	V_c /°C	A_3 /°C	A_{r3} /°C	C	Mn	Si	P	S	Al
S1	930	30	850	750	0.060	0.48	0.15	0.012	0.0060	0.012
S2	950	30	835	740	0.069	0.84	0.16	0.0094	0.0072	<0.01
S3	920	15	805	700	0.064	1.29	0.18	0.013	0.0059	0.011
S4	910	10	810	730	0.160	0.55	0.17	0.0093	0.0068	<0.01

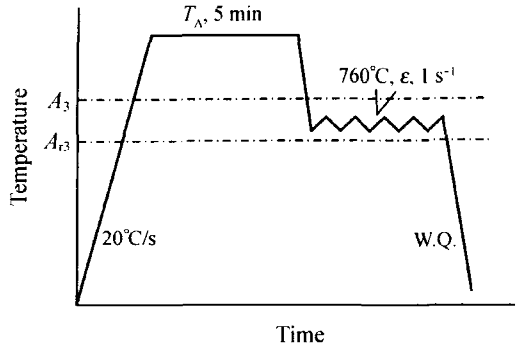

Figure 1 Schematic of DEFT process.

3 Results and discussion

3.1 Deformation-enhanced ferrite transformation (DEFT)

During the isothermal treatment of non-deformed undercooled austenite, ferrite nuclei mainly formed at grain boundaries at the initial stage of transformation and then grew into austenite intragranular or merge with each other till the transformation finished. So the ferrite grain number per-volume (N_V) decreased during the treatment at 760°C (shown as the solid marked curves in **figures** 2(a) and (b)), and 15-30 μm ferrite grains were achieved.

When deformation was exerted on the undercooled austenite, ferrite nucleated rapidly at austenite grain boundaries till the nucleation sites at grain boundaries were saturated. With increasing strain, stress concentrated in the austenite intragranular areas in front of the inter-phase between ferrite and austenite, which leaded to high-density structural defects. Additional sites for further nucleation in those places were produced. Ferrite nucleated repeatedly and rapidly during deformation. A solid chain of ferrite grains (stringed by the black curves in **figure 3)** appeared along the inter-phase repeatedly during the deformation, in the form of which the transformation was developing. Comparing with the isothermal treatment and TMCP [11], the transformation in the DEFT process was accelerated significantly and accomplished within 1.11s (figure 2(c)). The required time and space for ferrite further growth were restricted dramatically. The N_V, increased continuously (shown as the hollow marked curves in figure 2(a)) during DEFT. The microstructures of all the steels, obtained by DEFT, consisted of 2-4 μm ultra-fine equiaxed ferrite grains with minors distributed homogeneously **(figure 4).**

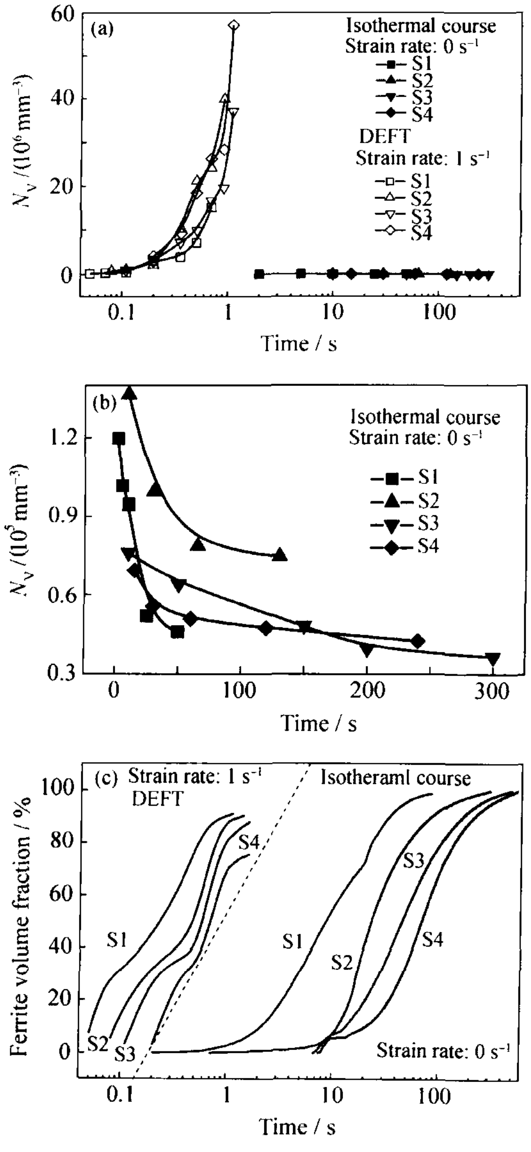

Figure 2 Effects of deformation on the ferrite grain number per-volume (N_V) (a, b) and transformation kinetics (c) at 760°C.

Khlestov's work [11] showed that the acceleration of nucleation caused by TMCP was most effective at the initial stage of transformation and diminished rapidly as the transformation was developing. It is because of the growth of ferrite that 10 μm is the limit of ferrite grain size by TMCP in low carbon steels. While in DEFT process, the development of transformation is a course of nucleating dominated and the further growth of ferrite is restricted dramatically by the ferrite formed subsequently. Based on the nucleation repeatedly and rapidly, the more pronounced refinement by DEFT is achieved than by TMCP.

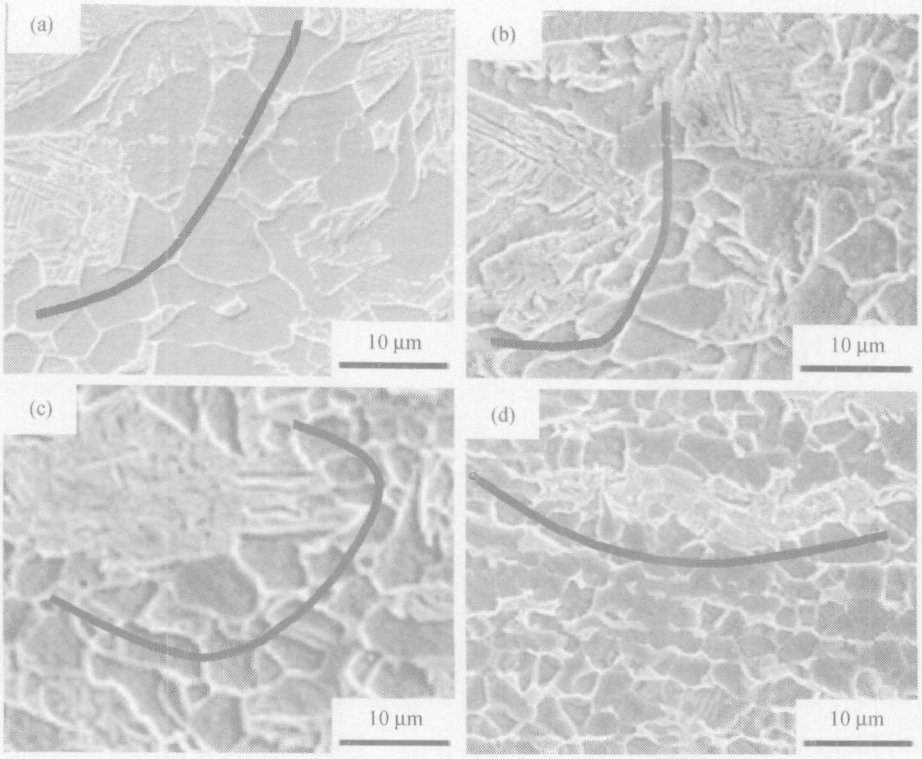

Figure 3 SEM micrographs showing ferrite chains stringed by black curves during the deformation of undercooled austenite in steel S1 (a, ε =0.11), S2 (b, ε=0.36), S3 (c, ε=0.51) and S4 (d, ε=0.92).

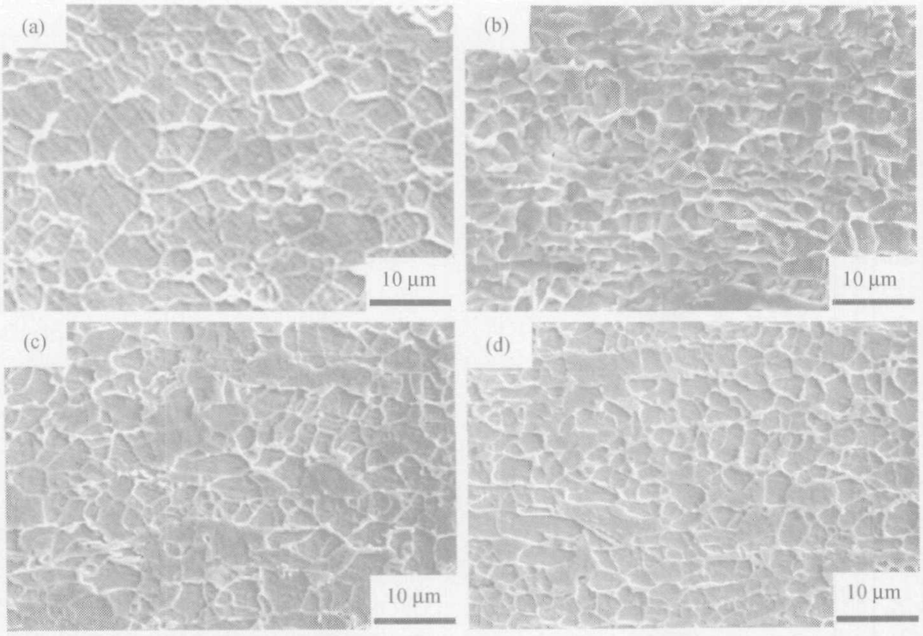

Figure 4 SEM micrographs showing the ultra-fine microstructure obtained when DEFT was finished in steel S1 (a, ε=0.70), S2 (b, ε=0.92), S3 (c, ε=1.11) and S4 (d, ε=1.11).

3.2 Effects of C and Mn content on DEFT

During the incubation period of DEFT, deformation is exerted on the undercooled austenite directly. The structural defects, such as the distortion of grain boundaries and the elongation of grains, will be produced at both the inter- and intra-granular of austenite, which promotes the forming of additional nucleation sites in those places. The longer the incubation period is, the higher the effective accumulated strain in austenite is, and the more additional nucleation sites are produced in deformed austenite.

The addition of austenite stabilizing elements C and Mn decreases the A_3 (table 1) and the degree of supercooling at the deformation temperature of 760°C of austenite. The incubation period and the transformation finish time during the isothermal treatment are prolonged with increasing the C or Mn content **(figure** 5(a)), especially the finish time.

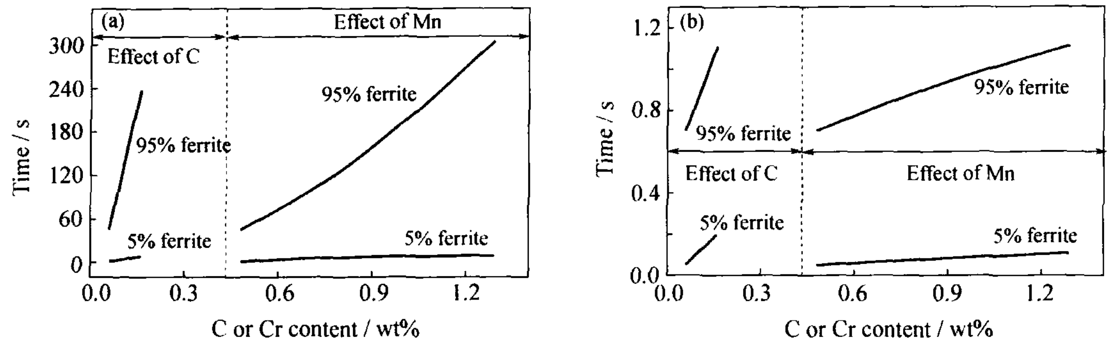

Figure 5 Effects of C and Mn content on the formation of 5% and 95% ferrite by isothermal treatment (a) and DEFT (b) at 760°C.

The effects of C and Mn on the incubation period and transformation finish time in DEFT are still present. The time for DEFT start (about 5% ferrite) and finish (about 95% ferrite) become longer with C or Mn content increasing (figure 5(b)). Under the higher effective accumulated strain, the more additional sites for nucleation are produced, and then the N_V increases with C or Mn content increasing (figure 6(a)).

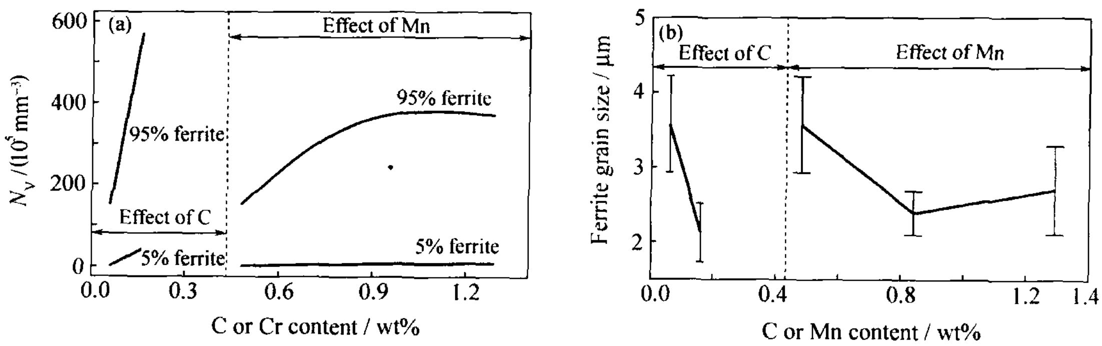

Figure 6 Effects of C **and** Mn content on the ferrite grain number per-volume *(N_V)* (a) **and** ferrite grain size (b) when DEFT was finished at 760°C.

On the other hand, the carbon-rich zone will be present in the austenite as soon as ferrite nucleates, which restricts to further growth of ferrite. The solid solution Mn atoms in ferrite will also exert solution drag effect on ferrite growth. The further ferrite growth rate decreases as C or Mn content increasing in steels.

It is because of the higher-density nucleation sites (figure 6(a)) and lower growth rate that the level of grain refinement increases as C or Mn content increasing (figure 6(b)).

Comparing with the effect of Mn, the addition of C is more favorable to the accumulation of strain in austenite. Firstly, the addition of C prolongs the transformation incubation period of DEFT more dramatically than that of Mn (figure 5(b)), which leads to a higher increment speed of N_V (figure 6(a)). Secondly, the restriction to further ferrite growth caused by the carbon-rich zone is more effective than that by drag effect of Mn atoms, which leads to much finer ferrite grains.

Furthermore, the effect of Mn on refinement is favored only within a certain range of 0.48%-0.84% Mn, further increase in the Mn content, rising to 0.84% or above, does not lead to further grain refinement (figure 6(b)).

4 Conclusion

The microstructures of 2-4 μm ultra-fine equiaxed ferrite grains with minors distributed homogeneously can be obtained by DEFT in all low carbon (Mn) steels. The more pronounced refinement is achieved as the C or Mn content increasing because of the higher-density nucleation sites and lower growth rate. The effectiveness of C on the level of refinement is more obvious than that of Mn.

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