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Original Article

Influence of alloying elements on as-casted microstructure and yield strength of Micro-Alloyed Low Carbon Steels

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Abstract

Micro-Alloyed rolling steels with low carbon content were hot deformed followed by direct cooling of blowed-air in two processes and additional annealing at relatively low temperatures. Effective yield strength was controlled by applying different mean grain size conditionings using Hall-Petch equation. It was shown that increasing the vanadium alloying element content increased the yield strength and also decreased the mean grain size. The development of the complex as-casted polygonal-acicular ferrite / pearlite microstructures during the cooling and annealing treatment was systematically investigated and correlated with yield strength.

Keywords: alloying elements, as-casted microstructure, yield strength, Micro-Alloyed Low Carbon Steels

1. Introduction

The name “Micro-Alloyed Low Carbon Cast or MLCC Steels” was first applied to a class of higher strength low carbon steels containing small additions of niobium and/or vanadium. Any attempt at a rational definition of micro-alloying based on the increases in strength produced by small additions would now include aluminium, vanadium, titanium, and niobium-treated steels. Such steels contain essentially less than 0.1% of the alloying additions, either as a single addition or in combination, and by this yield strength increments of two or three times that of a plain carbon-manganese steel can be attained. Niobium had been considered as an additive to steel prior to 1940 but the absence of a sophisticated market and the lack of understanding of the use of niobium discouraged any serious developments. By 1966, the mechanism of “interphase” precipitation had been discovered, together with the important role of transformation temperature in controlling the size and spacing of the interphase precipitated particles, and data was published on the solubility of niobium, vanadium, titanium and aluminium carbides, nitrides, or carbo-nitrides. The basic foundation for an understanding of the dissolution and reprecipitation kinetics of these compounds was now available. The solubility data for these compounds in austenite, also provided the base for a quantitative understanding of the mechanism of austenite grain refinement, which plays such an important role in the development of strength and toughness in normalized steels. In the construction industry, the material cost of building projects could be reduced by using higher strength steels with smaller cross sectional areas for a given force resistance. Traditional methods of increasing the tensile strength of mild steels had been to increase the carbon and/or manganese content, but such steels obviously had reduced weldability and were prone to weld cracking. In fact, the higher strength levels could be attained with much lower carbon and manganese levels, thus improving the weldability.

The control of grain size by manipulation of the hot rolling process variables of micro-alloyed steels opened the way for further reductions in carbon and alloy contents, which were very important for the weldability. The controlled

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rolling of low carbon micro-alloyed steel therefore provided the necessary strength and toughness levels, while at the same time producing steels of improved weldability. During the late 1960s and early 1970s, attention had been given to enhancing the strength of micro-alloyed steels. Combinations of alloyed elements, such as niobium-vanadium, titanium-vanadium, as well as the use of higher levels of microalloying additions, had produced steels with yield strength levels of up to 450 MN.m^{-2}, and development work had already been carried out on low carbon low alloy steels containing micro-alloying additions, in order to combine the benefits of microalloying with those of fine grained bainitic or acicular structure, giving yield strengths in excess of 550 MN.m^{-2}.

2. Microstructure-Property Relationships

Considerable attention has been given to the relationship between microstructure and properties of micro-alloyed steels. The properties considered here are strength, which are fundamental to the concept of micro-alloyed steel, and the ancillary, as well as the highly important / properties of toughness, ductility, and formability. These preperties depend upon microstructural features in different ways and in some cases depend upon different microstructural features. Weldability is generally accepted as being composition dependent when considered from the standpoint of cold cracking, but other problems, such as lamellar tearing, are directly related to ductility and toughness, which in turn are dependent upon microstructural features.

Attention has already been drawn to the early use of tensile strength as a design criterion, and the subsequent change to a design criterion on yield strength. The design stress was based on the strength characteristics multiplied by an appropriate safety factor; the safety factor being different of course from the two strength characteristics. This is important because the strengthening mechanisms, although having the same qualitative effects on each characteristic, do not have the same quantitative effects. Most strengthening mechanisms have greater effects on the yield strength in terms of both absolute and relative magnitude. The weight saving achieved through the use of micro-alloyed steels would certainly have been reduced considerably had design stresses remained linked to the tensile strength. The difference between these strength characteristics requires some understanding of both parameters (Gladman, 1997). In the production of higher yield strength steels parts for the construction, automotive, and petroleum industry the classical annealing of alloyed steels have been continuously substituted by vanadium-niobium micro-alloyed low carbon steels cooling controlled from the rolling temperature. However, there are some limitations in the 0.2%-proof stress and ductility. Therefore, a new variant of thermomechanical treatment has been developed in order to improve the mechanical properties of micro-alloyed low carbon to the level of Ni-alloyed annealed steels. Controlled rolling of steel sheets is a particular case of thermo-plastic treatment at high temperatures, which is directed towards the achievement of a ferrite-pearlite or ferrite-bainite-pearlite fine-grained structure. Grain pulverization and reduction processes are mechanisms influencing the improvement of both durability and plasticity properties. The principle of controlled rolling consists in choices of thermo-plastic rolling conditions in such a way that the kinetics of the phenomena occurring in the metal, i.e. recrystallization, reduction process, are supervised. This modified thermomechanical treatment is described by Gladman, (1997) and Korczak, (2004). Essentially, it consists in rolling at relatively high temperature for two hours followed by a two-step temperature of annealed cooling. In the first slow cooling step (blowed air) from the rolling temperature into the (γ+α) two phase region a desired fraction of soft proeutectoid ferrite is formed within a carbon enriched austenite. In the second step cooling (also blowed air) yields polygonal-acicular phases instead of pearlite and small amounts of retained austenite. An annealing treatment at relatively temperatures of austenite results to form a pearlite + ferrite structure in hypoeutectoid steel (Lakhtin, 1977). The paper describes the development of microstructures during the two-step cooling of annealing and its dependence on the variation of process parameters and microalloying as well as the relations between final microstructure and resulting mechanical properties.

3. Experimental Procedure

Experiments have been performed with a group of four grades of commercial rolling micro-alloyed low carbon cast steels are as follows, 17Mn6, 16MnV6, 22MnVNb6, and 18MnVTi6. The group of four MLCC steels have been studied to optimize the influence of carbon content and single and multiple microalloying additions on the austenite and ferrite grains size microstructure in as-casted state and as-annealed state at various temperatures. The composition (wt%) of these steels used in this study is given in Table 1. All steels are micro-alloyed with vanadium, titanium, niobium, and also

Table 1. Chemical composition of four MLCC steels, in wt %.

Steels/Elements	1	2	3	4
C	0.17	0.16	0.22	0.18
Mn	1.47	1.54	1.39	1.49
Si	0.39	0.35	0.38	0.36
P	0.012	0.016	0.017	0.017
S	0.010	0.015	0.017	0.016
Cu	0.15	0.22	0.22	0.24
Ni	0.20	0.14	0.16	0.15
V	<0.01	0.09	0.09	0.09
Ti	<0.01	<0.01	0.01	0.03
Nb	0.01	<0.01	0.05	<0.01
Al	0.056	0.045	0.079	0.080
N	0.009	0.006	0.017	0.011

aluminium, which is predominantly used for precipitation hardening of ferrite. 17Mn6 is a micro-alloyed steel for comparison with the other steels number 2-4. It is additionally micro-alloyed with titanium making use of small TiN-particles for effective inhibition of austenite grain growth during reheating and hot rolling. Furthermore, three microalloying variants, 16MnV6, 22MnVNb6, and 18MnVTi6, were prepared as shown in Table 1. The steels 16MnV6, 22MnVNb6, and 18MnVTi6 have enhanced contents of vanadium and steel 22MnVNb6 is micro-alloyed with high niobium to elevate the recrystallization temperature of austenite. The microstructures during the two processes of annealing were analyzed by methods of qualitative and quantitative metallography by Spektor analysis theory, the Hall-Petch relationship measurements of the chord lengths of the austenite grain size distribution, and the determination of the yield stress of polycrystalline aggregates in which ferrite grain size is the only variable. The working formulas for Spektor analysis and Hall-Petch relationship are shown in Equation 1 to 3 :

$$G = M + \left(6.64\log\frac{g}{100}\right) \quad (1)$$

$$\left(N_V\right)_j = \frac{4}{\pi\Delta^2}\left[\frac{\left(n_L\right)_j}{2j-1} - \frac{\left(n_L\right)_{j+1}}{2j+1}\right] \quad (2)$$

$$\sigma_y = \sigma_0 + Kd^{-0.5} \quad (3)$$

where G is the index number of the International Standard (ISO 643), M is the number of the closest standard chart, modified as a function of the ratio of the magnifications, g is the magnification of the image on the screen or photomicrograph is not x 100, $(N_v)_j$ is the number of particles of mean diameter per unit volume in the interval of j, $(n_L)_j$ is the number of chords per unit length of test line, σ_y is the yield strength or the stress at which the material permanently deforms, σ_o is a constant stress, K is a material constant, and d is the average diameter of the ferrite grains.

A reflection light or SEM microscope was used to investigate details of the microstructures at magnifications from x 75 to 1,500. Microstructures are an indication of the quality of heat treatment, of mechanical properties (Lakhtin, 1977). The grain size microstructures of the entire samples were studied and representative photomicrographs were taken. In order to determine the grain size, the specimens were specially polished and etched in a saturated piric acid solution at about 80°C and a 2% nital solution (Ganwarich, 2003-2005) for austenite and ferrite microstructures respectively. The concentration of the acid had to be adjusted for different samples. The grain size was then measured at x 75 using a filler eyepiece. With respect to macro- and microhardness measurements were carried out in order to characterize the global hardness of the complex microstructure as well as the hardness of its constituents (Richter *et al.*, 1998).

4. Result and Discussion

Figure 1 shows the microstructures of two processes cooled specimens for temperatures of hot deformed annealing (holding 2 hrs and blowed air cooling to 50°C) of 930°C (strain e = 0.9) and 1070°C for the steels 17Mn6 (Figure 1 A,B), 16MnV6 (Figure 1 C,D), 22MnVNb6 (Figure 1 E,F) and 18MnVTi6 (Figure 1 G,H). As estimated, the formation of proeutectoid ferrite begins predominantly at the austenite grain boundaries and the lower the blowed air temperature, the higher the polygonal-acicular ferrite/pearlite. However, in steel 16MnV6, 22MnVNb6, and 18MnVTi6 the ferrite formation is enhanced due to the higher vanadium, nitrogen, and a little lower carbon content. In steel 17Mn6, niobium retards the recrystallization of ferrite leading to acicular ferrite/pearlite. Besides, additional acicular ferrite/pearlite formation has been observed within the austenite grains of steel 17 Mn6.

Figure 2 demonstrates the influence of the blowed air temperature T_{ba} on the acicular ferrite/pearlite for deformation temperatures T_d = 930°C (typically for thermomechanical

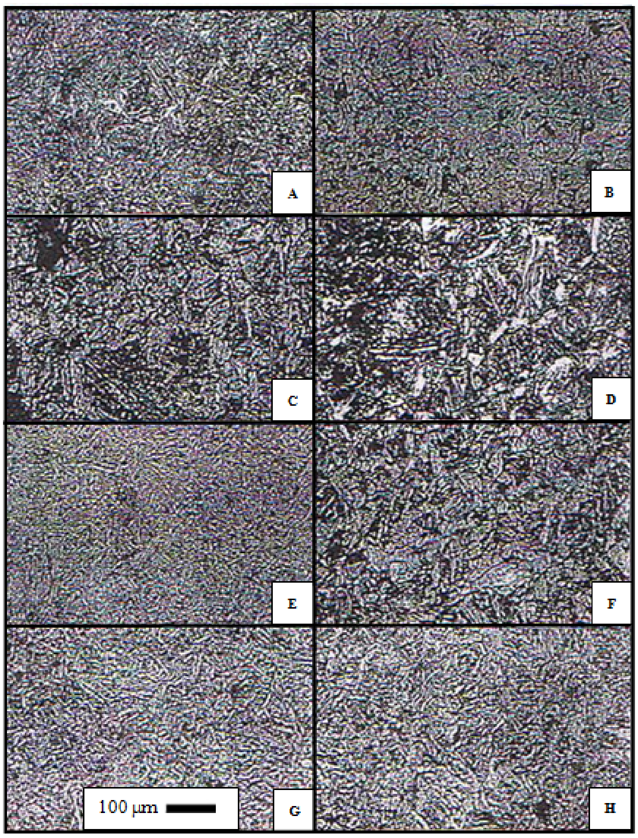

Figure 1. Microstructures of the steel 17 Mn6 (A,B), 16 MnV6 (C,D), 22 MnVNb6 (E,F), and 18MnVTi6 (G,H), deformed at 930°C (A,C,E,G), 1,070°C (B,D,F,H), and second step cooled with blowed air to 50°C, all photographs have same magnification.

treatment) and T_d = 1,070°C (conventional rolling, 1,070-1,200°C). The volume fractions of ferrite are significantly higher if deformation was applied at 930°C because of the higher ferrite nucleation density due to smaller austenite grain size and non-recrystallized elongated austenite grains with deformation bands within the grains of the Nb-steel, respectively. Table 2 shows size distribution and yield strength of ferrite grains of four micro-alloyed steels. The variation of yield stress with $d^{-0.5}(m^{-0.5})$ is shown in Figure 3. The follwing Hall-Petch relationship can be expressed for the microalloyed steel (Ganwarich, 2003-2005) as

$$\sigma_y = 40+0.881 \quad d^{-0.5} \tag{4}$$

where σ_y and d are yield strength (MN.m^{-2}), the mean ferrite grain size (mm) respectively.

The yield strength was carried out with percentage of vanadium content as showed in Figure 4. The yield strength was increased from 180 MN.m^{-2} (steel 17Mn6) to 225 MN.m^{-2} (steel 16MnV6) when the vanadium content was changed from < 0.01% to 0.09%. The higher values of yield strength appeared for steel 22MnVNb6 (236 MN.m^{-2}) and steel 18MnVTi6 (241 MN.m^{-2}), which were double micro-alloyed V-Nb or V-Ti, respectively. It must be emphasized that above mentioned values of computed yield strength are actually just the contributions originating from the ferrite grain size refinement. Real yield strength of the steels is higher owing to strengthening by manganese and pearlite content. According to Pickering (Pickering, 1978) 1% Mn alone increases the yield strength of low carbon steel by 50 MN.m^{-2}. Transformation strengthening caused by pearlite is so far subjected to discussion, however, one can expect positive effects. Altogether, the real yield strength might be higher in order of 100 MN.m^{-2}. In Table 3 the mean ferrite grain size as determined by Spektor's method is compared to values of G, d, and l estimated using International Standard (ISO 643) (International Standard, 2003) as a function of various parameters. The values of mean ferrite grain size ranged from 14 to 40 μm, and the agreement between the two methods is quite good. Vanadium is known to promote precipitation strengthening and makes smaller grain size than in steels without it. The mean grain size of ferrite in steel 17Mn6 is the largest because it has < 0.01V, < 0.01Ti, and 0.01Nb of micro-alloyed elements. The double micro-alloyed steel 18MnVTi6 exhibited the smallest ferrite grain size.

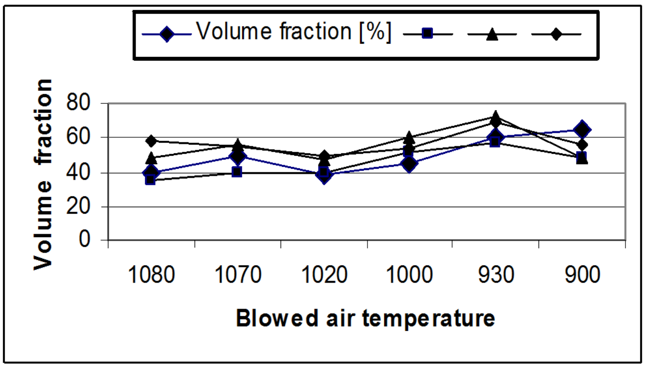

Figure 2. Influence of blowed air temperature (°C) T_{ba}, on the volume fraction of polygonal acicular ferrite (%) of four micro-alloyed steels for deformation temperature T_d = 930°C, 1,070°C (also other temp. are shown).

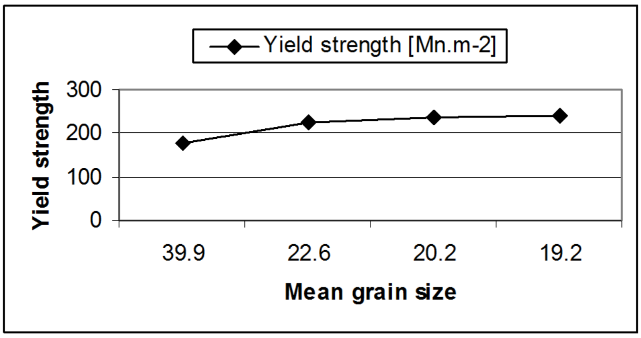

Figure 3. Effect of mean polygonal acicular ferrite grain size (mm) on yield strength (MN.m^{-2}) of four micro-alloyed steels.

5. Conclusions

Following conclusions can be drawn from this study :

1. The Hall-Petch relationship can be utilized to examine the dependence of yield strength on mean ferrite grain size of the micro-alloyed low carbon cast steels. One

Table 2. Size distribution and yield strength of polygonal-acicular ferrite grains of MLCC steels.

1	2	3	4	5	6	7
Steel	Range of chord lengths, μm	Number of chordsper mm., $(n_L)_j$	Diameter of grains, mm, d_j	Number of grain per mm^3, $(N_v)_j$	Evaluated mean grain size, μm, d	$\sigma_y = \sigma_o + Kd^{-0.5}$ (MN.m^{-2})
1	0-260	183	0.026-0.260	1.0130x10^5	39.9	179.5
2	0-150	688	0.015-0.150	13.4114x10^5	22.6	225.3
3	0-130	625	0.013-0.130	14.0886x10^5	20.2	236.0
4	0-140	876	0.014-0.140	22.6714x10^5	19.2	241.1

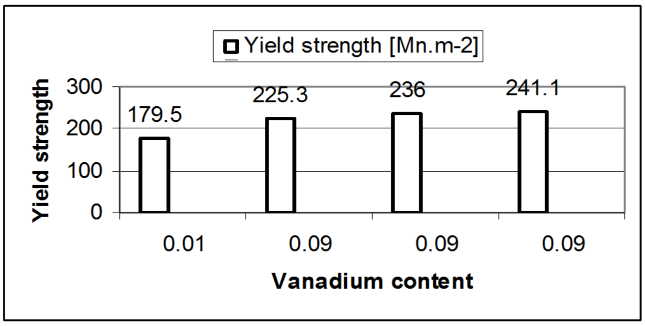

Figure 4. Yield strength (MN.m^{-2}) bar for four micro-alloyed steels at given vanadium content (wt%) additions.

method of controlling the properties of a steel is by controlling the grain size. Reducing the grain size, increases the number of grains and also the amount of grain boundary. Any dislocation moves only a short distance before encountering a grain boundary, and the strength of the steels increased.

2. Vanadium, Titanium, Niobium and Aluminium as microalloying elements increase the yield strength and decrease the mean ferrite grain size significantly also in as cast state.

3. Micro-alloyed low carbon cast steels discontinued with additional aluminium result in inherently fine-grained steels.

4. The described modifications of microstructures by annealing at about 400°C after two processes hot deformed cooling have resulted in the following improvements of mechanical properties depending on the applied microalloying; it increases 0.2% of the proof stress from 600-850 MN.m^{-2} to 870-1,100 MN.m^{-2} and increases the reduction area from 25-35% to 45-55%.

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Table 3. Evaluated mean grain size using Spektor's method with International Standard ISO643 (2003).

1	2	3	4	5
Steel	Evaluated mean grain size, μm d	Estimated grain size (Index), G	Mean diameter of grain, μm, d	Mean intersected segment, μm, I
1	39.9	6.5	37.7	34.2
2	22.6	8	22.1	20
3	20.2	8.5	18.9	17.1
4	19.2	9	15.6	14.1