Polygonal-Acicular Ferrite/Pearlite Microstructure and Mechanical Properties of Microalloyed Low Carbon Cast Steels

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Abstract

Microalloyed 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 as a Hall-Petch equation. It was shown that increasing the vanadium content increased the yield strength and also decreased the mean grain size. The development of the complex polygonal - acicular ferrite / pearlite microstructure during the cooling and annealing treatmemt was systematically investigated and correlated with mechanical properties.

1. Introduction

The name "Microalloyed 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 microalloying based on the increases in strength produced by small additions would now include aluminium, vanadium, titanium and of course niobium-treated steels. Such steels contain essentially less than 0.1% of the alloying additions used singly or in combination, and 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 materials 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 microalloyed steels opened

the way for further reductions in carbon and alloy contents, which were so important to weldability. The controlled rolling of low carbon microalloyed steel therefore provided the necessary strength and toughness levels whilst 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 microalloyed steels. Combination 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 microalloying 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}.

Microstructure-Property Relationships

Considerable attention has been given to the relationship between microstructure and properties of microalloyed steels. The properties considered here are strength, which is fundamental to the concept of microalloyed steel, and the ancillary, but nonetheless 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 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 characteristic multiplied by an appropriate safety factor, the safety factor being different of course for 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 term of both absolute and relative magnitudes. The weight saving achieved through the use of microalloyed 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 [1].

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 microalloyed low carbon steels controlled cooled from the rolling temperature. However, there are some limitations in 0.2%-proof stress and ductility. Therefore, a new variant of thermomechanical treatment has been developed in order to improve the mechanical properties of microalloyed low carbon to the level of Ni-alloyed annealed steels. Controlled rolling of steel sheets is a particular case of thermo-plastic treatment in high temperatures, which is directed towards achievement of ferrite-pearlite or ferrite-bainite-pearlite fine-grained structure. Grain pulverization and eduction processes are mechanisms influencing improvement of both durability and plasticity properties. The principle of controlled rolling consists in choice of thermo-plastic rolling condition in such a way that kinetics of phenomena occurring in metal i.e. recrystallization, eduction process is supervised. This modified thermomechanical treatment is described in the textbook of T.Gladman & the research paper of P.Korczak in the journal of materials processing technology on this

references [1&2]. Essentially, it consists in rolling at relatively high temperature on two hours followed by a two-step temperatures of annealed cooling. In the first slow cooling step (blowed air) from 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 [7]. The research paper describes the development of microstructure during 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.

2. Experimental Procedure

The test has been performed by the group of four grades of commercial rolling microalloyed low carbon cast steels are as follows :

1) 17Mn6

2) 16MnV6

3) 22MnVNb6

4) 18MnVTi6

The group of four samples MLCC steels have been studied to optimize the influence of carbon content and single and multiple microalloying additions on the austenite & ferrite grains size microstructure in as-cast state and as-annealed of various temperatures. The composition (wt%) of these steels used in this study is given in Table1. All steels are microalloyed with vanadium, titanium, niobium, and also aluminium which is predominantly used for precipitation hardening of ferrite. 17Mn6 is microalloyed steel for compare with other steel

on the number of 2-4 and is additionally microalloyed 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 that can see in Table 1. The steels 16MnV6, 22MnVNb6 and 18MnVTi6 have enhanced contents of vanadium and steel 22MnVNb6 is microalloyed with high niobium to elevate the recrystallization temperature of austenite.

Table 1 Chemical composition of four MLCC steels, 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

The evaluation of microstructure during the two processes of annealing was analysed by methods of qualitative and quantitative metallography by Spektor analysis theory and Hall-Petch relationship (measurement of the chord lengths of austenite grain size distribution and determination of the yield stress of polycrystalline aggregate in which ferrite grain size is the only variable. The working fomular is :

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

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

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

where G is the index number of the International Standard (ISO643), 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 microscope was used to investigate details of the microstructure (morphology of ferrite, pearlite, nonmetallic inclusions, micro-cracks, and also precipitates) at magnifications from x75 to 1,500. Microstructure is an indication of the quality of heat treatment, of mechanical properties [7]. The grain size microstructure of entire the relavant samples 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 & a 2% nital solution[6] of austenite & ferrite microstructure respectively. The concentration of the acid had to be adjusted for different samples. The grain size was then measured at x75 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 [8].

3. Result and Discussion

On the Figure 1 shows the microstructure of two processes cooled specimens for temperature of hot deformed annearling (holding 2 hrs and after that for blowed air cooling to 50°C) on 930°C(strain ε = 0.9) & 1070 $^{\circ}$C of the steels 17Mn6 (A,B), 16MnV6 (C,D), 22MnVNb6 (E,F) and 18MnVTi6 (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. Certainly, in steel 16MnV6, 22MnVNb6, and 18MnVTi6 the ferrite formation is enhanced due to the higher vanadium, nitrogen and a little lower carbon contents. In steel 17Mn6 niobium retards the recrystallization of ferrite leading to acicular ferrite/pearlite. Besides, additional acicular ferrite/pearlite formation has been observed at deformation bands within the austenite grains of steel 17Mn6.

Figure 2 demonstrates the influence of the blowed air temperature T_{ba} on the acicular ferrite/pearlite for deformation temperature T_d = 930°C (typically for thermomechanical treatment) and T_d = 1070°C (conventional rolling, 1070-1200°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 in the Nb-steel, respectively.

Table 2 shows size distribution and yield strength of ferrite grains of four microalloyed steels. The variation of yield stress with $d^{-0.5}(m^{-0.5})$ is shown in Figure 3. The follwing Hall-Petch relationships can be expressed for the microalloyed steel [6] :

$$\sigma_y \quad = \quad 40 + 0.881 \ d^{-0.5} \qquad (4)$$

where σ_y and d are yield strength (MN.m^{-2}), the mean ferrite grain size (μm) 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}) or steel 18MnVTi6 (241MN.m^{-2}) which were double microalloyed 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 [9] 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 effect. 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, đ & 1 estimated using International Standard 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 vary good. Vanadium is known to promote precipitation strengthening and make smaller grain size than in steels without it. The mean grain size of ferrite in steel 17Mn6 is largest because it has ＜0.01V, ＜0.01Ti, & 0.01Nb of microalloyed elements.

The double microalloyed steel 18MnVTi6 exhibited the smallest ferrite grain size.

4. Concusions

1. The Hall-Petch relationship can be utilized to examine the dependence of yield strength on mean ferrite grain size of the microalloyed low carbon cast steels. One method of controlling the properties of a steel is by controlling the grain size. By reducing the grain size, increase the number of grains and the amount of grain boundary. Any dislocation moves only a short distance before encountering a grain boundary, and the strength of the steels are 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. Microalloyed low carbon cast steels, killed with additionally aluminium result in inherently fine-grained steels.

4. The described modifications of microstructure 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 variant [3] : increase of 0.2%-proof stress from 600-850 MN.m^{-2} to 870-1100 MN.m^{-2} & increase of reduction area from 25-35% to 45-55%
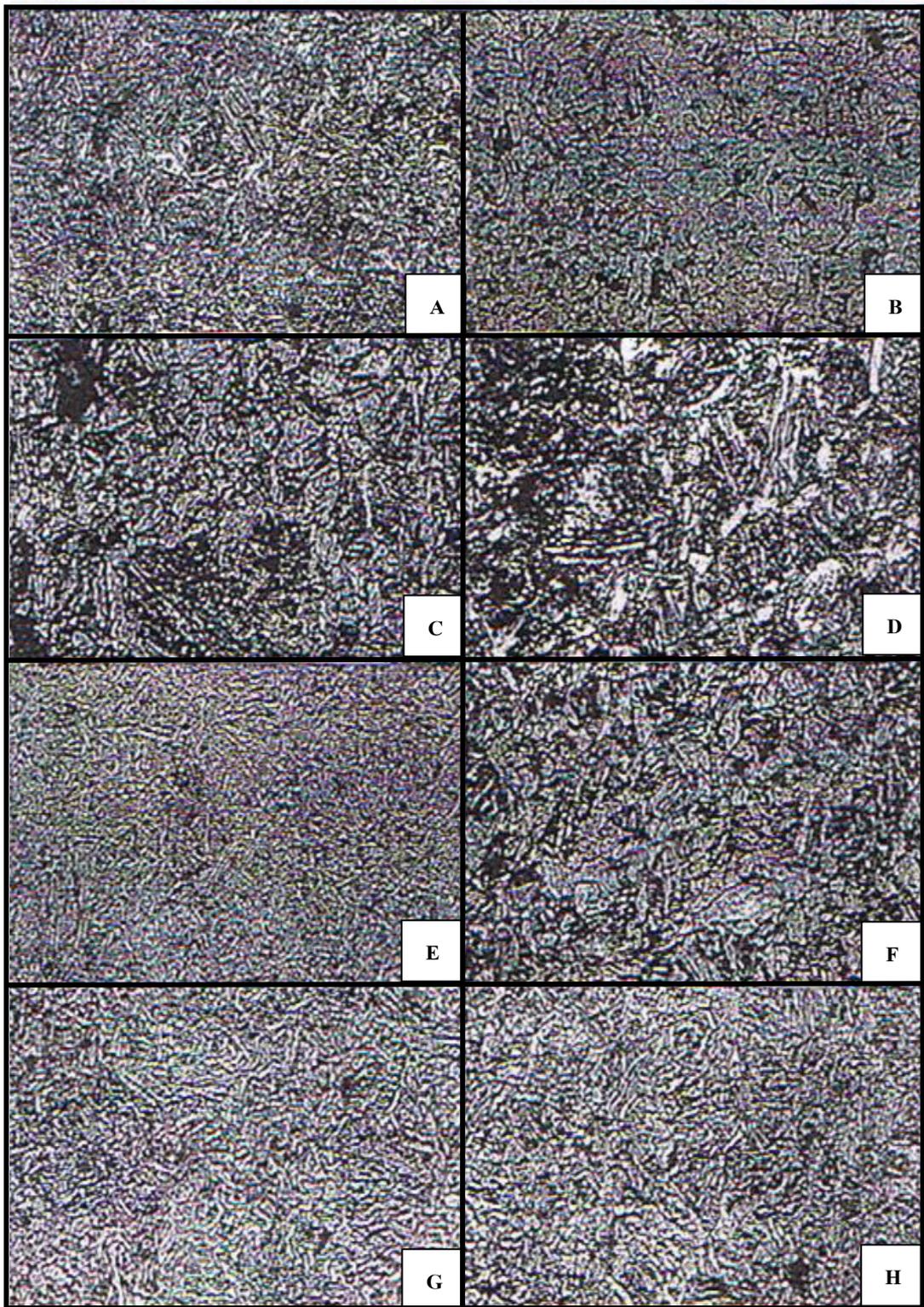
Figure 1 Microstructure of the steels 17 Mn6 (A,B), 16 MnV6 (C,D), 22 MnVNb6 (E,F) and 18MnVTi6 (G,H), deformed at 930°C (A,C,E,G), 1070° (B,D,F,H) and second step cooled with blowed air to 50°C, on the same magnification as 100 μm

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

1	2	3	4	5	6	7	8
Item	Steels	Range of chord lengths, μm	Number of chords per 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	17Mn6	0-260	183	0.026-0.260	1.0130×10^5	39.9	179.5
2	16MnV6	0-150	688	0.015-0.150	13.4114×10^5	22.6	225.3
3	22MnVNb6	0-130	625	0.013-0.130	14.0886×10^5	20.2	236.0
4	18MnVTi6	0-140	876	0.014-0.140	22.6714×10^5	19.2	241.1

Table 3 Evaluation mean grain size of Spektor's method with International Standard (ISO643) [10]

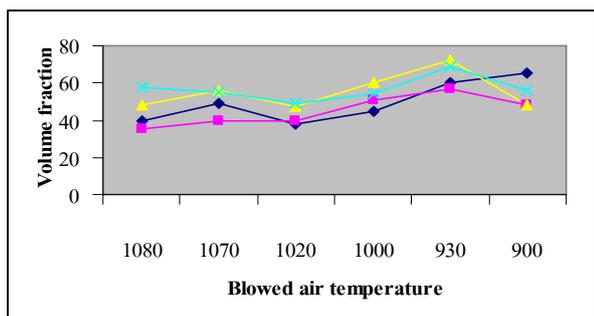| 1	2	3	4	5	6
Item	Steels	Evaluated mean grain size, μm, d	Estimated grain size (Index), G	Mean diameter of grain, μm, đ	Mean intersected segment, μm, I
1	17Mn6	39.9	6.5	37.7	34.2
2	16MnV6	22.6	8	22.1	20
3	22MnVNb6	20.2	8.5	18.9	17.1
4	18MnVTi6	19.2	9	15.6	14.1

Figure 2 Influence of blowed air temperature ($^\circ$C) T_{ba} on the volume fraction of polygonal acicular ferrite (%) of four microalloyed steels (green as steel 1, yellow as steel 2, black as steel 3 and pink as steel 4) for deformation temperature T_d = 930°C, 1070°C
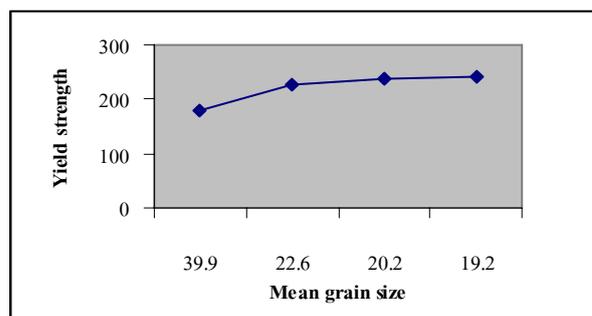
(also other temp. as shown)

Figure 3 Effect of mean polygonal acicular ferrite grain size (μm) on yield strength (MN.m^{-2}) of four microalloyed steels
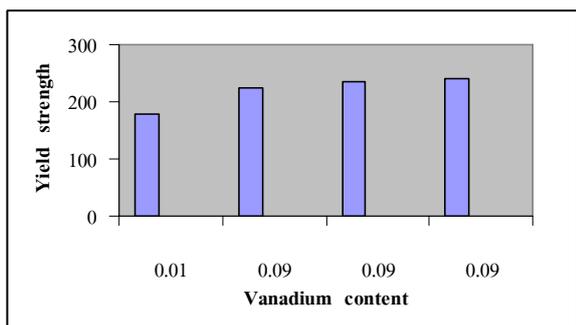
Figure 4   Yield   strength   (MN.m^{-2})   bar   for   present   four microalloyed steels   at   given   vanadium content (wt%)   additions

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