Archives of Materials Science and Engineering
Volume 70
Issue 1
November 2014
Pages 39-44
International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

Application of vanadium precipitation for lower rolling force and enhanced strength of hot strip steel

P. Suwanpinij [a],*, H.H. Dickert [b]
[a] The Sirindhorn International Thai-German Graduate School of Engineering (TGGS),
King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand
[b] Department of Ferrous Metallurgy (IEHK), RWTH Aachen University, Aachen, Germany
* Corresponding e-mail address: piyada.s.mme@tggs-bangkok.org

Received 29.08.2014; published in revised form 01.11.2014

ABSTRACT

Purpose: In this paper the application of vanadium precipitation for lower rolling force and enhanced strength of hot strip steel was discussed.

Design/methodology/approach: Fine precipitates of vanadium were firstly investigated by Scanning Transmission Electron Microscopy (STEM), Transmission Electron Microscopy (TEM) and Energy Dispersive X-Ray Spectroscopy (EDX). Further quantitative characterisation for the precipitation and the addition of high amount of nitrogen will be discussed.

Findings: The contribution for strength from different components, namely, grain refinement, second phase hard particles and precipitation strengthening was separately analysed.

Research limitations/implications: Basic knowledge in thermodynamics of the precipitation of microalloying elements is applied for the process design of hot strip rolling for reduced rolling force and improved strengthening effect.

Originality/value: A vanadium-added steel tends to need moderate rolling force through recrystallisation controlled rolling while the other with a small addition of 0.05% niobium requires significantly higher force.

Keywords: High Strength Low Alloyed (HSLA) steel; Precipitation; Hot rolling; Process design; Dual phase

Reference to this paper should be given in the following way:

P. Suwanpinij, H.H. Dickert, Application of vanadium precipitation for lower rolling force and enhanced strength of hot strip steel, Archives of Materials Science and Engineering 70/1 (2014) 39-44.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

According to the solubility product of the 3 micro-alloying elements, i.e. Ti, Nb and V [1], the authors make a mapping of the precipitation sequence along the hot rolling process to take the most advantage from the precipitation hardening and the resulting grain refinement is shown in Fig. 1. The grain refinement of ferrite in the final microstructure is the result of both the Recrystallisation Controlled Rolling (RCR) [1] or Thermomechanical

Controlled Process (TMCP) and the fine precipitates, which is the concept of high strength low alloy (HSLA) steel.

2. Experimental

Two steels with different microalloying concepts were selected to study in this work. Their chemical compositions are shown in Table 1. One is microalloyed with Vanadium while the other is microalloyed with Niobium.

According to thermodynamics and hence the precipitation sequence of the microalloying elements shown in Fig. 1, the RCR scheme was planned for the V-concept while heavy TMCP was planned for the Nb-concept. After the pre-deformation of the ingot in an open die forge to destroy the cast structure, the rolling cycles in Fig. 2 with the parameters listed in Table 2 were tested in a deformation dilatometer Bähr DIL 805 A/D with cylindrical samples with a diameter of 5 mm and a length of 10 mm.

The microstructure of each sample was examined by means of light optical microscopy. The Vickers hardness test was carried out in all samples. Carbon replicas of some samples were made for further investigation of the precipitates by means of scanning transmission electron microscopy (STEM). Some processing schedules were selected to perform as closely as possible with bar samples in the hot deformation simulator (Baehr TTS820). A tiny flat dog bone specimen was machined for the tensile testing.

Table 1.
Chemical compositions of the investigated steel

Material Name	C	Si	Mn	P	S	Cr	Mo	Al	Ti	V	N
V-concept	0.060	0.02	1.00	0.005	0.003	0.50	0.010	0.04	0.01	0.10	0.0200
Nb-concept	0.082	0.28	1.48	0.017	0.001	0.28	0.004	0.04	0.02	0.05	0.0015

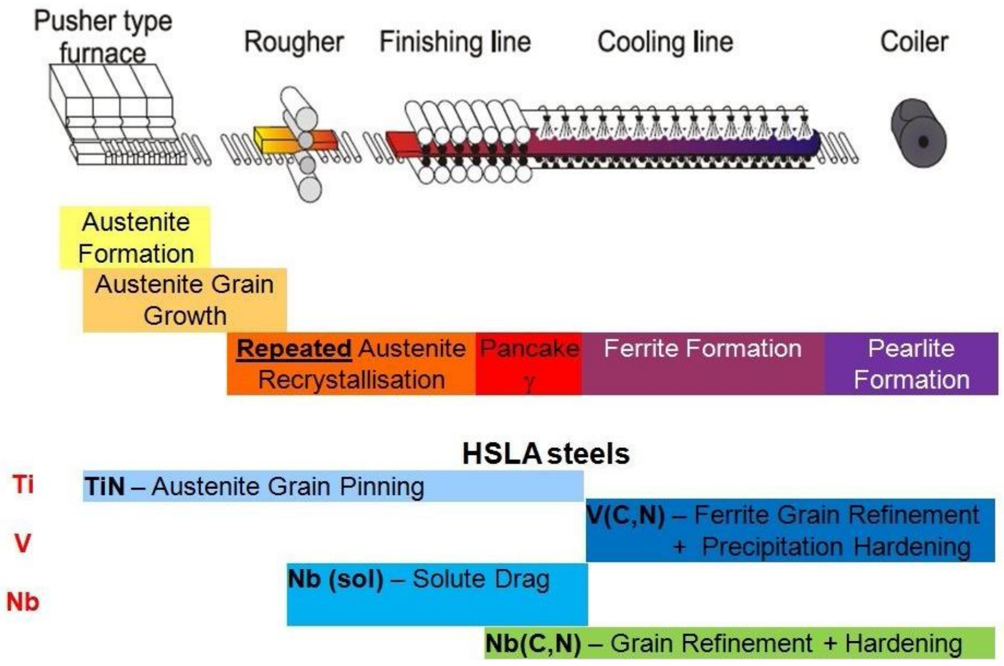


Fig. 1. The role of precipitation of the main microalloying elements according to thermodynamics

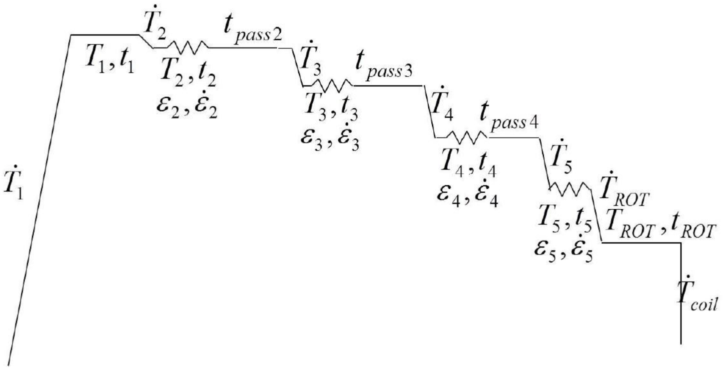


Fig. 2. Thermomechanical cycles carried out in the deformation dilatometer

Table 2.
The range of the parameters in the thermomechanical cycle in Fig. 2

Process Parameters	V-concept	Nb-concept
$\dot{T}_1, T_1, t_1$	200°C/minute, 1250°C, 15 minute	200°C/minute, 1250°C, 15 minute
$\dot{T}_2, T_2, t_2$	5°C/s, 1200°C, 3 s	0-5°C/s, 1200-1250°C, 3 s
$\varepsilon_2, \dot{\varepsilon}_2, t_{pass2}$	0.2, 12 s^{-1}, 10 s	0.2-0.3, 12 s^{-1}, 10-30 s
$\dot{T}_3, T_3, t_3$	60°C/s, 1150°C, 3 s	60°C/s, 1150-1250°C, 3 s
$\varepsilon_3, \dot{\varepsilon}_3, t_{pass3}$	0.4, 12 s^{-1}, 10 s	0.3-0.4, 12 s^{-1}, 10-30 s
$\dot{T}_4, T_4, t_4$	*null*	*null* or 60°C/s, 1100°C, 3 s
$\varepsilon_4, \dot{\varepsilon}_4, t_{pass4}$	*null*	*null* or 0.3, 12 s^{-1}, 10 s
$\dot{T}_5, T_5, t_5$	60°C/s, 900°C, 3 s	60 °C/s, 900 °C, 3 s
$\varepsilon_5, \dot{\varepsilon}_5$	0.0-0.6, 12 s^{-1}, 0 s	0.0-0.6, 12 s^{-1}, 0 s
$\dot{T}_{ROT}, T_{ROT}, t_{ROT}$	60°C/s, 680°C, 6 s	60°C/s, 680°C, 6-20 s
$\dot{T}_{coil}$	0.1 – 60°C/s	0.1 or 60°C/s

3. Results

3.1. Deformation stress

Figure 3 shows the deformation stress in a double hit test intentionally done at low temperature, say, 970°C, with a strain of 0.3 in both steels. It can be clearly seen that the V-concept is beneficial for smaller rolling stands as it requires lower rolling force after the interpass time of 3 s.

3.2. Resulting microstructures

The resulting microstructures of both steel concepts with different processing parameters are also shown in Fig. 4. From various combinations of the processing parameters under the limitation of the deformation dilatometer, obvious two ferrite grain sizes in Nb-concept samples can be observed in the sample with slow final cooling rate ($\dot{T}_{coil}$), simulating coiling (Fig. 4a). This can be explained by the slow ferrite formation during the isothermal holding followed by the formation of larger ferrite grains during the slow final cooling. Figs. 4b,c illustrate the ferrite formation just during the isothermal holding simulating the run out table (ROT), followed by quenching. Compared with the microstructure of V-concept steel in Fig. 4d-f, the so-called solute drag effect [2-4] by Niobium, resulting in slow austenite recrystallisation and larger austenite grain as well as the retarded ferrite formation can be claimed. That higher deformation stress is required at the same interpass time compared with that for the V-concept shown in Fig. 3 can be a good evidence of the retarded recrystallisation.

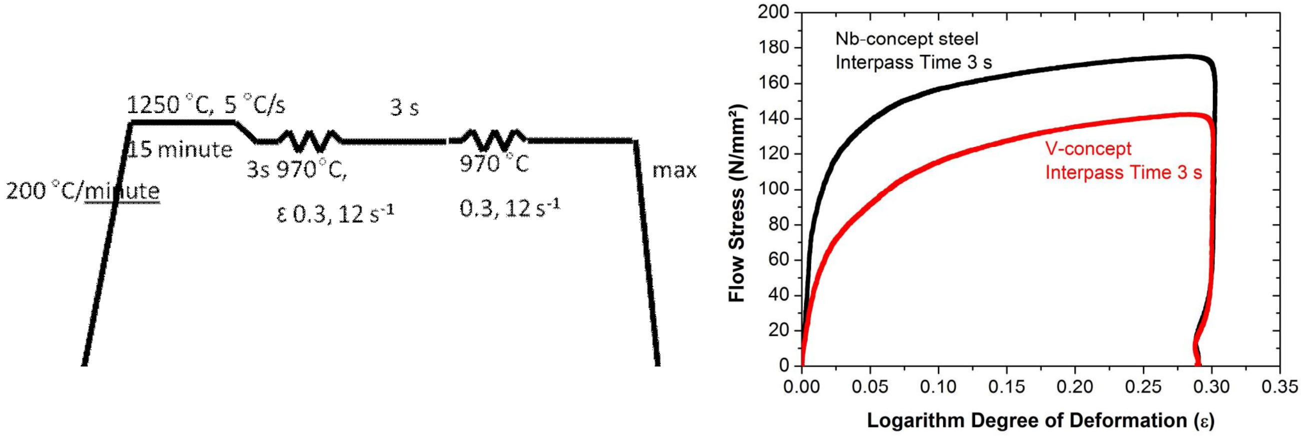
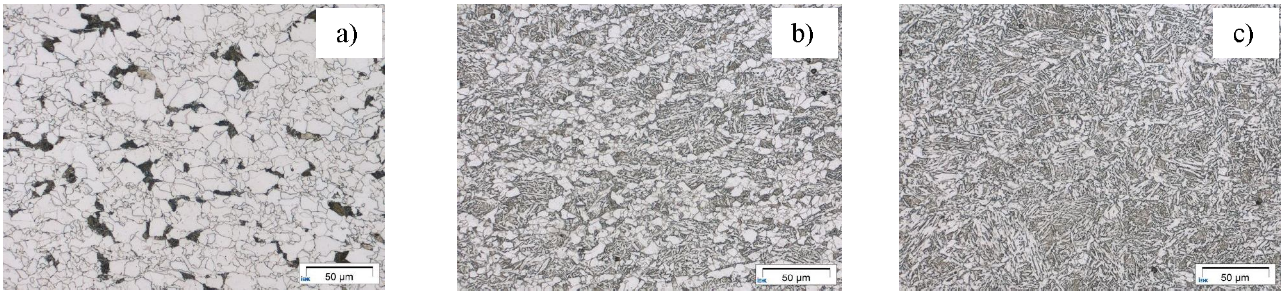


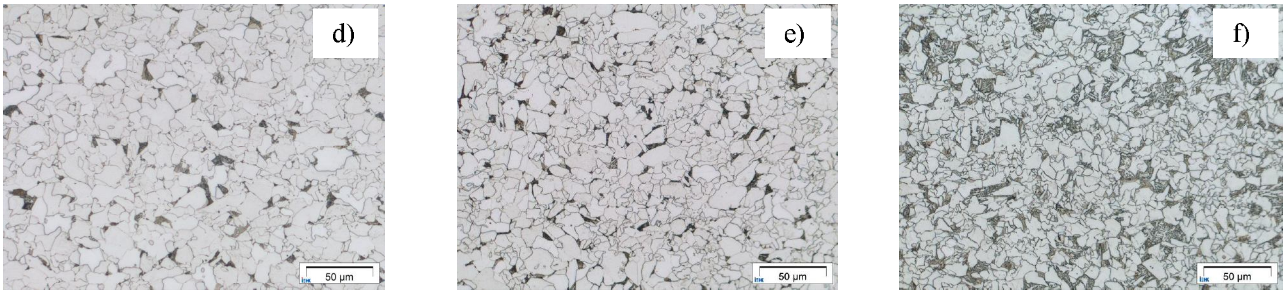
Fig. 3. The schedule of the double hit test at 970°C with a strain of 0.3 and its resulting stress-strain curve



a) $T_2 = 1250°C/\varepsilon_2 = 0.3/t_{pass2} = 30$ s, $T_3 = 1250°C/\varepsilon_3 = 0.3/t_{pass3} = 30$ s, $T_5 = 900°C/\varepsilon_5 = 0.6$, $t_{ROT} = 20$ s, $\dot{T}_{coil} = 0.1°C/s$

b) $T_2 = 1200°C/\varepsilon_2 = 0.2/t_{pass2} = 10$ s, $T_3 = 1150°C/\varepsilon_3 = 0.4/t_{pass3} = 10$ s, $T_5 = 900°C/\varepsilon_5 = 0.6$, $t_{ROT} = 10$ s, $\dot{T}_{coil} = 60°C/s$

c) $T_2 = 1200°C/\varepsilon_2 = 0.2/t_{pass2} = 10$ s, $T_3 = 1150°C/\varepsilon_3 = 0.4/t_{pass3} = 10$ s, $T_4 = 1100°C/\varepsilon_4 = 0.3/t_{pass4} = 10$ s, $T_5 = 900°C/\varepsilon_5 = 0.3$, $t_{ROT} = 6$ s, $\dot{T}_{coil} = 60°C/s$



d) $\varepsilon_5 = 0.3$, $\dot{T}_{coil} = 0.1°C/s$

e) $\varepsilon_5 = 0.3$, $\dot{T}_{coil} = 5°C/s$

f) $\varepsilon_5 = 0.3$, $\dot{T}_{coil} = 60°C/s$

Fig. 4. The microstructure investigated by light optical microscopy after various processing cycles. Only the varied underlined parameters in Table 2 are listed. a)-c) The Nb-concept steel d)-e) The V-concept steel

With a fixed retained strain (ε_5) of 0.3 and increasing cooling rates from ($\dot{T}_{coil}$) 0.1 to 60°C/s (Fig. 4d-f), larger amount of the hard phases with reducing amount of the soft ferrite is clearly revealed in the microstructure of the V-concept steel. The slowest cooling rate yield pure ferrite-pearlite microstructure. The intermediate cooling rate results in little hard phases while the maximum cooling rate changes the microstructure into ferrite-martensite/bainite.

3.3. Precipitation hardening of vanadium

The hardness value of the samples of the V-concept steel under different retained strain (ε_5) and cooling rate ($\dot{T}_{coil}$) is shown as a bar chart in Fig. 5. The hardness and the converted ultimate tensile strength (UTS) according to the DIN EN ISO 18265 standard are plotted in the doubled Y axes.

The lower hardness with decreasing cooling rate corresponds to less amount of hard phase together with the increasing amount of ferrite. However, it can be clearly seen that the lowest cooling rate of 0.1°C/s with larger amount of ferrite without hard phase results in higher hardness than that with the cooling rate of 1-5°C/s. This is quite clear that the precipitation is the most effective with this cooling rate and results in the most precipitation hardening and grain refinement.

The increase of the retained strain generally accelerate the ferrite formation and hence the grain refinement. By increasing it from 0.0 into 0.3, the strength of the samples under all cooling rates is improved. This can be explained by the fact that the grain refinement by RCR and TMCP as well as precipitation strengthening as well as the grain refinement by the precipitates work together. But surprisingly when the retained strain increases into 0.6, the resulting grain refinement and strengthening are not optimum in case of a cooling rate of 0.1°C/s as the increase in strength is very little. This can be assumed that premature strain induced precipitation might take place due to higher degree of deformation.

Figure 6 shows fine particles revealed by means of Energy Dispersive X-Ray Spectroscopy (EDX) in a carbon replica of the sample with the microstructure shown in Fig. 4d. The EDX analysis gives a hint that the precipitates shown in Fig.6 are either VN or V(C,N) or their mixture. As the sample is a carbon replica, it cannot be clearly identified, unfortunately, in which form they are.

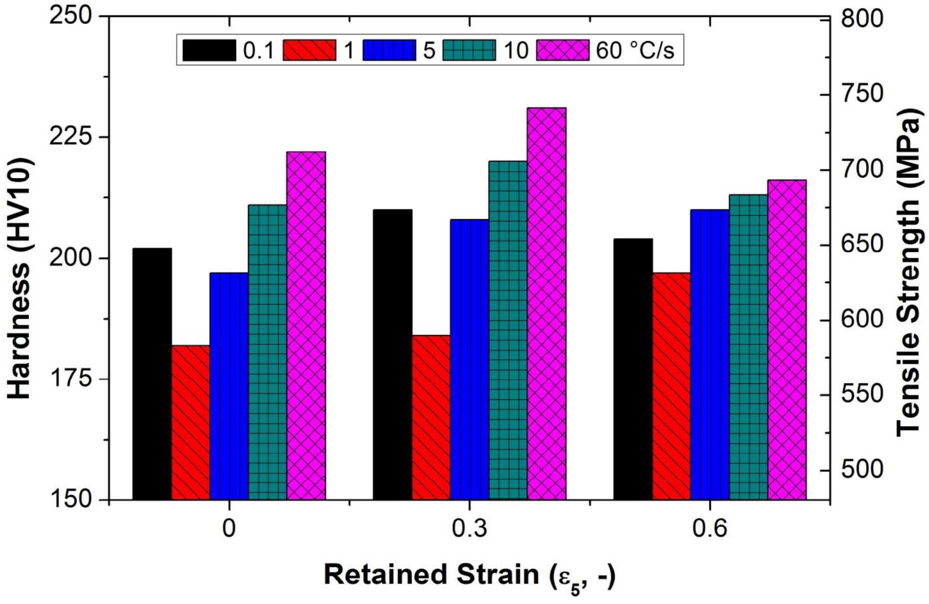


Fig. 5. A bar chart the different final cooling rate ($\dot{T}_{coil}$) and the retained strain (ε_5) in the last deformation step and their resulting hardness values

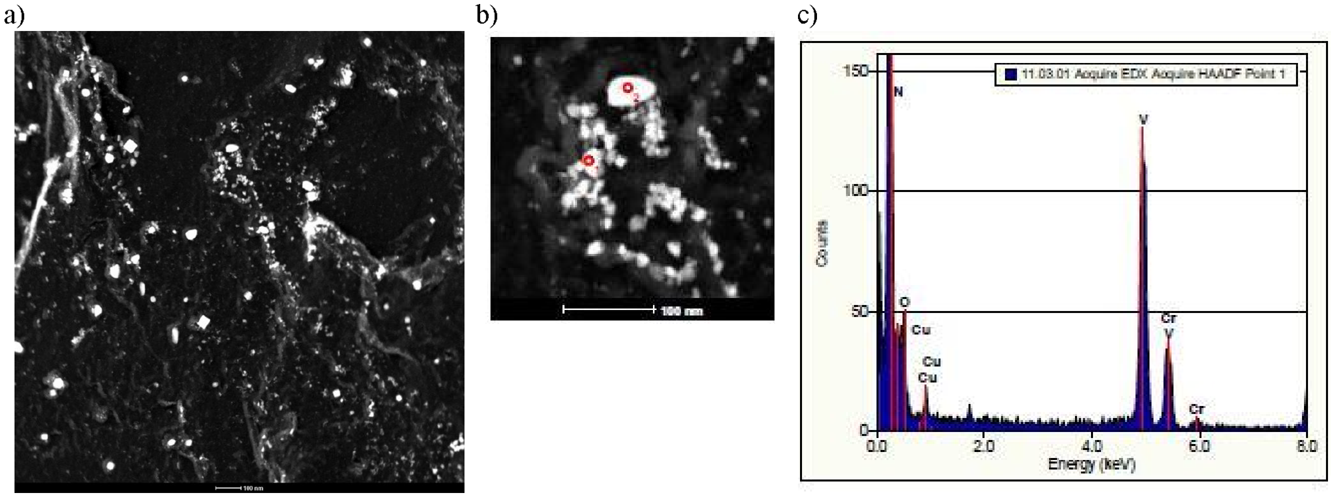


Fig. 6. Shows the precipitate in the sample in Fig. 4d investigated by means of STEM of its carbon replica and its EDX analysis at point 1 in Fig. 6b

3.4. The enhanced mechanical properties by hard phases

Compared with the sample with the cooling rate of 1 C/s, which is expected to inherit the least precipitation with mainly ferrite-pearlite microstructure, the quenched samples with the cooling rate of 60°C/s are significantly strengthened by harder phases, i.e., martensite and bainite, as it becomes a dual phase (DP) steel. A rough contribution of the strengthening by hard phases can be estimated by subtracting with the hardness of the sample with the cooling rate of 1°C/s. Therefore, the strengthening by the hard phases is in order of 150 MPa.

The higher cooling rates of 10 and 60°C/s with the retained strain of 0.6 result in, unfortunately less strength than that obtained by the retained strain of 0.3. This can be explained that the ferrite transformation kinetics is very much enhanced that the resulting ferrite fraction is higher and less fraction of harder phases can be induced.

4. Conclusions

The V-concept steel reported in this work exhibits a tensile strength as high as 670 MPa with ferrite-pearlite microstructure and as high as 740 MPa with dual phase structure while requiring a relatively low rolling force. An increase in the strength up to 80 MPa is the result of the facilitated precipitation during slow cooling alone, when compared with the case of higher cooling rates. Forming sufficient hard phases enhances the tensile strength as high as 150 MPa compared with the cases with ineffective precipitation with only ferrite-pearlite microstructure.

Acknowledgements

The authors would like to thank the financial support from Seed Fund Project for TGGS under the ERS scheme from RWTH Aachen University.

References

[1] T. Siwecki, G. Engberg, Recrystallization controlled rolling of steels, Proceedings of the International Conference "Thermomechanical Processing in Theory, Modelling and Practice", 121-144.

[2] N.A. Ahmad, A.A. Wheeler, W.J. Boettinger, G.B. McFadden, Solute Trapping and Solute Drag in a Phase-Field Model of Rapid Solidification, Physical Review E 58 (1998) 3436-3450.

[3] I. Loginova, J. Odqvist, G. Amberg, J. Ågren, The phase-field approach and solute drag modelling of the transition to massive γ → α transformation in binary Fe-C alloys, Acta Materialia 51 (2003) 1327-1339.

[4] P. Suwanpinij, Multi-scale modelling of hot rolled dual-phase steels for process design, RWTH Aachen University, Doctoral Thesis, 2012, opened access at http://darwin.bth.rwth-aachen.de/opus3/volltexte/2013/4343/