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1. Recent Vanadium Related Publications

Use of Vanadium Microalloyed Forging Steels in China

Vanadium microalloyed forging steels have been widely used in automotive components with ultimate tensile strength up to 1100 MPa as a replacement for traditional quenched and tempered (QT) steels, particularly in Western Europe, USA and Japan since the introduction of the first grade (49MnVS3) in Germany in the mid-1970's. The advantages of significant cost saving due to elimination of post forging heat treatment, straightening and stress relieving, reduced distortion, improved machinability, more consistent properties and lower material cost compared to QT alloy grades, as well as higher productivity are the driving forces for the application of these steels. The majority of these non-QT steels are produced from medium carbon steels with small additions of vanadium, which provides substantial precipitation strengthening to achieve the desired high strength.

In China, development of non-QT steels started in the early 1980s, however it is only recently that non-QT steels used in the automobile industry have received much attention. There have been increasing research and development projects since 2011. The Central Iron and Steel Research Institute (CISRI) has played a leading role in those activities, working with steel works, forging companies and automotive manufacturers, to develop domestic non-QT steels replacing QT steels and imported non-QT steels for making automotive components, such as connecting rods, crankshafts and steering knuckles. To promote use of non-QT steels in China, Vanitec and CISRI have co-operated on a three year research project since 2013. The following paper presents the results of other work carried out by CISRI and published in 2015.

Effect of Vanadium on the High-Cycle Fatigue Fracture Properties of Medium-Carbon Microalloyed Steels for Fracture Splitting Connecting Rod

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This paper was published in Materials & Design (Vol. 66, 2015, pages 227–234) and the authors gave details of the effect of vanadium additions up to 0.45% on the fatigue properties of new medium carbon microalloyed forging steels for the fabrication of fracture splitting connecting rods with excellent fatigue properties. 37MnSiV steel with three levels of vanadium and a conventional medium carbon microalloyed steel 38MnVS for comparison in the as-forged condition were used (Table 1).

It is well known that fatigue strength is generally the dominant engineering performance criterion in forged automotive components because it has been estimated that fatigue fracture contributes to approximately 90% of the mechanical service failures. This paper demonstrated that both fatigue strength and fatigue strength ratio increased with increasing V content for the four microalloyed steels (Fig. 1) and were also superior to those of 40Cr-QT and C70S6 steels.

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

Steel	C	Si	Mn	P	S	Cr	V	Al	N
V1	0.37	0.80	1.05	0.033	0.086	0.17	0.15	0.021	0.018
V1	0.38	0.77	1.07	0.032	0.085	0.18	0.28	0.017	0.017
V3	0.38	0.74	1.03	0.033	0.088	0.18	0.45	0.024	0.020
38MnVS	0.37	0.18	1.32	0.008	0.061	0.14	0.12	0.018	0.011

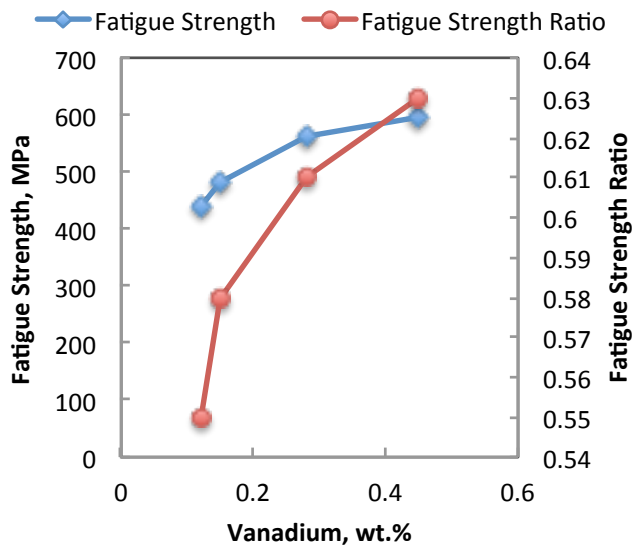


Fig. 1 Effect of V on fatigue strength and fatigue strength ratio

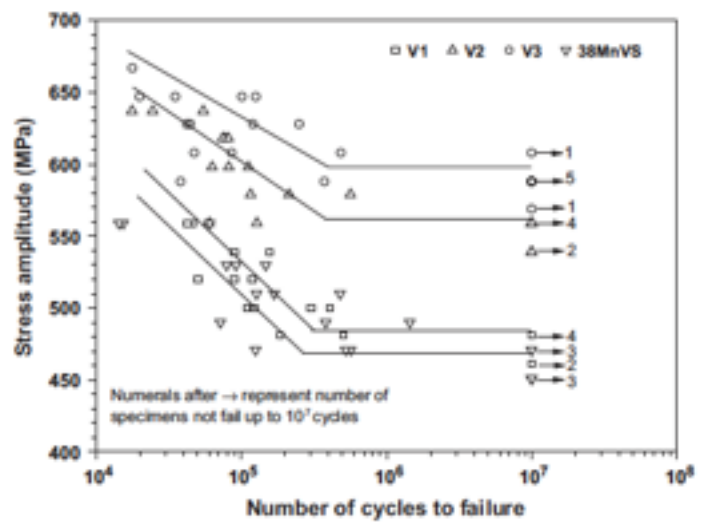


Fig. 2 S-N curves obtained from rotating bending fatigue for the tested steels

In addition, the S–N curve tended to shift to longer life and higher stress with increasing V content (Fig. 2). TEM study showed that 95% of the V(C,N) particles observed in the ferrite-pearlite microstructure of the test steels after forging were less 5 nm and these fine particles made a significant

contribution to precipitation strengthening. The authors suggested that vanadium improves the fatigue properties of the ferrite-pearlite forging steels mainly through its effect on precipitation strengthening.

Vanadium Microalloying Yields Significant Strength and Formability Advantages in Ferritic Steels

In recent years, there has been an increasing demand in the automobile industry for improving fuel efficiency, therefore weight reduction by application of high strength steel sheets for automobile components has become increasingly important. Since most automobile members made by steel sheets are formed by press forming, the steel sheets are required to have high strength as well as excellent formability. In addition, a key in-service requirement of automobile parts is high fatigue resistance. However, the challenge with many conventional high-strength steels is that as they become stronger, they also become less formable. Furthermore, high strength steels strengthened using additional hard phases, such as martensite and bainite, in a ferritic matrix exhibit poor resistance to fatigue crack initiation and propagation. Recently, a new type of hot rolled steel, which has a single-phase ferrite microstructure with a nano-precipitate

reinforced matrix, has been developed by Tata Steel Ijmuiden Bv (for example patent US2015/0099139 A1) and by JEF Steel Corporation (for example patent US2015/0030880 A1). In comparison with conventional high strength steels (HSLA and AHSS) with similar tensile strength, the new steels provide superior stretch-flange formability and better fatigue performance. In addition, the new steels have similar weld performance characteristics to HSLA steels and are easier to weld than AHSS grades. According to Tata Steel, it is claimed that the new steel will offer vehicle manufacturers the opportunity to make chassis components that are 10% lighter than more conventional products and reduce component manufacturing costs by up to 50%. Brief introductions of these two recent patents are given as below:

Automotive Chassis Part Made from High Strength Formable Hot Rolled Steel Sheet

Rolf Arjan Rijkenberg and David Neal Hanlon

Tata Steel Ijmuiden BV, Velsen-Noord, Netherlands

Tata Steel has recently developed a new high strength hot rolled steel sheet with an excellent combination of tensile strength and formability for chassis applications (for example patent US2015/0099139 A1). The steel sheet has a fine-grained and substantially single-phase ferritic microstructure (a ferrite fraction not lower than 97%) strengthened with a high density of fine precipitates containing vanadium, molybdenum and optionally niobium. Some examples of chemical composition of the new steel are given in Table 2. To achieve a desired strength level, the precipitation strengthening based on fine V-Mo- (optional Nb) carbides in ferrite is crucial and it is mainly influenced by vanadium content. Figure 3 shows that the

tensile strength (UTS) and precipitation strengthening (PS) of the steel sheets increase with increasing vanadium content. It is claimed that the precipitation strengthening effect of vanadium, in the 0.06Nb-Mo-V compositions, can be as high as ~1400 MPa/wt.%V, when used in combination with a sufficient amount of molybdenum. However, in the absence of molybdenum, the strengthening effect of vanadium is reduced to ~890 MPa/wt.%V. It is suggested that molybdenum is required to prevent coarsening of the fine carbide precipitates in order to achieve a high degree of precipitation strengthening.

Table 2 Chemical composition of the steels (1/1000 wt.%) and ferrite grain size (μm)

Steel	C	Si	Mn	P	S	Al	N	Mo	Nb	V	Grain Size
0.2Mo-V	25	19	1290	13	4	41	6	200	57	32	2.98
	26	19	1280	10	5	40	9	200	28	46	3.42
	51	19	1590	13	5	39	6	200	28	76	3.22
	48	100	1590	14	5	43	4	200	27	78	3.43
	61	100	1570	14	4	44	5	200	57	98	2.83, 2.95, 3.11, 3.26
	45	190	1620	13	5	46	6	200		190	4.06
0.5Mo-V	92	180	1600	14	5	41	6	510	57	180	2.02
	85	190	1600	13	5	47	6	510	28	190	2.20
	91	190	1560	15	5	48	4	500	54	240	2.49, 2.63

At similar tensile strength level, the new steel sheets provide superior stretch-flange formability compared to conventional hot rolled high strength low alloy (HSLA) steels and hot or cold rolled advanced high strength (AHSS) steels, including ferrite-bainite (FB), complex phase (CP), and dual phase (DP) steel sheets, as shown in figure 4. It is suggested that the single phase ferritic microstructure has little internal stresses and is free of carbon-rich phase constituents, which may act as potential nucleation sites for premature edge cracking during stretch-flanging of a high-strength steel with a tensile

strength higher than 550 MPa. In addition, the new steel sheets show enhanced fatigue performance, as a result of single-ferrite phase microstructure, compared to advanced high strength steels with multi-phases. The new steel sheets could offer a distinct benefit over current HSLA or AHSS steel sheets for applications, such as chassis and suspension parts, where an excellent combination of high strength, high stretch flange formability and good fatigue performance is required.

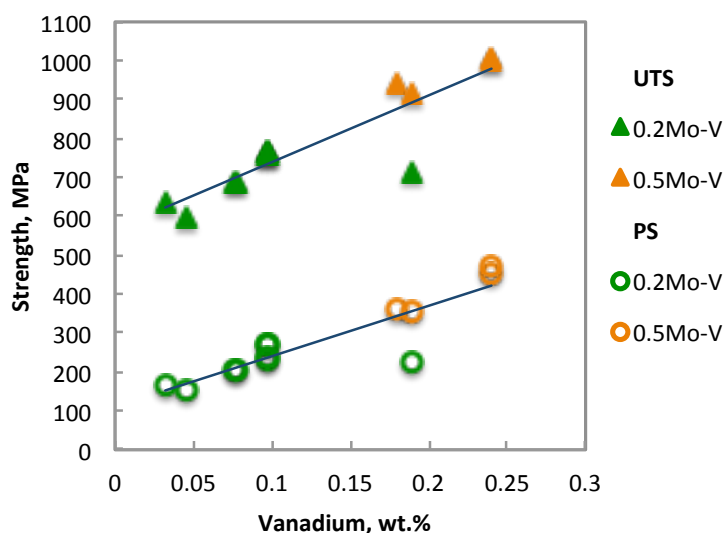


Fig. 3 Effect of vanadium on UTS and precipitation strengthening (PS)

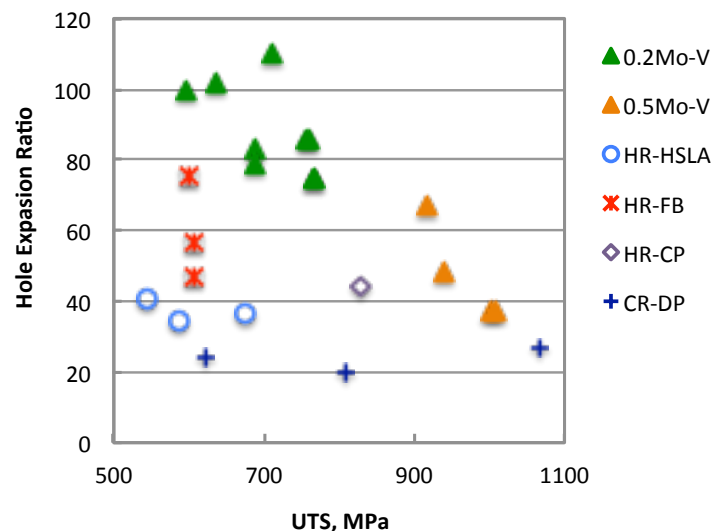


Fig. 4 The new single-phase vanadium microalloyed steel sheets show significantly higher hole expansivity than HSLA and AHS steel sheets

Vanadium also contributes to grain refinement, achieved by recrystallisation controlled rolling. In addition, it is claimed that the benefit of using a composition containing vanadium and molybdenum, that is free of niobium, is that it will lead to lower rolling loads in the hot strip mill, which will widen

the dimensional window. It is further claimed that the use of this niobium free composition will not only allow production of this steel grade on a conventional Hot Strip Mill (HSM), but also on a Compact Strip Production (CSP) line, leading to reduced energy input and lower processing costs.

High Strength Hot Rolled Steel Sheet for Automobile Members

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JEF Steel Corporation, Japan, has developed a new grade of V-Ti microalloyed high strength (UTS \geq 980MPa) hot rolled steel sheet having excellent bending workability for automobile structural members (for example patent US 2015/0030880 A1), ensuring both reduction in weight and improvement in formability of automobile members. This

development is based on a single-phase ferrite (area ratio of ferrite \geq 95%) microstructure with high strength and good workability containing fine (\leq 10nm) carbides of vanadium and titanium precipitated during/after austenite to ferrite transformation. Some examples of the steel compositions used in this patent are given in Table 3.

Table 3 Chemical composition of the hot rolled steel sheets, wt.%

Steel	C	Si	Mn	P	S	Al	N	Ti	V
A	0.081	0.01	1.05	0.01	0.0056	0.041	0.0038	0.158	0.10
B	0.079	0.02	0.85	0.02	0.0051	0.041	0.0029	0.186	0.12

The inventors have found that in order to obtain a tensile strength as high as 980 MPa, or more, in a single-phase ferrite, hot rolled steel sheet, it was extremely helpful to have a fine particle distribution of carbides in the ferrite phase. They indicated that to obtain the desired high tensile strength, additions of vanadium (\sim 0.10%) and titanium (\sim 0.15) in combination were necessary to form a high dispersion of fine ($<$ 10 nm) Ti-V carbides in the ferrite

matrix. It was difficult to produce a single-phase ferrite, hot rolled steel sheet with the desired high tensile strength by using only Ti carbides or V carbides.

The patent shows that vanadium is effective for enhancing the strength of the steel sheet by forming fine Ti-V composite carbides in ferrite, and titanium promotes the precipitation of vanadium.

To produce a high strength hot rolled steel sheet having excellent bendability, a ferrite single-phase microstructure is preferable. The inventors suggested that when a secondary phase, such as bainite, martensite, cementite or pearlite, is incorporated into the ferrite microstructure, voids are generated at interfaces between the ferrite phase and the secondary phase having different hardness from each other during punching, which deteriorates the bending workability of the steel sheet. Therefore, the second phase should be less than 5% to ensure good workability. In addition, the patent showed that an average ferrite grain size exceeding 8 μm more likely results in mixed grain size

microstructures. Then, in such mixed grain size microstructures, coarse ferrite grains are more susceptible to stress concentration during bending working, which leads to a significant reduction in the bending workability of the steel sheet. Accordingly, the upper limit of the average grain size of the ferrite phase is to be $\leq 8 \mu\text{m}$.

In addition, it is claimed that the hot rolling process used in manufacturing the high strength ferrite single-phase hot rolled steel sheet is virtually similar to the ordinary process for manufacturing general steel grades.

Stress–Strain Behavior of Ferrite and Bainite with Nano-Precipitation in Low Carbon Steels

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This research work was published in *Acta Materialia* (Vol. 83, 2015, pages 383–396). Naoya Kamikawa and the co-authors systematically investigated stress–strain behavior of ferrite and bainite containing nano-sized vanadium carbides in a low carbon steel with a chemical composition of Fe–0.10%C–0.22%Si–0.83%Mn–0.014%P–0.014%S–0.003%N–0.001%Ti–0.288%V. A cast ingot of the steel prepared by vacuum melting was hot-rolled at the finish rolling temperature of $\sim 940^\circ\text{C}$. Hot-rolled samples were homogenized in Ar atmosphere at 1180°C for 24h, and were used as starting materials.

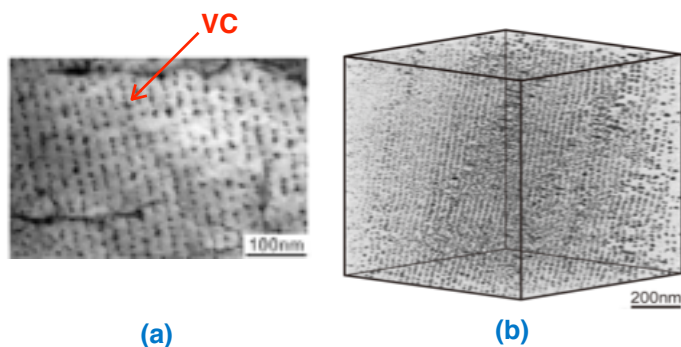


Fig. 5 (a) Bright field TEM image of the sample isothermally transformed at 690 C for 300s, showing periodic sheets on which vanadium carbides are dispersed. (b) 3D Reconstructed Image: VC (dark contrast), ferrite (transparent)

The starting materials were heat-treated in a vacuum furnace at 1200°C for 600s for austenitization and solution treatment, and immediately isothermally transformed at 690°C or 600°C in a salt bath for different holding periods in the range from 20s to 172.8 ks (48 h), followed by water quenching.

The isothermal treatment temperature of 690°C was chosen to obtain ferrite structure with interphase precipitation of nano-sized VC particles, while the temperature of 600°C was chosen to obtain bainite structure with precipitation of VC particles by aging.

For isothermal transformation at 690°C , the ferrite transformation was almost completed after the holding for 300s with an average ferrite size of $\sim 29\mu\text{m}$. There was no significant grain growth of ferrite during long time holding until 48h. TEM observation revealed interphase precipitation of VC in the ferrite matrix with an average sheet spacing of $\sim 20\text{--}30 \text{ nm}$ and particle size of 4.5 nm for holding time of 300s. Fig. 5a shows a TEM image of VC particles precipitated in the ferrite matrix. Figure 5b is a 3-D reconstructed image using the FIB/FE-SEM technique showing the interphase precipitation of VC. The average particle size increases with increasing the holding period at 690°C .

For isothermal transformation at 600°C , the bainitic transformation was almost completed after holding for 3h. The average width of bainitic lathes was measured to be $\sim 1 \mu\text{m}$, and the dislocation density inside the bainitic ferrite was measured to be $1.2\text{--}1.6 \times 10^{14} \text{ m}^{-2}$ in all cases.

TEM study revealed that there were no precipitates after 300s holding at 600°C , indicating that carbon and vanadium atoms were still supersaturated in the bainitic ferrite matrix. However, prolonged holding for 3h, or a longer period, led to precipitation of nano-sized VC particles, indicating that the nano-sized VC particles were precipitated by aging during long-time holding after bainite transformation. TEM observation showed that the VC particles were precipitated on dislocations, lath boundaries and within the bainitic ferrite matrix. The average VC particle size was 3.2 nm after holding for 3h and was slightly coarsened to 5.0 nm by the 48h holding.

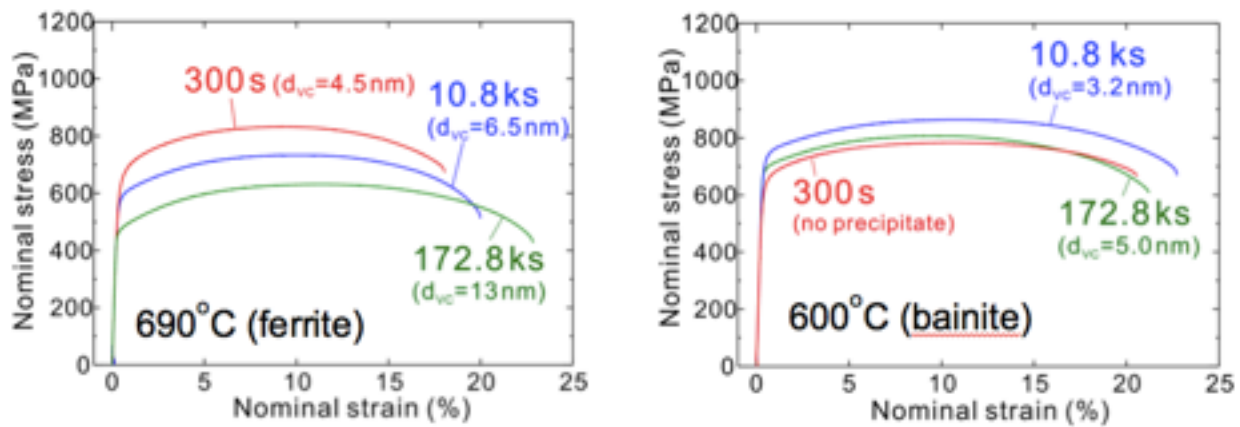


Fig. 6 Nominal stress–strain curves of the samples isothermally transformed at 690 °C and 600 °C for different holding periods. The average diameter of vanadium carbides is indicated in the figure.

Tensile tests (Fig. 6) showed that for the ferrite sample with the VC diameter of 4.5 nm, transformed at 690°C for 300s, the yield stress was high (640 MPa), but gradual work hardening took place after yielding, leading to a UTS of 830 MPa. For the samples dominated by bainite structure, the yield stress was very high, even in a sample with no precipitates, but work hardening was relatively small in all cases. In addition, the change in strength with increasing the holding period was not as significant as that of the ferrite samples. In samples with an identical diameter of VC particles, the yield stress of the ferrite sample was lower than that of the bainite sample, but the

work hardening was larger in the ferrite than in the bainite in the beginning of tensile deformation, leading to a similar flow curve in the later stage of deformation. It is interesting to note that the elongation in ferrite and bainite samples is relatively large, as high as 10% in uniform elongation and 20% in total elongation, almost identical and constant, independent of transformation temperature as well as holding period. This work demonstrates that sufficient ductility is maintained in both ferrite and bainite steels, despite the high strength, due to increase of work hardening and uniform distribution of dislocations achieved with fine VC precipitation.

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3. Calendar of Technical Conferences and Seminars

2015-2016	Events
10-12 Feb. 2016 Ranchi, India	4 th International Conference on Thermomechanical Simulation and Processing of Steel (Simpro'16)
7 Apr. 2015 London, UK	89 th Vanitec Projects and Publications Panel Meeting
16-19 May 2016 Pittsburgh, USA	The Iron & Steel Technology Conference and Exposition (AISTech 2016)
29 May - 2 Jun. 2016 Graz, Austria	International Conference on Processing & Manufacturing of Advanced Materials (THERMEC2016)
23-27 Oct. 2016 Salt Lake City, USA	Materials Science & Technology (MS&T) 2016
16-18 Dec. 2016 Chengdu, China	The 1 st International Conference on Automotive Steel (AutoSteel 2016)

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