

# Development of High Strength Micro-alloyed Steel for Commercial Vehicles with Excellent Low-temperature Toughness

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## Abstract

*In recent years, the reduction of CO<sub>2</sub> emissions has become a critical global issue in the effort to mitigate climate change. Consequently, there is increasing demand for steel materials that eliminate the need for post-forging heat treatment, thereby reducing CO<sub>2</sub> emissions during the manufacturing of automotive components. Micro-alloyed steels for hot forging applications enable the omission of quenching and tempering processes after forging and have been widely adopted in the production of various automotive parts. However, their application to the suspension components in large commercial vehicles, such as trucks and buses, remains limited. One of the primary challenges is their insufficient toughness at low temperatures. To address this issue, Nippon Steel Corporation has investigated the factors contributing to reduced low-temperature toughness and has successfully developed a high-strength micro-alloyed steel with enhanced low-temperature properties. This paper presents previous development efforts related to micro-alloyed steels and reports on the fundamental studies aimed at improving their low-temperature toughness.*

## 1. Introduction

Since the adoption of the “Paris Agreement” at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change in 2015, which set the goal of limiting the global average temperature increase to below 2°C, there has been a strong demand for improved fuel efficiency and reduction of carbon dioxide (CO<sub>2</sub>) emissions in automobiles. While electric vehicles are attracting attention due to their zero CO<sub>2</sub> emissions during driving, significant CO<sub>2</sub> is also emitted throughout the entire life cycle of automobiles, including material procurement, manufacturing, disposal, and recycling. Therefore, reducing CO<sub>2</sub> emissions across the entire life cycle has become increasingly important. Most mechanical structural components of automobiles are manufactured from steel through hot or cold forging, heat treatment, machining, and, if necessary, surface hardening processes such as induction hardening or carburizing and quenching. Among these, heat treatment processes are major sources of CO<sub>2</sub> emissions. Consequently,

there is a growing need for steel materials that enable the omission of heat treatment processes to reduce CO<sub>2</sub> emissions during component manufacturing. Nippon Steel Corporation has been developing steels designed to reduce heat treatment processes for various automotive components.

This paper introduces, as part of these efforts, Nippon Steel’s micro-alloyed steel for hot forging. This steel enables the omission of quenching and tempering (heat treatment) after hot forging, and efforts have been made to achieve higher strength and toughness to expand its application to a wider range of components, thereby realizing the omission of heat treatment for many automotive parts.<sup>1-8)</sup> However, many suspension components for large commercial vehicles such as trucks and buses have not yet adopted micro-alloyed steels. Compared to passenger vehicles, commercial vehicles are heavier and subjected to greater dynamic and impact loads, requiring a balance of high strength and toughness (impact value). Additionally, considering use in cold regions at high latitudes, it is neces-

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sary to ensure low-temperature toughness (impact value) at  $-50^{\circ}\text{C}$ . In response to these requirements, we have developed a high-strength, micro-alloyed steel with excellent low-temperature toughness for commercial vehicles, and this paper describes our efforts in this area.

## 2. Review of the Development of Micro-alloyed Steel for Hot Forging

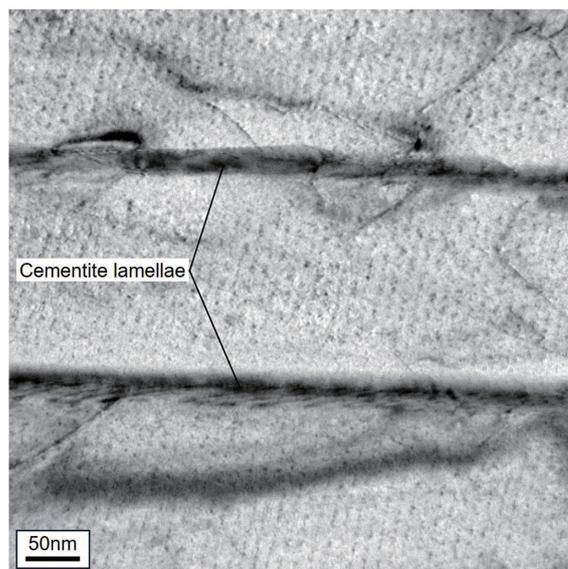
### 2.1 Advantages of micro-alloyed steel

Many mechanical structural components, such as automotive engine parts, suspension components, and construction machinery parts, have traditionally been manufactured as hot-forged products using carbon steel or alloy steel. Conventionally, these components are produced through a process involving hot forging for shaping, quenching and tempering (heat treatment) to refine the steel microstructure, and machining for dimensional accuracy. Micro-alloyed steel for hot forging is a steel material that satisfies the required mechanical properties without the need for quenching and tempering after hot forging. The application of micro-alloyed steel not only reduces costs by eliminating heat treatment, but also eliminates heat treatment distortion, thereby removing the need for straightening after tempering and reducing the amount of machining required. Furthermore, process simplification leads to shorter lead times and improved productivity, resulting in additional cost reductions. Moreover, omitting heat treatment contributes to energy savings and  $\text{CO}_2$  emission reductions, which has rapidly increased expectations for micro-alloyed steel from the perspective of global environmental conservation.

### 2.2 Strengthening of micro-alloyed steel

Micro-alloyed steel was first developed in Europe (West Germany) in the 1970s.<sup>9)</sup> The initial micro-alloyed steels were carbon steels containing more than 0.45 mass% C, with small additions of vanadium (V) or niobium (Nb) to enable the omission of heat treatment. After hot forging and cooling, the microstructure of these steels consists mainly of pearlite and ferrite-pearlite. The micro-alloyed V, dissolved in the austenite matrix during high-temperature heating above  $1200^{\circ}\text{C}$  prior to forging, precipitates as carbides at the austenite/ferrite interface during the transformation from austenite to ferrite or pearlite upon cooling after forging. This periodic, point-like precipitation along the moving interface is known as “interphase precipitation”.<sup>10-14)</sup> The carbides precipitated by interphase precipitation are nanometer-sized and strengthen the ferrite in both the proeutectoid ferrite and the pearlitic ferrite. **Figure 1** shows a TEM image of V carbides precipitated in the ferrite of a pearlite structure, where the periodic, point-like precipitates in the ferrite are V carbides formed by interphase precipitation.

By utilizing this precipitation phenomenon, it is possible to achieve strength equivalent to or greater than that of quenched and tempered carbon steel, even when the micro-alloyed steel is simply cooled after hot forging. In Japan, in particular, the demand for lighter automotive components to improve fuel efficiency has driven the development of higher-strength micro-alloyed steels.<sup>4-8)</sup> Methods to increase the precipitation strengthening effect of interphase precipitation include increasing the amount of precipitates and reducing their size.<sup>15-17)</sup> Specifically, the former can be achieved by increasing the addition of carbide-forming elements (V, Ti, Nb, Mo, etc.) within the solubility range during pre-forging heating. The latter can be achieved by co-adding multiple carbide-forming elements and promoting ferrite or pearlite transformation at lower tempera-



**Fig. 1** Transmission electron microscope image of vanadium carbides precipitated in ferrite for pearlite microstructure

tures. Since smaller interphase-precipitated carbides result in higher strength, these fine carbides are considered to contribute to ferrite strengthening via the Ashby-Orowan mechanism.

In addition to precipitation strengthening by interphase precipitation, other strengthening methods include solid solution strengthening of ferrite by increasing Si content, increasing the pearlite fraction (dispersion strengthening by cementite) by increasing C content, and refining the pearlite lamellar spacing (microstructural refinement strengthening) by increasing Cr content.

Although these strengthening methods ensure the strength of micro-alloyed steel, its toughness is inferior to that of quenched and tempered steel. Therefore, its application has been limited to engine components such as crankshafts and connecting rods,<sup>7,8)</sup> which do not require high toughness, and improving toughness has been essential for expanding the application of micro-alloyed steel.

### 2.3 Toughening of micro-alloyed steel

During hot forging, the heating temperature exceeds  $1200^{\circ}\text{C}$ , resulting in the growth of coarse austenite grains, which transform into coarse pearlite during cooling after forging. In ferrite-pearlite microstructures dominated by pearlite, microstructural refinement is effective for improving toughness (impact value). Methods for refining ferrite-pearlite microstructures include utilizing the pinning effect of precipitates to prevent austenite grain coarsening during forging heating, and promoting intragranular ferrite transformation by using precipitates as nucleation sites for ferrite within austenite grains.<sup>1-6,18)</sup>

To utilize the pinning effect of precipitates, it is necessary for a large number of fine precipitates to remain undissolved as pinning particles in the austenite matrix during high-temperature heating in hot forging. Common pinning particles include MnS and TiN.

MnS precipitates between secondary dendrites during solidification, forming relatively large particles with diameters ranging from several micrometers to several tens of micrometers. These particles are elongated during hot rolling, and their cross-sectional diameter perpendicular to the rolling direction is about  $1\ \mu\text{m}$ , depending on the rolling reduction. Fine MnS particles smaller than  $0.5\ \mu\text{m}$  dis-

solve during high-temperature heating for hot forging, but this accounts for only about 2% of the total volume, so most of the precipitated MnS can be used as pinning particles. The finer the MnS pinning particles, the more effective they are in preventing austenite grain coarsening during forging heating. To refine MnS, a large number of oxide particles, which serve as nucleation sites for MnS precipitation, are dispersed. Observation of MnS in Al-deoxidized steel reveals that composite oxides consisting of  $\text{Al}_2\text{O}_3$  surrounded by MnO exist, indicating that MnS preferentially precipitates on oxides. By dispersing a large number of easily precipitated oxides, MnS can be finely dispersed. Since MnO has sulfide capacity, it forms  $\text{Mn}(\text{O},\text{S})$ , which acts as the actual nucleation site for MnS precipitation. When Al is added,  $\text{Al}_2\text{O}_3$ -MnO is formed, increasing the nucleation sites for MnS and resulting in finer dispersion. However, excessive Al addition reduces the oxygen content in the steel, preventing the formation of MnO, which is a weak deoxidation oxide, and thus decreases the nucleation sites for MnS, resulting in coarser MnS.<sup>3-5, 18)</sup>

In addition to finely dispersed MnS, the combined use of TiN provides a significant effect in preventing austenite grain coarsening during forging heating. For large forged components subjected to high-temperature heating above 1200°C, micro-alloyed steel utilizing both MnS and TiN is effective in refining the austenite grains during forging heating.<sup>4, 5, 18)</sup>

In micro-alloyed steel, MnS not only acts as a pinning particle for austenite grains but also serves as a nucleation site for intragranular ferrite transformation. Intragranular ferrite forms within austenite grains, and by promoting its formation, the ferrite-pearlite microstructure is refined, significantly improving toughness. MnS is present within intragranular ferrite, and VN precipitates on MnS. Observation of specimens quenched during ferrite transformation reveals that intragranular ferrite nucleates on VN precipitated on MnS.<sup>19)</sup> The Baker-Nutting orientation relationship exists between VN and intragranular ferrite, and this high lattice coherency is considered one of the main reasons why VN precipitated on MnS acts as a nucleation site for intragranular ferrite.<sup>20)</sup>

By combining these technologies, the strength and toughness of micro-alloyed steel have been improved, making it suitable for automotive suspension components. However, as mentioned earlier, many commercial vehicle suspension components require high strength and toughness (impact value) to withstand large dynamic and impact loads, and in many cases, the low-temperature toughness

(impact value) of micro-alloyed steel does not meet the requirements, limiting its application. In response to this situation, we have developed a high-strength micro-alloyed steel with excellent low-temperature toughness for commercial vehicle suspension components.

### 3. Development of High-strength Micro-alloyed Steel with Superior Low-temperature Toughness

#### 3.1 Investigation of the effect of Ti addition on the toughness of micro-alloyed steel

In micro-alloyed steel, titanium (Ti) is sometimes added to either enhance or reduce toughness. For the former, as described in the previous section, TiN is precipitated as a pinning particle to refine the ferrite-pearlite microstructure, thereby improving the toughness of automotive suspension components.<sup>1, 3-5)</sup> For the latter, TiC or (V,Ti)C is precipitated to strengthen the ferrite in the proeutectoid ferrite or pearlite, resulting in reduced toughness, which is desirable for cracking connecting rods.<sup>7, 8, 21)</sup> A cracking connecting rod is manufactured by forging the cap and rod sections as a single piece and then fracturing (cracking) them apart. Since the fractured surfaces are used to fasten the connecting rod to the crankshaft, a brittle fracture surface is required, and thus low toughness is necessary for the steel.

To understand these opposing phenomena, the effect of Ti addition on the toughness of micro-alloyed steel was investigated. Test steels were prepared by adding 0.01% and 0.02% Ti to a base steel of 0.36 mass% C–0.14% V, as well as a Ti-free variant. After vacuum melting, round bars with a diameter of 68 mm were produced. The bars were heated to 1200°C and held for 15 minutes, then hot-forged to a thickness of 20 mm in the radial direction and air-cooled on a wire mesh. **Figure 2** shows the microstructures at the center of the forged bars. All samples exhibited ferrite-pearlite microstructures dominated by pearlite, and the addition of Ti resulted in microstructural refinement. Charpy impact test specimens were prepared from near the center of the forged bars, aligned along the longitudinal direction. According to JIS Z 2242, the specimen height was 10 mm, width 5 mm (sub-size), with a U-notch of 5 mm depth and a notch root radius of 1 mm. Instrumented Charpy impact tests were conducted at temperatures ranging from –80°C to 100°C. The impact value, defined as the absorbed energy required to fracture the specimen divided by the cross-sectional area, was used as an indicator of toughness.

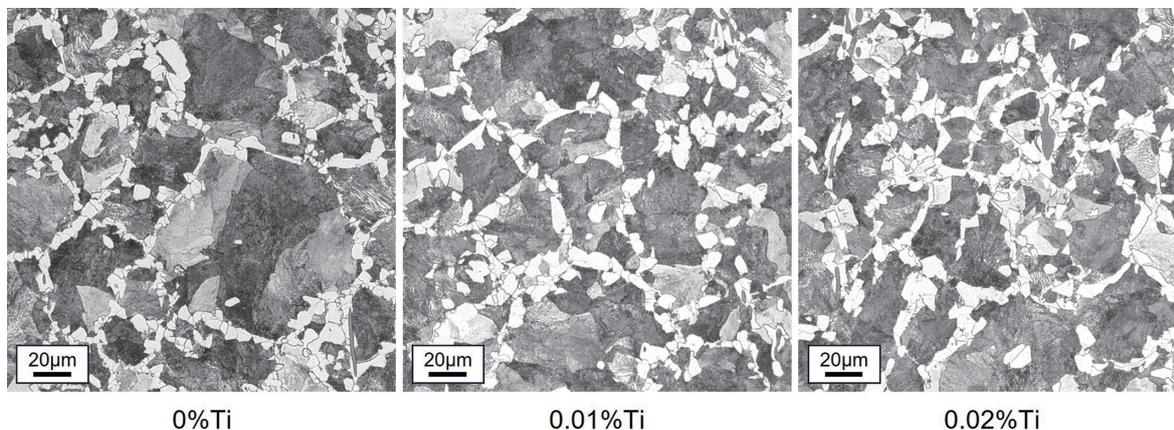


Fig. 2 Microstructures after hot forging and cooling

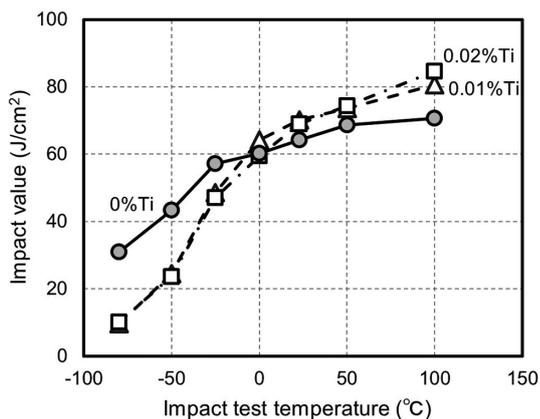


Fig. 3 Change in impact values with impact test temperature

Figure 3 shows the variation of impact value with test temperature. In all cases, the impact value decreased with decreasing test temperature, and the Ti-added steels exhibited a marked decrease. Notably, above 0°C, the addition of Ti increased the impact value, whereas below 0°C, the addition of Ti significantly decreased the impact value.

### 3.2 Investigation of the factors causing the decrease in low-temperature toughness due to Ti addition

To investigate the factors responsible for the decrease in low-temperature toughness caused by Ti addition, the absorbed energy obtained from the instrumented Charpy impact test was separated into crack initiation and crack propagation energies based on the load-time curve. Figure 4 shows the crack initiation and propagation energies at -50°C. In all cases, the proportion of crack initiation energy in the total absorbed energy was high, and the addition of Ti significantly reduced the crack initiation energy. To further investigate the cause of the decrease in crack initiation energy, the fracture surfaces after impact testing at -50°C were observed using a scanning electron microscope to identify the fracture origin. Figure 5 shows the area around the fracture origin and the morphology at the origin for the Ti-added steel. Regardless of Ti addition, river patterns indicative of cleavage fracture were observed near the fracture origin. However, only in the Ti-added steel, TiN particles on the order of micrometers were observed at the fracture origin. These results indicate that the fracture origin in the Ti-added steel was coarse TiN, and that the TiN fractured at a lower stress than the cleavage stress of the pearlite matrix, resulting in a significant decrease in crack initiation energy.

Based on these findings, a high-strength micro-alloyed steel with excellent low-temperature toughness was developed, enabling the application of micro-alloyed steel to large commercial vehicle suspension components.

## 4. Conclusion

This paper has introduced past development cases of Nippon Steel's micro-alloyed steel for hot forging, and discussed the fundamental studies on the newly developed high-strength micro-alloyed steel with superior low-temperature toughness. The developed steel has been adopted for mass production as a material for large commercial vehicle suspension components, contributing to the reduction of CO<sub>2</sub> emissions by eliminating heat treatment processes.

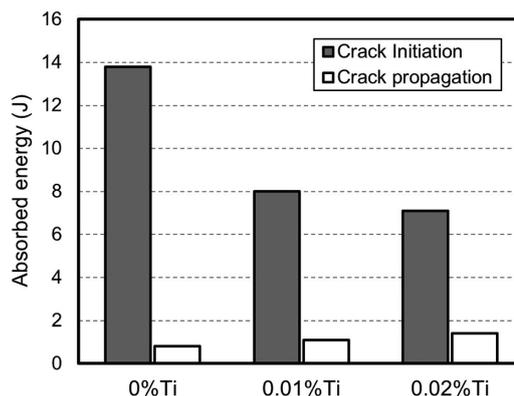


Fig. 4 Crack initiation and propagation energy in impact tested at -50°C

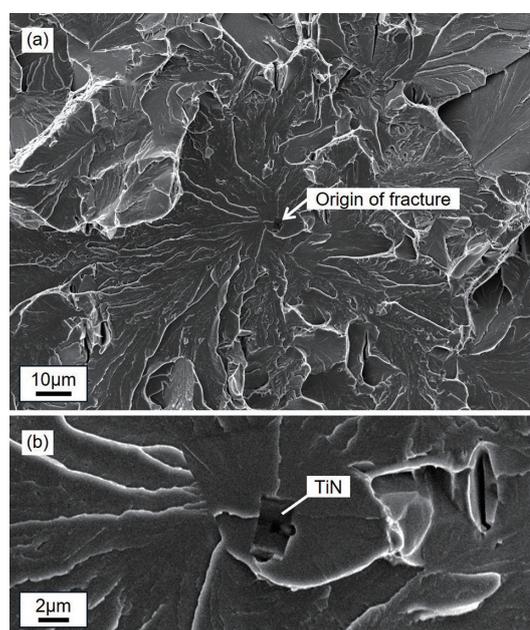


Fig. 5 Fracture surface morphology of titanium-containing materials, (a) around the fracture origin, (b) origin of fracture

## References

- 1) Koyasu, Y., Takada, H., Takahashi, T., Takeda, H., Ishii, N.: Seitetsu Kenkyu. (337), 41 (1990)
- 2) Koyasu, Y., Kanisawa, H., Ochi, T., Yanase, M., Takada, H., Naito, K., Ishikawa, F.: Shinnittetsu Giho. (343), 30 (1992)
- 3) Takada, H., Ochi, T., Ishikawa, F., Yasuda, S., Maeda, C.: Bulletin of the Japan Institute of Metals. 32 (6), 429 (1993)
- 4) Takada, H., Koyasu, Y.: Shinnittetsu Giho. (354), 6 (1994)
- 5) Takada, H., Koyasu, Y.: Kinzoku. 65 (3), 199 (1995)
- 6) Kanisawa, H., Ochi, T.: Shinnittetsu Giho. (371), 23 (1999)
- 7) Sano, N., Hasegawa, T., Iida, Z., Takada, K.: Materia Jpn. 46 (1), 28 (2007)
- 8) Hasegawa, T., Sano, N.: J. Jpn. Soc. Heat Treat. 47, 343 (2007)
- 9) Frodl, C., Randak, A., Vetter, K.: Härtereitechnische Mitteilungen. 29 (3), 169 (1974)
- 10) Morrison, W.B.: Journal of the Iron and Steel Institute. 201, 317 (1963)
- 11) Davenport, A.T., Honeycombe, R.W.K.: Proceedings of the Royal Society of London. Series A. 322, 191 (1971)
- 12) Edmonds, D.V.: Metallurgical Transactions. 4, 2527 (1973)
- 13) Freeman, S., Honeycombe, R.W.K.: Metal Science. 11, 59 (1977)
- 14) Honeycombe, R.W.K.: Metal Science.
- 15) Funakawa, Y., Shiozaki, T., Tomita, T., Yamamoto, T., Maeda, E.: ISIJ International. 44, 1945 (2004)

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- 16) Daitoh, Y., Torizuka, S., Hanamura, T.: Tetsu-to-Hagané. 97 (9), 480 (2011)
- 17) Kamikawa, N., Abe, Y., Miyamoto, G., Funakawa, Y., Furuhashi, T.: ISIJ International. 54, 212 (2014)
- 18) Takada, H.: Doctoral Dissertation, Graduate School of Engineering, Hokkaido University. (2002)
- 19) Ochi, T., Takahashi, T., Takada, H.: Iron and Steel Maker. February, 21 (1989)
- 20) Ishikawa, F., Takahashi, T., Ochi, T.: Metallurgical and Materials Transactions. 25A, 929 (1994)
- 21) Aihara, K., Yamada, Y., Kondo, T., Gejima, F., Yamashita, D., Ehira, A., Matsugasako, R.: 2015 JSAE Annual Congress (Spring) Technical Sessions Proceedings. S368, 1943 (2015)



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