Microalloyed steel has become a standard material for line pipe, automotive and construction use. Since the end of the 1960s the development of these steel grades has resulted in ever-increasing strength levels combined with excellent toughness and welding properties. However, until recently, the potential of microalloyed high-strength steel has not been used to the same extent in structural hot-rolled steel sections or in forged engineering steels. However, customers and steel producers are showing growing interest in this proven technology and this paper provides the metallurgical background and examples for the use of niobium microalloyed steel in hot-rolled beams, rebar and forgings.

Niobium has a threefold influence on the mechanical properties of steel: grain size refinement during thermomechanical hot forming, lowering the $\gamma \rightarrow \alpha$ transition temperature ($\text{Ar}_3$), and precipitation hardening. Grain refinement is the only mechanism that simultaneously increases strength, toughness and ductility. This makes Nb the most effective microalloying element, even if added in small quantities, as shown in Figure 1.

The grain refining effect of Nb is due mainly to delaying or preventing recrystallisation in the last hot forming steps. Flattened grains and a high dislocation density of the austenite enhance ferrite nucleation. By lowering the $\gamma \rightarrow \alpha$ transformation temperature, Nb simultaneously enhances the ferrite nucleation rate and reduces the grain growth rate, and the combined effect leads to a particularly fine-grained transformation structure. In order to make optimum use of its metallurgical potential Nb has to be in solid solution by heating at an adequate reheating furnace temperature to dissolve Nb(C,N) precipitates before hot forming. The solubility of Nb(C,N) is given in Figure 2.

BEAMS

H beams are taken as an example of hot-rolled sections, as they represent a large part of this product group. When compared to flat products, due to the greater loads involved in producing the complex shape, beams require higher rolling temperatures where the flow stress is lower. In addition, deformation is rather inhomogeneous, ranging from about 4% in the web to flange transition area, to 50–80% in the web and flanges. Therefore, thermomechanical treatment, applying well-defined temperatures and hot-forming schedules is often difficult to realise. Hot rolling is usually performed in the recrystallisation-controlled rolling (RCR) mode in order to obtain a homogeneous fine grain size and high strength in the final product. Beams are usually rolled in the upper austenite region after reheating to 1,250°C in order to benefit from the...
The contribution of different microalloying elements to precipitation hardening can be taken from Figure 1, highlighting that Nb is the most effective alloying element even when added in small quantities.

With higher strength steels and/or flange thickness above 20mm, hot rolling in the upper austenite region is not sufficient to meet the specified strength. In addition, beams may have to match toughness requirements at -20°C or even lower temperatures, such as for offshore application. Further grain refinement is the most effective method to fulfill these requirements and can be achieved by lower finish rolling temperatures.

Figure 3 gives the grain sizes and toughness (in terms of Charpy impact energy) in the flange for various distances from the web after conventional hot rolling applying a 1,040°C FRT and for the so-called High Temperature Process (HTP) concept with an FRT of 960°C. For HTP hot rolling start temperature was 1,080°C as in conventional processing then after the 5th pass, a delay time of around 90 seconds was introduced in order to allow the hottest parts of the beam to cool down below 1,000°C. The last two passes were performed with a finish rolling temperature of ≤960°C. This hot forming below the austenite recrystallisation stop temperature leads to the fine microstructure of the HTP beam. The chemical composition is given in Table 1. The mechanical properties given in Table 2 correspond to the web to flange transition area, ie, the most critical position.

**REINFORCING BAR (REBAR)**
Formable and weldable high strength rebar is produced by fast cooling after rolling or by microalloying.
Vanadium has so far typically been used for this purpose, but given the high price of vanadium, use of Nb is being reconsidered. Use of low carbon content and Nb alloying provide a good combination of high strength, excellent ductility, toughness and weldability. Earthquake resistance and low temperature properties for cryogenic applications such as liquid natural gas (LNG) storage tanks (-100 to -125°C) are particularly improved by use of Nb metallurgy.

Conventional production applies air cooling after hot rolling, which is typically completed at 1,000–1,050°C and strength is mainly controlled by the C and Mn contents. Lowering the C content will improve toughness while the associated loss in strength can be compensated for by microalloying. Figure 4 gives the yield strength for different Nb and V additions in air-cooled 0.18% carbon steel having a ferrite-pearlite microstructure [2]. About 0.03% Nb will generate a yield strength of about 480MPa. For the same effect, more than 0.06% V will be necessary. Nb will also boost the effect of V when used in combination.

European specifications limit the carbon content to ≤0.24% and the carbon equivalent CE to ≤0.52. Therefore, reinforcing bar producers generally apply water cooling followed by self-tempering after hot rolling, as in the TEMPCORE® process. In such a process, microalloying is limited to high strength or larger bar diameter application where about 0.03% Nb will generate 600–650MPa minimum yield strength.

**ENGINEERING STEELS**

Engineering steels comprise forging steel grades such as for case hardening, quench and tempering (QT) as well as for cold heading, springs and roller bearings. Although engineering steels usually have an elevated carbon content, the basic principles of microalloying also apply to this steel group and will be explained using the example of case carburising steel.

Automotive components such as transmission gears have to meet complex requirements. The surface of forged parts is often carburised and quenched to add a hard surface to a tough core, combining excellent wear resistance and fatigue strength. The conventional carburisation process applies austenitising temperatures between 880 and 930°C giving a carburisation depth of about 2mm after 20 hours. Increasing the carburising temperature to 1,050–1,100°C leads to an almost 60% reduction of the processing time. However, these elevated temperatures will result in considerable austenite grain growth. Table 3 gives an example of a typical carburising steel grade, 16MnCr4, as specified in the European standard EN10084, as well as different microalloyed variants. The specification allows the addition of microalloying elements by agreement with the customer.

The base steel plus Al, N and Nb shows grain size stabilisation up to a simulated carburising temperature of 1,075°C (Figure 5), relying on the combined action of
The AlN particles prevent grain growth until they become ineffective by Ostwald ripening at about 1,075°C. The formation of coarse Nb nitrides at high temperature will not effectively prevent grain growth once the AlN particles have dissolved. In contrast, fine Nb precipitates significantly reduce austenite grain growth during high temperature annealing. The 16MnCr5 base steel plus Nb contains fine Nb(C,N) precipitates that are most effective in grain size stabilisation. This is illustrated in Figure 5, which also shows the benefits of a combined Nb and Ti addition to the base steel composition, where fine TiN particles act as a nucleus for Nb precipitation.

**Microalloyed ferritic-pearlitic steels** Ferritic-pearlitic steel grades with precipitation hardening from the hot working temperature have been developed on the basis of microalloyed low and medium carbon steels. These steels are controlled cooled after forging and have partially replaced quench and tempered (QT) steels. Benefits have been experienced through elimination of heat treatment, reduced distortion, improved machinability and more consistent properties. The European standard EN 10267 specifies the technical delivery conditions. Vanadium is typically used to provide strength via precipitation hardening, however, EN 10267 allows the substitution of V by Nb. As demonstrated in Figure 1, the addition of Nb will generate comparable increase in strength by a considerably reduced addition of alloying element. Figure 2 shows that reheating before forging to about 1,250°C brings the Nb into solid solution.

The combined addition of Nb and Ti controls the austenite grain size during austenitising. Besides increased strength and toughness, a fine homogeneous microstructure offers improved fatigue resistance. As fatigue crack propagation takes place along the soft ferrite network on the former austenite grain boundaries, lowering the austenite grain size and avoiding inner-granular ferrite nucleation will help to overcome this problem. Raising the silicon content enhances inner-granular ferrite nucleation.

Dispersion hardening reduces the toughness of the forged part. This can be compensated for by a smaller grain size and reduced carbon, and thus pearlite, content. In the course of an optimisation project in China [4], toughness was increased by reducing the C content, thus increasing the amount of ferrite from 19 to 54%. The resulting decrease in strength was compensated for by addition of 0.04% Nb to the existing 0.10% V content. Almost 100% of the Nb was found as precipitates. Furthermore, the quantity of precipitated V was increased from 40 to 65%. Thus the addition of 0.04% Nb doubled the volume fraction of precipitates.

The development of microalloyed ferritic-pearlitic steels took advantage of the triple role of Nb, namely grain refining, reducing pearlite interlamellar spacing by lowering the γ to α transition temperature and precipitation strengthening. Table 4 gives the example of the NbV microalloyed Metasafe (trade name) steel grades that have been developed in France [5].
Conventional forging is performed well above 1,000°C. However, Nb is most effective in refining the final microstructure by delaying austenite recrystallisation during hot forming in the lower or metastable austenite region. The addition of 0.04–0.08% Nb and 0.1% V to a CMn steel (0.30% C, 1% Mn, 0.6% Cr, and 0.007% S) resulted in an excellent combination of toughness (Charpy V notch =135J/cm² at room temperature) and strength (TS=960 MPa) after controlled forging at 900°C.

Low carbon martensitic forgings Direct quenching (DQ) after forging is an economic technology where the martensitic microstructure is allowed to auto temper without any further heat treatment. Martensite formation is enhanced by elements like Mn, Mo, Cr and B, but also Nb. The fine-grained auto tempered martensitic steels display high yield strength (945–1225MPa) coupled with excellent toughness. Some examples of DQ steel grades are given in Table 5.

SUMMARY
The broad experience of Nb metallurgy in flat products can be extended to structural and engineering steel grades. Rising requirements for fatigue strength, toughness and weldability can be met by reduced C content with the resulting decrease in strength compensated by the addition of a small amount of Nb.

References

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