EFFECTS OF NIOBIUM ADDITIONS ON THE PROPERTIES AND LIFE CYCLE OF STEELS FOR HOT WORKING TOOLS

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Abstract

Mechanical, thermal, and chemical loads influence the life cycle of hot working tools. For economic hot forming processes, tools and dies are made from classical hot work steels of the CrMoV and NiCrMoV steel groups. The CrMoV steels, with a secondary hardening effect, are mainly used in the die-casting industry and as high stressed dies in drop forging presses. Hammer dies have a higher demand on toughness, so NiCrMoV grades are used. In every case, tool properties depend on the steelmaking processes and the final heat treatment. Increasing demands on tools are created by changes in process technologies, such as using bigger tools and dies or critical cavity geometries. In this case, there is a need for a further optimization of classical tool steels in view of the toughness behavior. This paper shows one way to increase mechanical-technological properties through small additions of niobium that lead to a higher toughness of existing steels grades. Thus, microalloying can be used for alloy design of new hot work steels.

Introduction

An essential function of any hot work steel is the capacity to retain sufficient hardness at working temperature during forging or casting. High hardness is best for resisting wear, but this can lead to premature cracking of the tool. If the hardness of the selected steel is too low, the steel will rapidly erode under working conditions and lack thermal stability. In addition, selection of hot work steels has to include the complexity of the mechanical, thermal, and chemical loads and the expected life cycle (number of forgings to be produced). Prime requirements can be summarized as follows:

- Good machinability (most steels for forging tools will be supplied in the pre-hardened condition);
- Resistance to the mechanical and thermal stresses without fracture in service;
- High life cycle (high number of produced forgings without losing shape);
- Low tool costs over the whole supply chain from steel to final product [1].

Appropriate people in the forge shop, adequate production facilities and the correct tool steel are the basics for a successful hot forming process. Forge masters have faced new challenges given by increasing demands on product sizes, new high strength pre-material for hot deformation, and more complex component geometries. An example for such new challenges is given in Figure 1 [2].

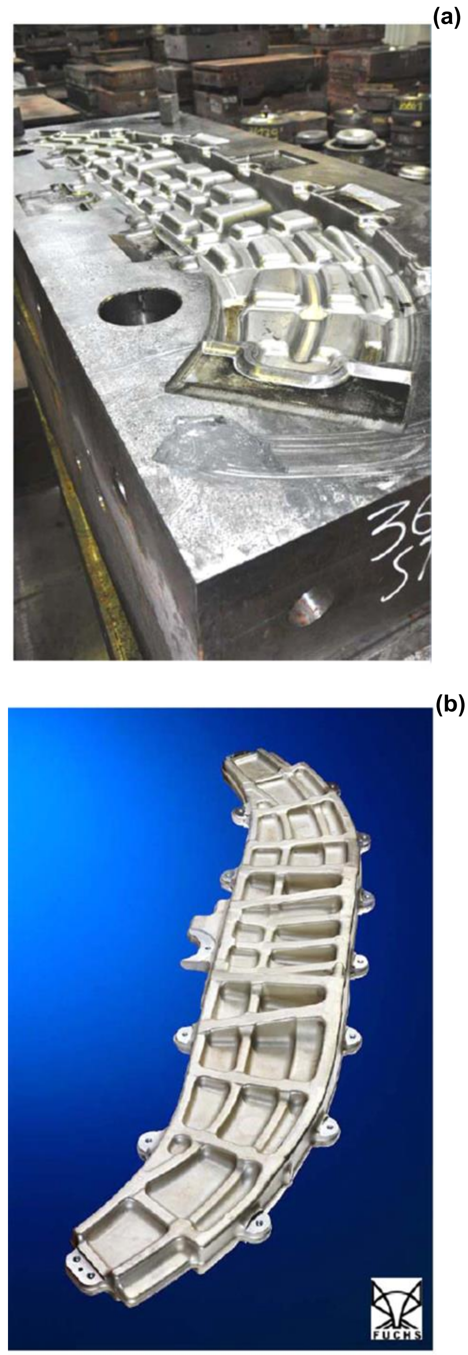


Figure 1. Example of a complex forging. (a) Die tool, (b) aluminum forging for an airplane [2].

For a higher tool life cycle, the use of a perfect tool steel is a precondition. The main requirements on material characteristics are listed as follows:

- Homogeneous microstructure (uniform distribution of carbides, low segregation);
- High cleanliness (and residual non-metallic inclusions have to be shape-controlled);
- Low content of sulfur and phosphorus.

By fulfilling these requirements, a higher toughness level in the hardened condition is expected. In addition, the correct heat treatment to attain the desired working hardness, surface treatment (if required), and maintenance of the tool during production are responsible for a high tool life. Figure 2 shows the load conditions affecting the hot working steel during drop forging [2].

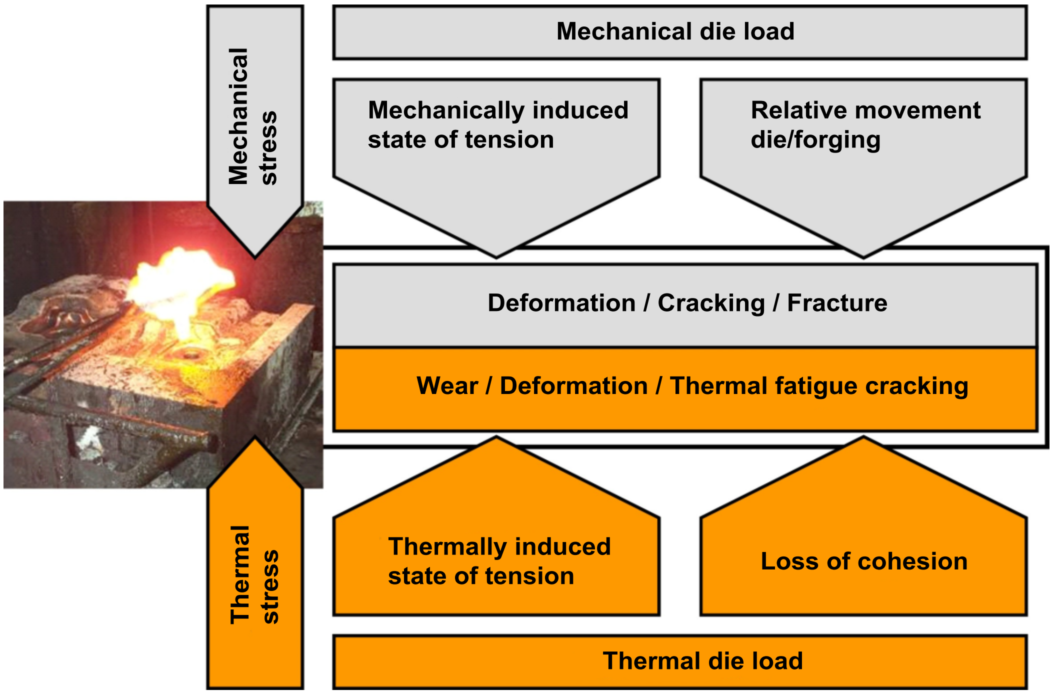


Figure 2. Load condition of a forging tool [2].

The task of a tool steel producer, therefore, is to contribute to extending the life cycle of the tool by modification of existing tool materials, or developing new alloying concepts.

Production of Hot Work Steels and Alloying Principles

The classic route for producing tool steels, like hot work steel, is the electric arc furnace process. Scrap is melted down using electrical energy to first produce crude steel, which then undergoes further treatment and refining by secondary metallurgy in a ladle furnace and degassing station. In most cases, the steel is also deep desulfurized in secondary metallurgy, and then poured by ingot casting or continuous casting for further processing. One of the most important steps is metal forming using the correct hot rolling and forging processes. Much of the steel used for tool and mold making is made from rolled billets. Larger dimensions are produced by forging. After forming, the steel manufacturer carries out a suitable heat treatment, which may be either a preliminary heat treatment prior to machining, or a final heat treatment in the case of pre-hardened tool steels. Figure 3 shows the process route for manufacturing as-forged dimensions [3].

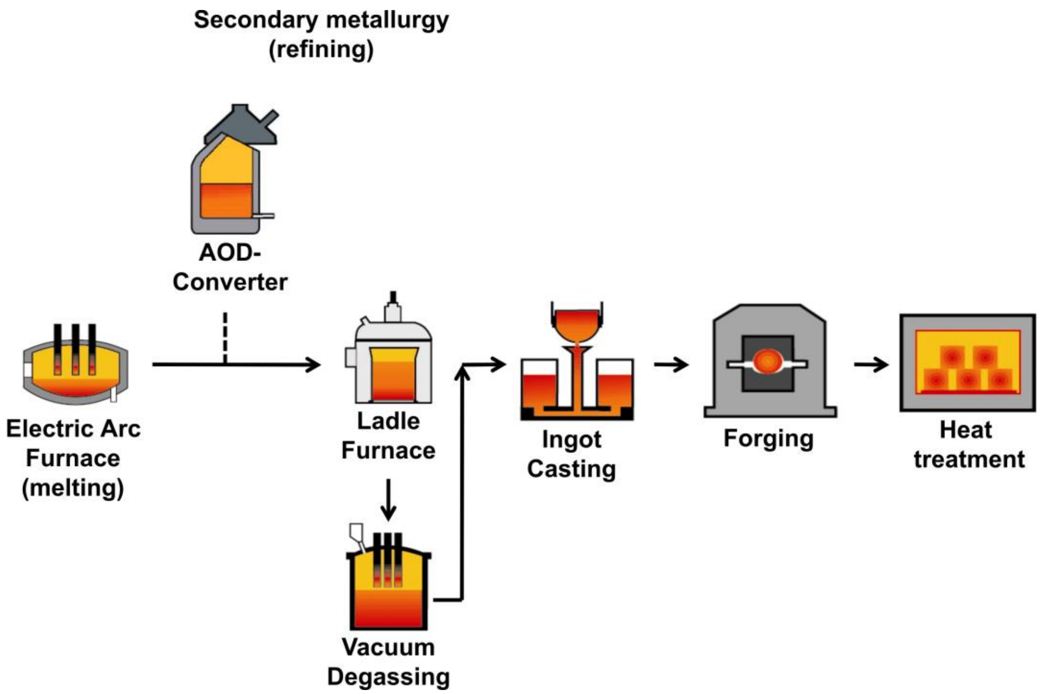


Figure 3. Process route for manufacturing forged tool steels.

In addition to conventional steelmaking, there are also special metallurgical processes available. These technological solutions are mostly combined with the established traditional methods of steelmaking and applied metallurgy. Special melting processes, such as electro slag remelting (ESR) or vacuum arc remelting (VAR), achieve very fine solidification structures because of the increased local solidification speeds associated with these processes. They also reduce the incidence of non-metallic impurities, sometimes introduced from the pre-melt, which can have an influence on the final toughness, as shown in Figure 4 [3].

Over the years, requirements of hot work steels have been increasing, especially for die casting tools. To follow customer demands, steel makers have been carrying out a lot of process improvement in steel melting, and in heat treatment of the slabs and ingots, as well as heat treatment of the produced hot work steels. The latest results of process improvement are low content of tramp elements in the steel to protect against embrittlement during service [4]. The measures are very expensive, so that the steel user has to balance performance requirements, steel costs and the expected life cycle of the tools.

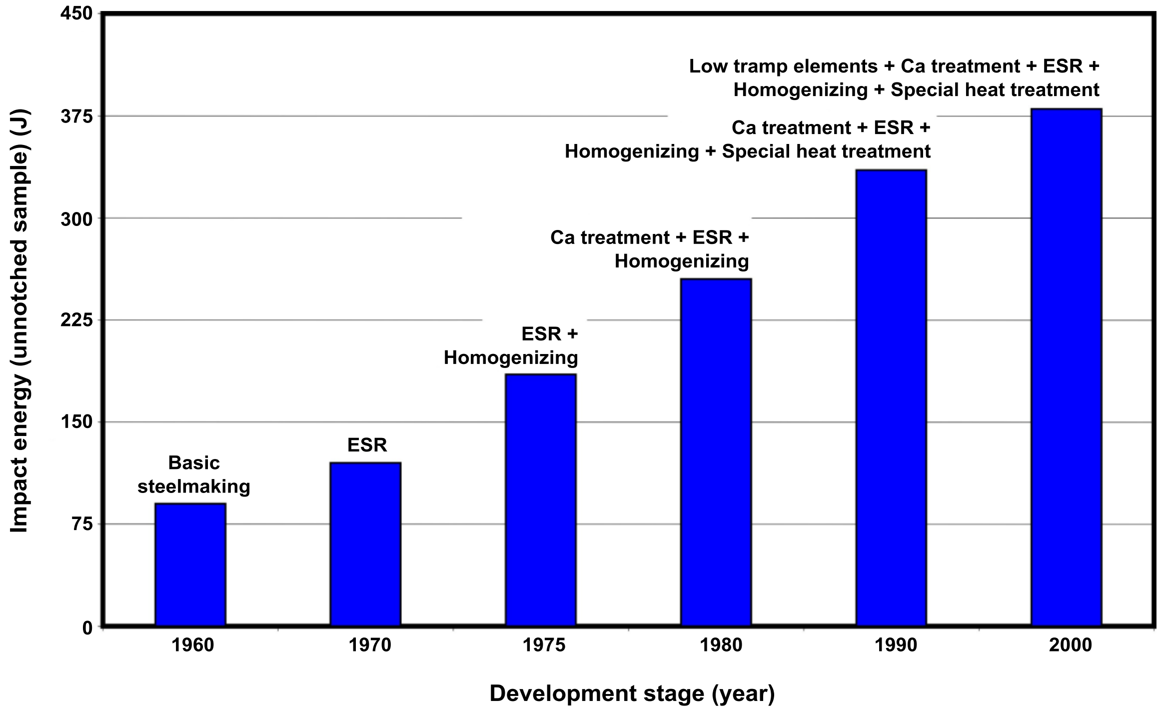


Figure 4. Measures in production of hot work steels to fulfill highest material toughness requirements [4].

The selected alloying design of hot work steel has a significant influence on the properties and the life cycle of the tools. Table I gives an overview of hot work steels according to the DIN EN ISO standard 4957 [5].

Table I. Major Hot Work Steels for Forging Dies According to DIN EN ISO 4957, wt.% [5]

Steel grade	Standard		C	Si	Mn	Cr	Mo	Ni	V	Application
55NiCrMoV7	1.2714	min.	0.50	0.10	0.60	0.80	0.35	1.50	0.05	Hammer dies, die holder
		max.	0.60	0.40	0.90	1.20	0.55	1.80	0.15	
32CrMoV12-28	1.2365	min.	0.28	0.10	0.15	2.70	2.50	-	0.40	Press dies
		max.	0.35	0.40	0.45	3.20	3.00		0.70	
X37CrMoV5-1	1.2343	min.	0.33	0.80	0.25	4.80	1.10	-	0.30	
		max.	0.41	1.20	0.50	5.50	1.50		0.50	
X38CrMoV5-3	1.2367	min.	0.34	0.30	0.30	4.80	2.70	-	0.40	
		max.	0.40	0.50	0.50	5.20	3.20		0.60	
X40CrMoV5-1	1.2344	min.	0.35	0.80	0.25	4.80	1.20	-	0.85	
		max.	0.42	1.20	0.50	5.50	1.50		1.15	

Mainly, performance of the different steel concepts is influenced by the carbon content and by alloying with chromium, manganese, silicon, molybdenum, nickel, and vanadium. Increasing the carbon content will cause an increase in the strength and in the hardenability, but toughness will be reduced. The effect of the other alloying elements on properties of hot work steel is given in Table II.

Table II. Effect of Alloying Element on Properties of Hot Work Steel

Property	Si	Mn	Cr	Mo	Ni	V
Wear resistance	-	-	+	++	-	++
Hardenability	+	+	++	+	+	+
Toughness	-	±	-	+	+	+
Thermal stability	+	±	+	++	+	++

In practice, hot work steels using the CrMoV alloying concept show inadequate toughness and low thermal conductivity, but a high heat and wear resistance. In comparison, the NiCrMoV steel concept shows better toughness properties driven by the high nickel content, but the wear resistance is lower. This results from a lower content of carbide-forming elements, such as chromium, molybdenum and vanadium.

Classical hot work steels of the CrMoV group show, during tempering in a temperature range of 400 to 550 °C, a secondary hardness maximum due to generation and then coarsening of precipitates (carbides) during tempering. Figure 5 compares a tempering diagram of the grade X40CrMoV5-1 with steel grade 55NiCrMoV7. This latter steel shows a normal tempering curve, comparable with classical quenched and tempered steels.

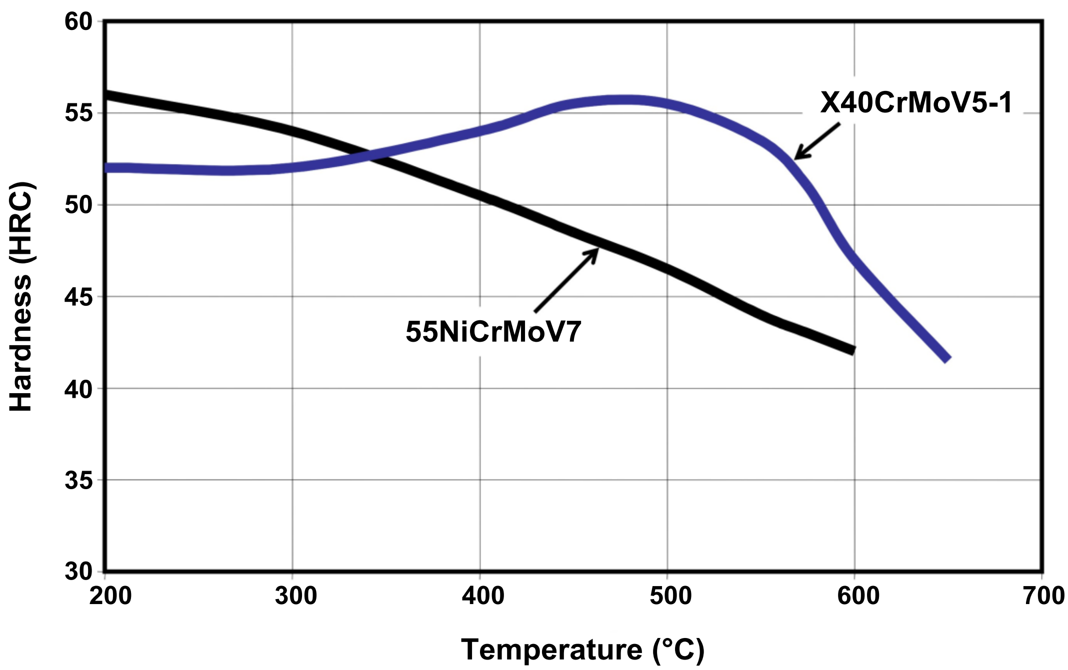


Figure 5. Tempering diagram of the hot work steels 55NiCrMoV7 and X40CrMoV5-1.

To extend the life cycle of hot work steels, improvement of the thermal fatigue behavior is necessary. Due to the relationship between grain size and toughness of the material, controlling grain size and preventing grain coarsening during heat treatment is a possible option. Figure 6 shows the effect of toughness and grain size; coarse grains cause premature crack formation and result in material pitting, Figure 6(a). Finer grains lead to fine incipient cracking with no material pitting, Figure 6(b).

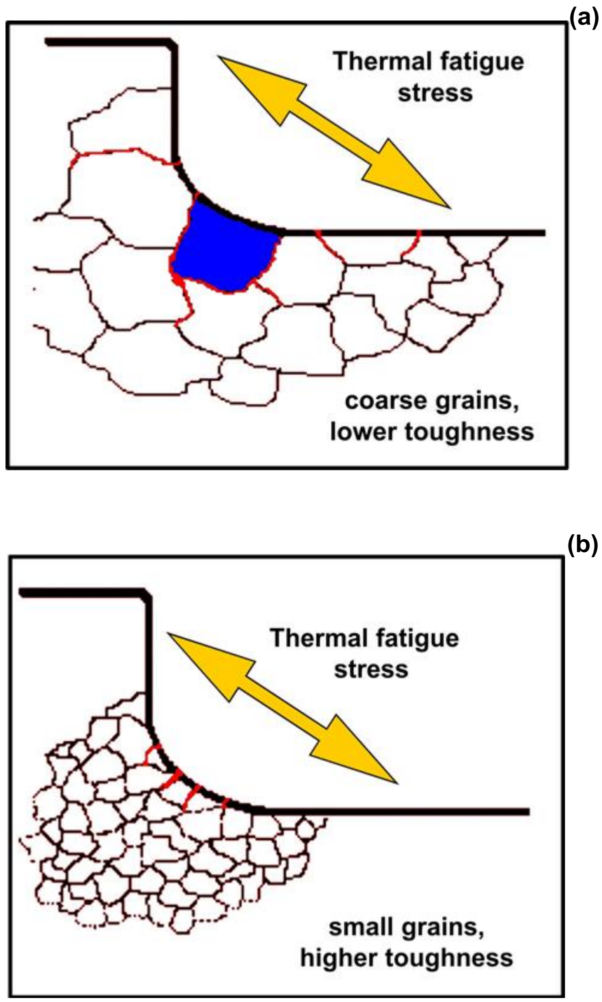


Figure 6. Effect of material toughness and grain size on thermal cracking of tools [6].

Effect of Niobium Additions on Properties and Life Cycle

Niobium is an element with high affinity for carbon and forms very stable carbides. Therefore, it is well suited as a carbide forming alloying element in the production of tool steels. In many cases, niobium is added to hot work steels in a range up to 0.20 wt.%. The target of such microalloying is to inhibit austenitic grain growth during heat treatment. Furthermore, an investigation to reduce vanadium content in X40CrMoV5-1(AISI H 13) to 0.5 wt.% and add 0.1 wt.% niobium has been carried out. The modified grade shows the same properties as H13 grade with 0.95 wt.% vanadium, but production costs are lower and the austenite grain size is finer. A similar alloying concept according to this described design has found industrial application in the die casting industry [7-9].

Furthermore, smaller additions of niobium support the enhancement of properties of hot work steels. One example is given by microalloying heavy-duty forgings of a NiCrMoV steel, due to increasing demands in terms of quality. In order to convert raw ingots into high-quality forged products with uniform properties, it is necessary to control grain size during the whole manufacturing process. A significantly finer ferrite grain leads to better testability of heavy-duty forgings by ultrasonic inspection and for adjusting the mechanical-technological characteristics. Figure 7 shows results of the calculated and measured grain size of a forged hot work steel block. The NiCrMoV steel with a high content of precipitates, Heat B, was microalloyed with niobium. It is evident that the melt with a small niobium addition shows a finer grain size in the simulation by the BGH Edelstahl software MICDEL, as well as in metallographic investigations in the central position of the forged and heat treated bar. In principle, improvement of microstructure of heavy-duty forgings made of hot work steels is possible by microalloying [10].

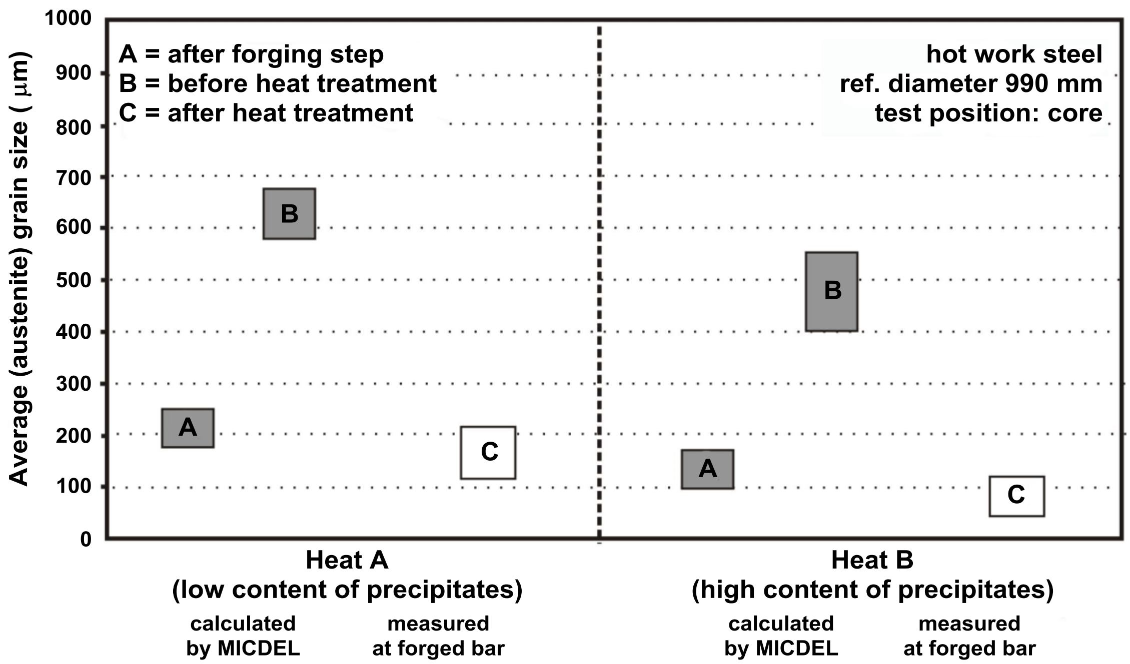


Figure 7. Calculated and measured grain sizes of a forged hot work steel block with different amount of precipitates [10].

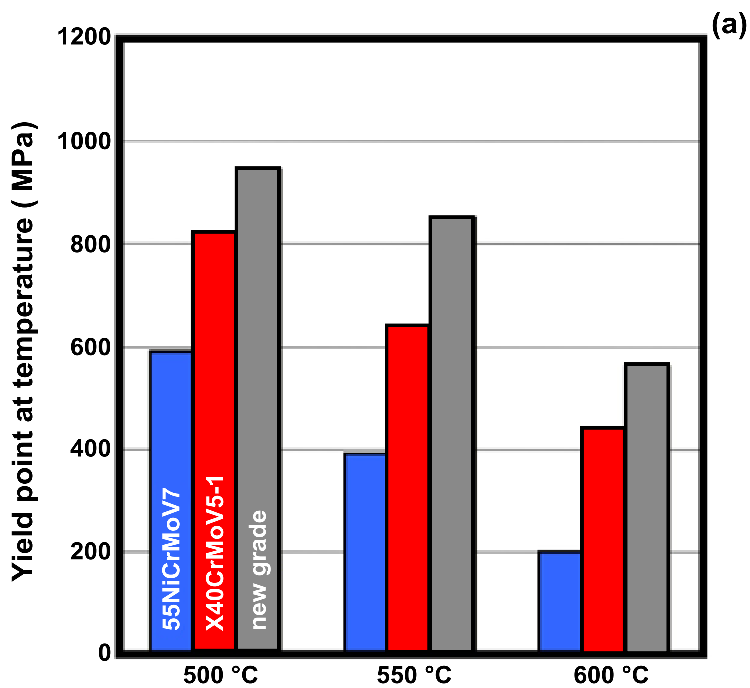
Another example of the use of niobium in hot work steels is the possibility to create a new steel type [2,11,12]. The idea behind the development was to combine the positive properties of the CrMoV and NiCrMoV steel groups, ie. toughness combined with wear resistance. The chemistry of the new grade is given in Table III.

Table III. Alloying Concept of New Hot Work Steel Grade, target analysis, wt.% [11]

C	Si	Mn	Cr	Mo	Ni	V	Nb
0.35	0.25	0.50	2.70	1.00	0.65	0.20	0.04

In practical use, the new steel shows very good properties with regard to the state-of-the-art tools. This behavior is conferred by a very good thermal conductivity, high temperature yield strength and good toughness. The life cycles of the tools made with this new steel grade exceed those from the hot work tool steel X40CrMoV5-1 and therefore, the development represents an economical alternative. Yield strength and toughness of the new grade, in comparison with the classical hot work steel 55NiCrMoV7 and X40CrMoV5-1, are given in Figure 8.

During the development of this steel grade, Thermo-Calc calculations of precipitation have been carried out which show the existence of carbides at significantly higher temperatures for the niobium alloyed variant, when compared to the niobium free steel. In the range of usual tempering temperatures, the quantity of secondary hardening carbide is higher compared to grade X40CrMoV5-1. This explains the results of the new steel grade in mechanical-technological tests and the reported behavior and life cycle of tools in the field [11].



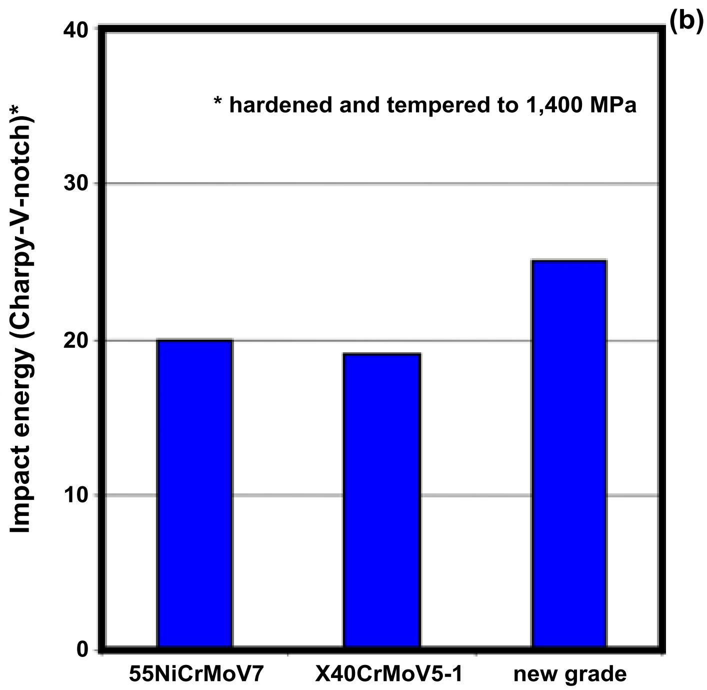


Figure 8. Yield strength and toughness of a new Nb microalloyed hot work steel in comparison to classical grades; (a) Yield strength, (b) Charpy toughness [12].

A special application of this hot work tool steel is the so-called mandrel bar for production of seamless rolled tubes. In general, the steel X40CrMoV5-1, or slight variations, is used; the strength is adjusted to about 1150 MPa. In addition, there are relatively high toughness demands. A variety of measures has been attempted over the years to increase the toughness.

By adding niobium, toughness should be improved. A pilot industrial heat has been cast and the steel bars for mandrels have been produced under the same process condition as for steel bars without niobium. Figure 9 shows the results of the mechanical testing of steel bars for mandrels with dimensions from Rd. 200 to 300 mm with the same heat treatment parameters, compared with the results of a melt modified with niobium. It is shown in this example, that toughness is somewhat higher in the niobium steel than in the classical steel. It is now to be tested whether the improvement in the toughness can be reproduced.

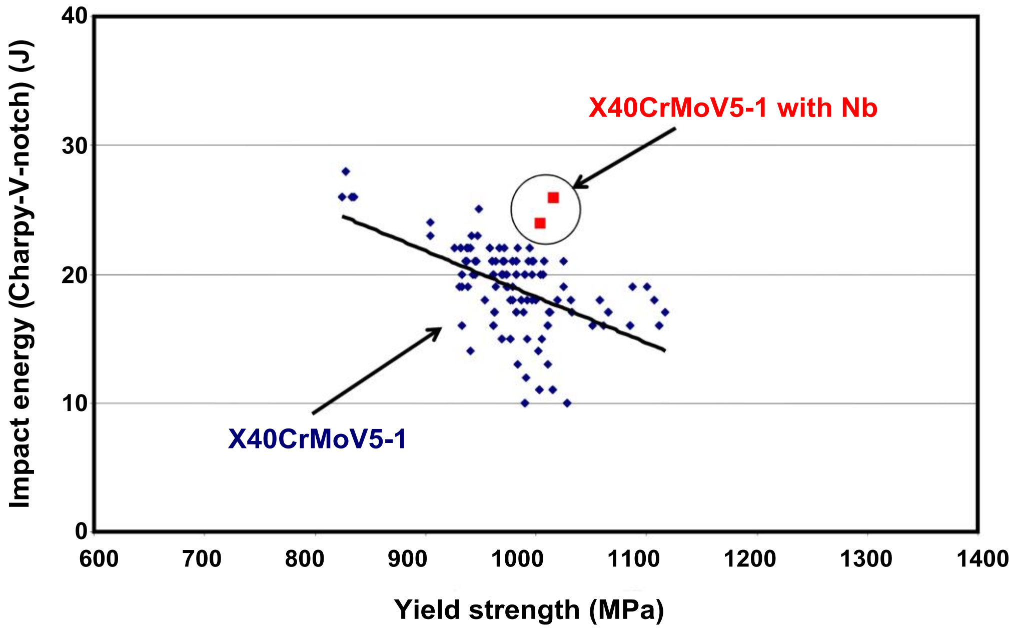


Figure 9. Results of mechanical testing steel bars in X40CrMoV5-1 for mandrels, toughness versus yield strength, in comparison with results for a Nb modified heat of the same grade.

Conclusions

In the selection of hot work tool steels, it is necessary to pay attention to balancing working hardness and toughness. Toughness influences the tool wear and thus, overall costs. It is possible to influence the grain sizes of hot work tool steels through additions of niobium. During heat treatment, grain coarsening is reduced due to the presence of niobium carbides. This should be reflected in improved toughness behavior.

Accordingly, a pilot industrial heat has been cast and the steel bars for mandrels have been produced under the same process condition, as for those without niobium. For an equivalent strength, the Nb-containing bars indeed exhibited superior toughness as expected. Further work is in progress to confirm the reproducibility of this effect.

This mode of action of niobium could be used to develop new steel grades, as well as optimizing existing steel grades.

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