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PRACTICAL ADVANTAGES OF NIOBIUM AND MOLYBDENUM ALLOYING IN THE PRODUCTION AND PROCESSING OF FORGED ENGINEERING STEELS

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Abstract

Ever-increasing quality demands on forged engineering steels require specific modifications of the chemical composition of existing alloys or even necessitate the development of new steel grades. The current paper mainly focuses on the metallurgical principles of addition of niobium and molybdenum to forged case carburising and quenched and tempered steel grades. The influence of niobium alloying on the grain size stability after carburising at high process temperatures, in combination with further development of the typical chemistry of case-hardening steels, has been worked out. An additional practical study shows the effects of microalloying on the grain size of heavy-duty forgings.

Introduction

Forged engineering steels are nowadays used for diverse applications in the automotive and machine building sector. A special feature of this group of products is that steelmakers produce both forged steel bar and open-die forgings for direct use in machine building, as well as forged or rolled billets for conversion in forging shops or ring rolling mills to manufacture finished components. The products therefore have to meet different requirements, giving rise to widely differing demands on the engineering steels and their manufacturing process. In the case of forged steel bar and open-die forgings, as used in machine building and plant engineering, the principal focus is on:

- mechanical properties, and
- testability (especially ultrasonic testing).

Since some particular applications require machining followed by additional heat treatment (eg. case-hardening) or surface finishing, it is desirable to ensure process stability when designing a steel product. It is also an important point in applications of products made from billets, since they undergo further hot forming including (preliminary) heat treatment, and the batch frequency is sometimes high. These factors are now considered in relation to niobium and molybdenum alloyed engineering steels.

Technical Rules for Selecting Forged Engineering Steels

There are various sets of rules for designing machine components, and each manufacturer also draws on its own experience. The principal factors when selecting steel at the engineering design stage are tensile strength and yield strength and also the toughness of the material concept. One of the core questions relates to assessing through-hardenability. In the case of complex, highly stressed components, the aim is to achieve a uniform martensitic/bainitic heat-treated structure throughout the cross-section. Toughness is a measure of the material's potential crack arresting capability, and, in the case of engineering steels, depends on the microstructure or the microstructure homogeneity, and the grain size. When selecting a steel it is therefore necessary to consider that appropriate tempering temperatures can be used to achieve the required strength. There should also be a uniform, homogeneous grain structure. Figure 1 shows the relationship for various steel concepts between the yield strength and the nominal diameter of relevance for heat treatment purposes. This shows that as the alloy content increases, the dimensions associated with through-hardenability increase. With the special grades it should be borne in mind that in some cases other elements, such as niobium, are added as microalloys, and there can also be a reduction in the tramp elements. Metallurgical process engineering measures are also necessary, since high steel purity is required to generate excellent mechanical properties [1].

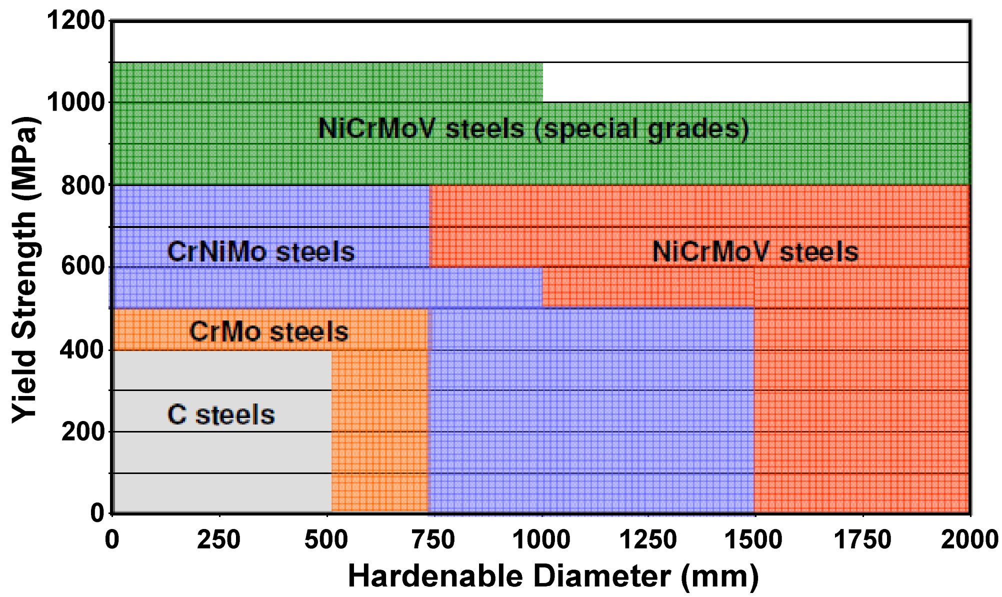


Figure 1. Diagram of the yield strength to be expected across the hardenable diameter for heat treatment purposes for various steel grade concepts.

This paper examines the various alloying concepts in greater detail, using the example of a plastic mould steel, Figure 2. Two fundamental trends are evident in the case of this material. Firstly, the tools for plastics processing are becoming ever larger, and, secondly, steel users specify a relatively high hardness, since this improves machinability (eg. HSC, milling, polishing) [2].

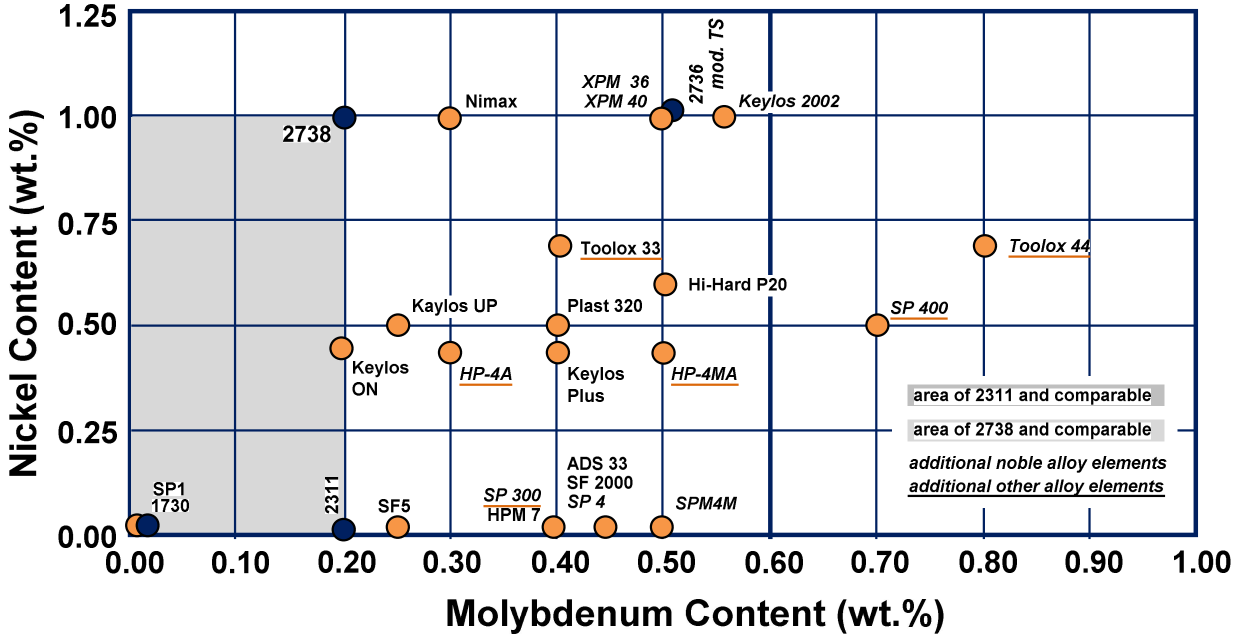


Figure 2. Diagram of the currently available material concepts or steel grades for plastic moulds ("Noble elements": V, Nb, Ti).

Development of the original materials DIN 1.2311 and 1.2738 was therefore pursued in two directions. The nickel and molybdenum content was raised to increase through-hardenability for larger moulds, and the molybdenum content was increased to ensure sufficiently high tempering temperatures, despite high hardness requirements; microalloying elements such as niobium were also added when appropriate.

Optimisation of Case-hardening Steels

Case-hardening steels constitute a special group of steels, since the heat treatment process to chemically influence the surface layer (case-hardening) that follows machining also has to be considered when seeking to achieve the desired optimisation of material properties. This process gives the component (usually a toothed component) a hard surface with a carbon content of around 0.8 wt.% and a tough core with the base carbon content of around 0.2 wt.% that is typical for case-hardening steels. The carburisation process depends on the temperature and time, so it is in the interests of economic efficiency to choose the highest carburising temperatures. Component sizes have also increased over time, so that quite long carburising times are sometimes needed in machine building to achieve the case-hardening depths required by the engineering design.

When optimising case-hardening steels, it is also necessary to consider that process stability is a prime consideration in automotive applications because of the batch frequencies and/or the chain of linked production steps, whereas in applications in machine building and plant engineering the focus is on the material's reliability, especially because of the different load cycles and unit sizes. Analysis of the cost structure of a middleweight goods vehicle revealed that the axle and engine/drive elements make up around 50% of the production cost [3]. There is therefore great potential for reducing manufacturing costs if full use is made of the available properties, or if these can be further improved.
The main parameters of case-hardening steels can be summarised as follows:

- Hardenability and homogeneity;
- Microscopic and macroscopic purity;
- Mechanical properties (strength and toughness);
- Wear resistance at roller contact surfaces;
- Dimensional change and distortion behaviour during and after heat treatment;
- Treatment and machining properties (hot and cold forming and machinability).

Most of these properties are associated with the grain size of the steels. Figure 3, for example, shows the relationship between grain size and the service life of a case-hardened component. This shows that both mixed grain and coarse grain sizes significantly reduce service life [4]. In this example there is a reduction in load capacity of 40% between a fine-grain steel (generally defined by a grain size figure of ASTM = 5 or finer) and a coarse-grain steel.

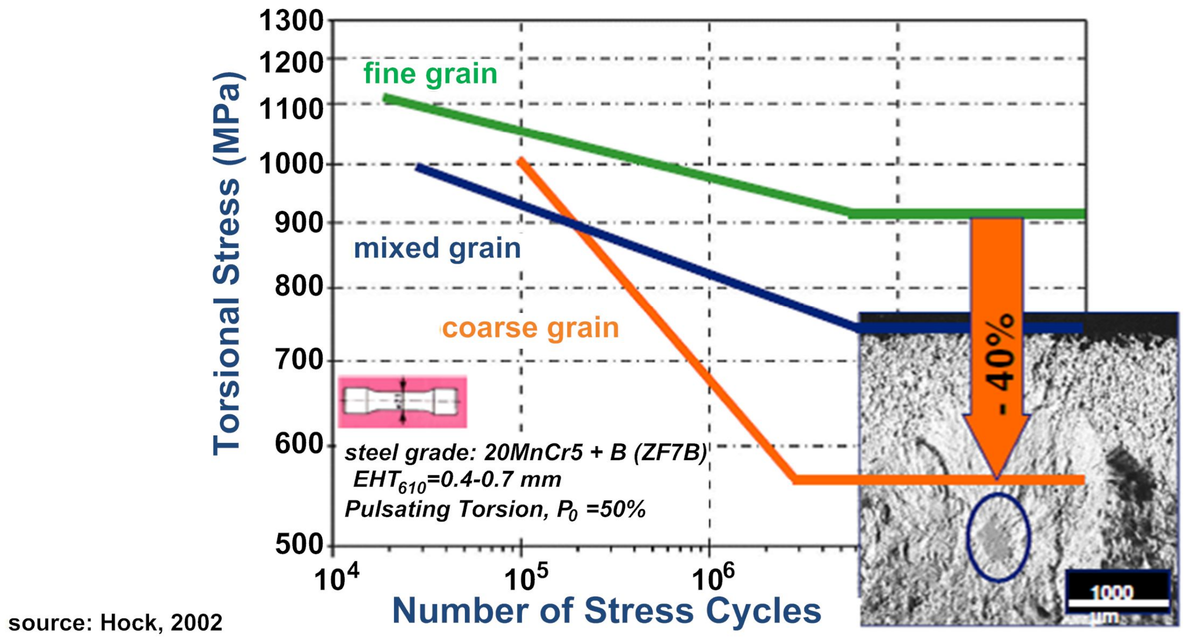


Figure 3. Relationship between grain size and service life of a case-hardened component.

Some work has been carried out in the past to improve the fine grain stability of case-hardening steels. Aluminium nitrides are generally used to ensure fine grain stability in the case of standard case-hardening steels, but aluminium nitrides dissolve above 950 °C, (or somewhat lower or higher temperatures depending on the steel grade and preliminary heat-treatment condition), and grain growth sets in. Microalloying elements can be added to achieve higher dissolution temperatures making it possible to achieve more economic carburising at higher temperatures. For example, adding niobium causes niobium carbo-nitrides to form in addition to the aluminium nitrides, and the dissolution temperature of these niobium carbo-nitrides is significantly higher than 1050 °C. Another finding is that additional grain refinement can generally be achieved even at lower temperatures by adding microalloying elements. Figure 4 shows this finding in the case of a MoCr steel [5]. Another important factor to consider is the nitrogen content in the steel. In order to create optimum conditions, a minimum nitrogen content of around 100 ppm should be maintained. As already mentioned, fine-grain stability in the case of the classic case-hardening steels also depends on the production conditions and heat-treatment cycles. A further reason for adding microalloying elements in case-hardening steels is to ensure fine-grain stability regardless of process route.

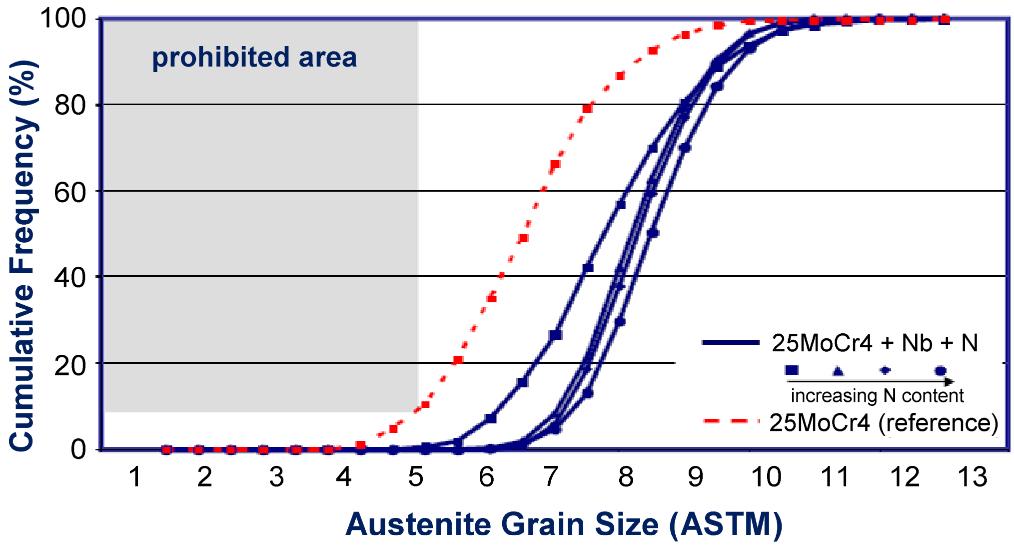


Figure 4. Grain growth tests of microalloyed melts of a MoCr steel in the ferrite-pearlite annealed pre-condition after 950 °C and 25 hours holding time [5].

Figure 5 shows the result of a test on a melt of material 25MoCr4 [6]. Here too, around 300 ppm of niobium was added as an alloy, and grain growth tests conducted on samples taken from rolled billets (as rolled) and from drop forgings subsequently produced (FP annealed). It is evident that the fine-grain stability with a grain size of ASTM 5 or finer is guaranteed in both cases at 1050 °C and a holding time of 30 hours. This example indicates no correlation with the production route or the process route selected.

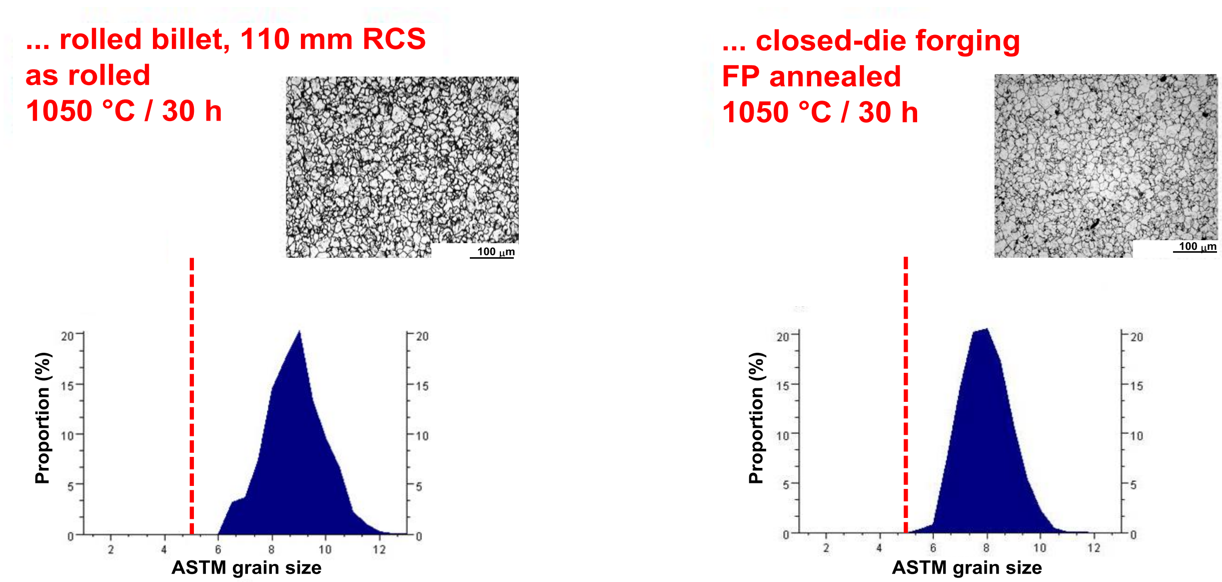
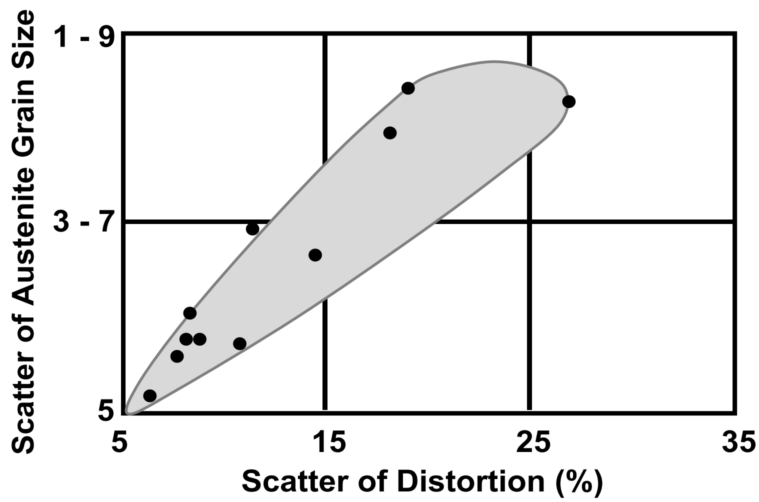


Figure 5. Fine grain stability of a microalloyed 25MoCr4 steel in two different product forms (rolled billet and closed-die forging, same melt) 30 hours holding time at 1050 °C [6].

A further advantage of microalloying in case-hardening steels arises from a process stability improvement in downstream processing of the steel. Due to the reduced spread of grain sizes observed, a lower spread of dimensional changes and distortion can be expected. A seminal study by Randak [7] was supplemented by further studies on components made of forged steel bar; these studies likewise illustrated a positive effect with the observed grain being achieved by adding microalloying elements, Figure 6 [8].



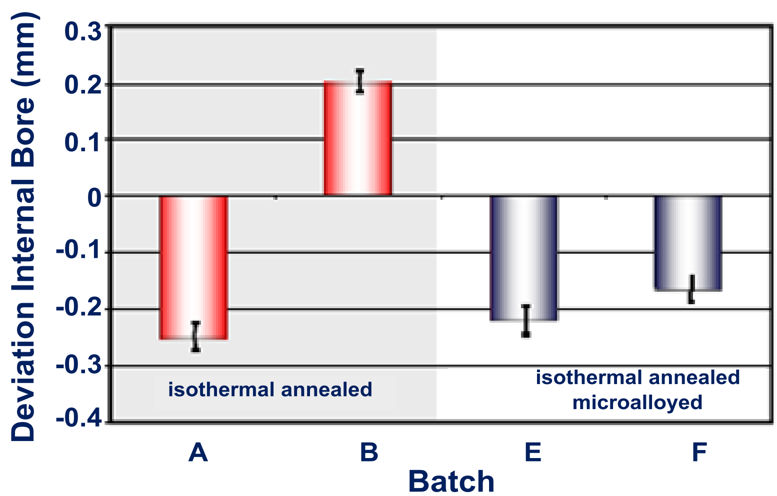


Figure 6. Relationship between grain size and microstructure on the dimensional change and distortion of case-hardened components [7,8].

Increasingly stringent quality requirements for steel grades resulting from new challenges in machine building and plant engineering are also leading to a constant ongoing development of existing materials. For case-hardening steels, the scope for development is principally as follows:

- Increase core strength and toughness;
- Increase fatigue strength under reverse bending stresses;
- Increase hardenability;
- Reduce or homogenise dimensional change and distortion.

Table I shows the chemical composition and the mechanical properties of more recent material concepts compared to the 18CrNiMo7-6 grade to DIN EN 10084/9/. The first concept seeks to satisfy the future requirements for larger gear units, and represents a higher strength variant of the case-hardening steels (new steel concept 1). Hardenability has basically been increased compared to the standard steel 18CrNiMo7-6 by increasing the manganese and molybdenum content. The nickel and chromium content was reduced for reasons of alloying efficiency. It would in principle also be possible to add niobium to promote grain refinement. The second concept shows an economic variant of the standard steel 18CrNiMo7-6, which is designed to achieve alloying efficiency without significantly changing the properties required. For example, hardenability was increased by increasing manganese and chromium, based on a molybdenum chromium steel. In order to achieve toughness comparable to a nickel alloyed case-hardening steel, niobium was added as an alloy. The intention is to form stable special carbides with molybdenum, promoting the steel concept's fine-grain stability. There is also a comparison of the mechanical properties of the two new steel concepts after blank hardening at 880 °C/2 hours/oil quench/180 °C/2 hours. The enhanced hardenability of the new steel concept 1 is also expected to be evident in the figures for tensile strength, and in rotating-bending fatigue tests. It also shows that the toughness values are still at quite a good level despite the high strength achieved. It was observed as regards the new steel concept 2 that strengths comparable to the alloy-efficient concept can be achieved with only a moderate loss of toughness. Further characteristics of the two materials are currently being studied in a publicly funded project [10].

Table I. Overview of Chemical Composition and Mechanical/Technological Characteristics of More Recent Steel Concepts for Case-hardened Components [10].

Steel Grade	**C**	**Si**	**Mn**	**Cr**	**Mo**	**Ni**	**Nb**
20MnCr5 mod.	0.26	0.12	1.46	1.23	0.54	0.91	-
20CrMo5 mod.	0.21	0.25	1.17	1.15	0.21	0.22	0.04
18CrNiMo7-6 (1.6587)	0.15/0.21	≤ .40	0.50/0.90	1.50/1.80	0.25/0.35	1.40/1.70	-

content (wt.%)

	Concept 1 20MnCr5 mod.	**Concept 2 20CrMo5 mod.**	**18CrNiMo7-6**
Tensile strength, R_m (MPa)	1758	1182	1182
Impact energy, A (J)	47	55	80
Rotating fatigue limit $\sigma_{(50\%)}$ at $N=10^7$(MPa)	722	491	510
Hardenability at 11 mm (HRC)	51	44	41
Hardenability at 25 mm (HRC)	50	36	36

Grain Size Control in Heavy Forgings

Large open-die forgings for power generation plant construction are considered particularly challenging. Ever larger forgings are needed as power densities increase, also necessitating the processing of very large ingots that now reach weights of up to 650 tonnes. But there are nevertheless still high expectations as to their mechanical properties (strength and toughness) and through-transmission characteristics in ultrasonic testing which also makes grain size an important factor in this steel application. Niobium can also be used as a microalloying element to enhance grain sizes in the case of heavy forgings. Figure 7 shows a result of a study carried out on a plastic mould steel. The grain sizes were simulated for a relevant nominal diameter for heat-treatment purposes of 1130 mm. Despite the addition of niobium as a microalloying element, it is evident that after the forming process proper, grain sizes increase again as the forging cools [11].

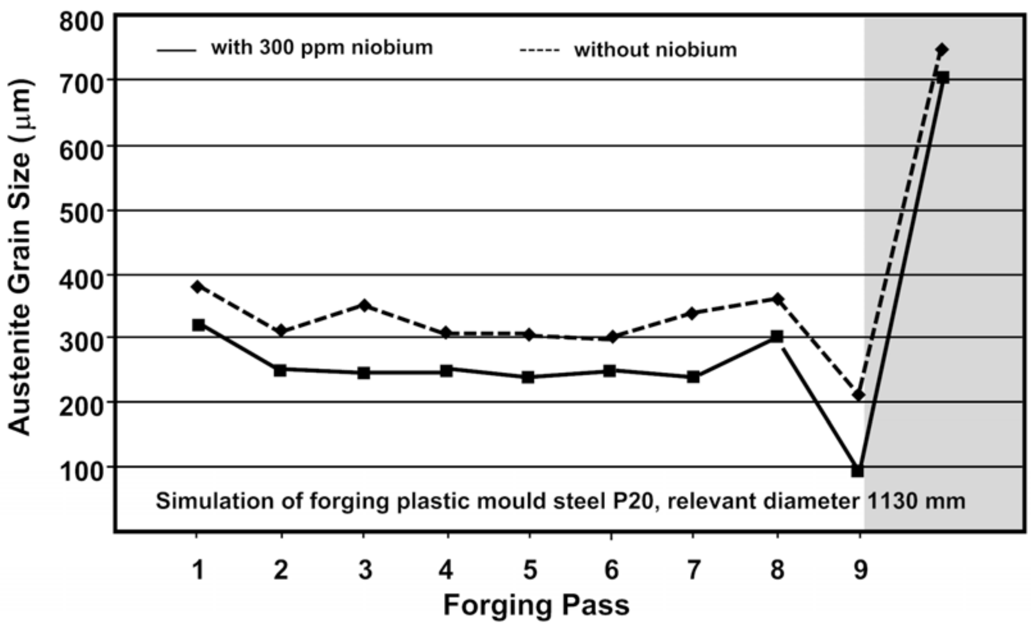


Figure 7. Effect of niobium on the austenite grain size in the core of a forging during and after the forging process and cooling in air to 800 °C [11].

The results of the simulations carried out are consistent with the results of tests using a hot-forming simulator. Figure 8 shows the grain sizes determined using metallographic methods for samples forged in the laboratory with similar parameters to the industrial production process. The grain size tends to be somewhat finer in the case of the niobium alloyed variant. It should however be noted that in the example quoted, the hot-forming temperature was above the solution temperature of the niobium carbo-nitrides. A further study is therefore required to determine the effect of the forging temperatures [11].

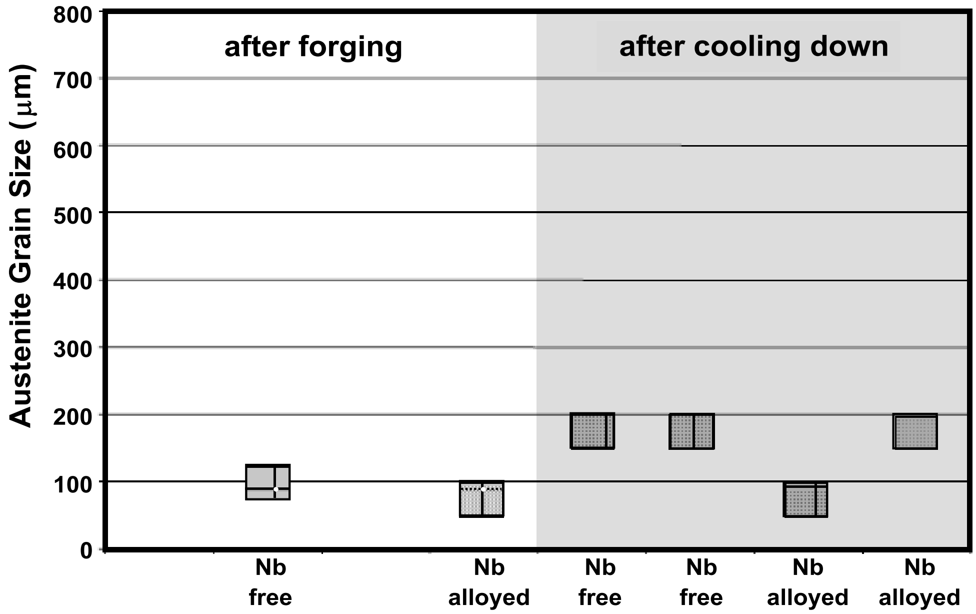


Figure 8. Austenite grain size in the surface layer of a forging after the forging process and cooling in air determined by hot forming tests [11].

Figure 9 summarises this study; in this case upsetting tests were carried out with two different melts of material 27NiCrMoV11-6. The aim was to compare the grain sizes of a conventional melt with a microalloyed melt at various forging temperatures, decreasing through A, B and C. As the result shows, there is a significant difference between the worst and best case.

It is, therefore, possible to have a beneficial effect on the grain sizes of a forging by adding niobium and selecting a temperature range [12].

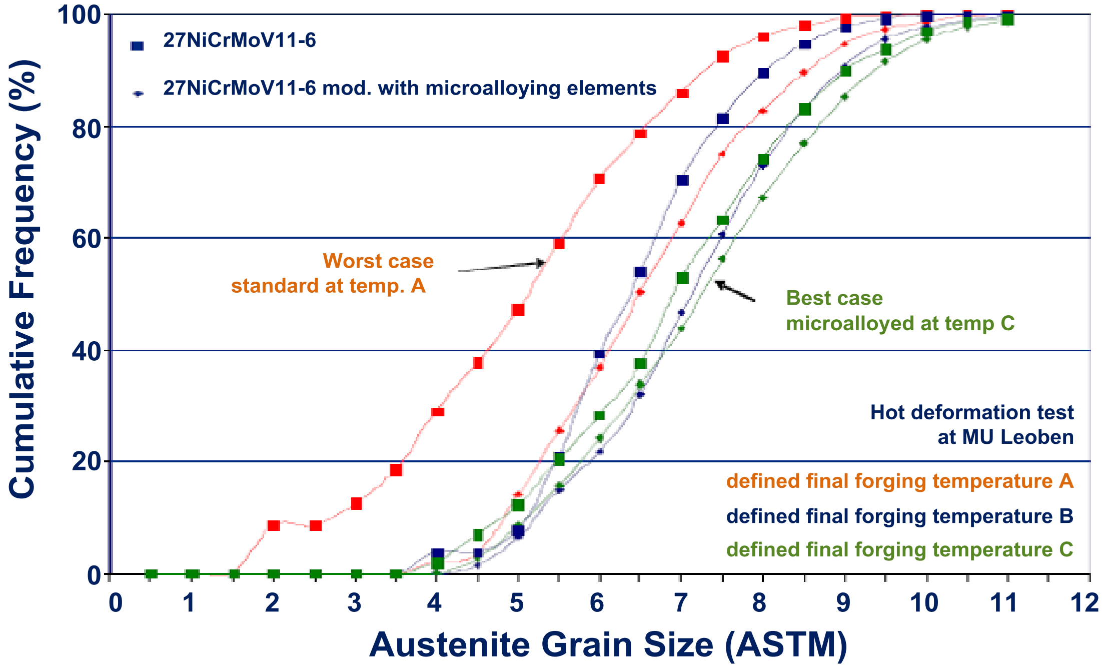


Figure 9. Grain size distribution of upsetting tests as a function of chemical composition and process parameters in forging [12].

Conclusions

The alloying elements molybdenum and niobium offer numerous practical benefits for forged engineering steels on tempering. Molybdenum contributes principally to increasing through-hardenability and hardness retention, thus steel grades for larger components in particular are alloyed with molybdenum. An additional point here is also that molybdenum suppresses temper brittleness in forgings. Adding niobium provides a way forward in the development of existing steels. Especially in steels with molybdenum, very fine and stable special carbides form because of the synergistic interaction between molybdenum and niobium, which can be used to improve the mechanical and technological properties. In case-hardening steels, this can be used to homogenise the grain size, also improving the fine grain structure and stability, regardless of process routes. Niobium can furthermore affect grain sizes at the production stage, which is of particular relevance in the case of heavy forgings made from large blooms with a corresponding solidification cross-section. This may also provide a route to simplifying the heat-treatment sequence in the case of large forgings, without having to accept constraints on ultrasonic inspection.

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