Niobium Bearing Structural Steels
Edited by: Steven G. Jansto and Jitendra Patel
TMS (The Minerals, Metals & Materials Society), 2010

NIOBIUM MICROALLOYING OF HEAVY PLATE PRE-HARDENED TOOL & MACHINE STEEL

Per Hansson
SSAB, Oxelösund, Sweden

Keywords: Pre-hardened Steel, Continuous Casting, Steel cleanliness, Mechanical properties, Mould/Die Manufacturing

Abstract

The last few decades have seen rapid development of hard machining steels having higher hardness, approximately >380 HBW, which itself has enabled the development of tool and machine/engineering steels being delivered as pre-hardened (quenched and tempered) from the steel producer. When compared with conventional tool/machine steels, such steels demonstrate numerous advantages, among which the most important are: (i) shorter manufacturing time due to elimination of any heat treatment stage; (ii) guaranteed mechanical properties, and; (iii) a shorter time to market for new products.

This paper focuses on the development and introduces the market of two grades, having nominal hardness of 300 and 450 HBW respectively, with low alloy contents giving them much better machinability when compared with traditional tool steels of similar hardness. The paper discusses the additional improvements gained in toughness, in combination with reduction and elimination of expensive alloys via a combination of niobium/titanium-microalloying pertaining to effectively control the austenite grain size in the production route. Furthermore, the re-designed steels have been found to be more versatile in being suitable for moulding, cold-work as well as for hot-work applications. Their low alloy content also makes these new steels attractive in substituting commonly used machine/engineering steel grades.

Introduction

Pre-hardened steels have hitherto mainly been produced as abrasion resistant grades (having hardness above approximately 360 HBW) and as high strength constructional steel grades having strength levels, $Rp_{0.2}$, above 690MPa. Such grades are normally used in applications where bending and also welding are of great importance during the manufacturing of a component. As little, or no, machining is carried out during the component manufacturing steps, the machining property of such steels becomes one of minor interest. However, hard machining in steels having higher hardness, above approximately 380 HBW, has seen rapid development during the last few decades. This has enabled steel manufacturers to develop pre-hardened steels dedicated to different applications where machining is the major manufacturing step. Examples are to be found in tooling and also machine/engineering components. Figure 1 shows a schematic description of the different application areas of Q&T (Quench and Tempered) steels.

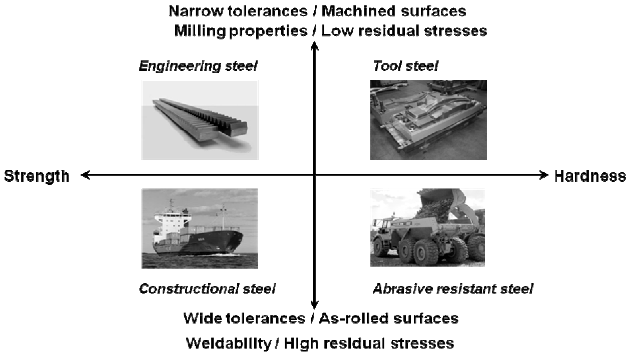

Figure 1. Schematic description of different steel type applications and the demands put on different grades.

Tool/machine/engineering steel grades are usually delivered in the as soft-annealed condition from the steel manufacturer, and heat treatment, quenching and tempering, normally takes place after rough machining of the mould/die/component. However, this process route has some drawbacks such as dimensional changes that take place during heat treatment, a cracking risk that cannot be neglected, and uncertainties of which mechanical properties are achieved of the heat-treated mould/die/component. Consequently, much effort and time is spent after heat treatment to adjust the details to their final dimensions.

The new steels, marketed under the TOOLOX trade name, have been developed aimed to supply manufacturers with tool/machine steel grades being dimensionally stable when machining them. Furthermore, these are also supplied with guaranteed mechanical properties.

Steel Development

The main objectives in the development of these new steels were to:

- Develop new grades which are not within any existing standards;
- Supply steel which are pre-hardened, i.e. does not require heat treatment in mould/die manufacturing;
- Supply steel which have guaranteed mechanical properties, and;
- Produce grades that are dimensional stable during machining.

Chemical composition and slab manufacturing

Today, common materials on the tool steel market are the well-known grades of P20 (plastic mould steel), H13 (hot-work steel) and D2 (cold-work steel). In comparison, TOOLOX 33 has only one similarity to P20 namely the same hardness on delivery. Furthermore, TOOLOX 33 offers ESR-quality and much improved machinability when compared with P20. TOOLOX 44 has a delivery hardness of 450 HBW (approximately 45 HRC), ESR-properties, and offers a machinability quite near the one of P20 despite its much higher hardness. Table 1 gives the typical chemical compositions of these grades.

Table 1. Typical chemical compositions, P, S and B in ppm, other elements are given in weight-%.

Grade	C	Si	Mn	P	S	Cr	Mo	V	Nb	B
P20	0.40	0.30	1.45	Max. 350	Max. 350	1.95	0.20	-	-	-
H13	0.40	1.0	0.4	Max. 300	Max. 300	5.2	1.35	1.00	-	-
D2	1.55	0.25	0.30	Max. 300	Max. 300	11.5	0.70	1.00	-	-
TOOLOX 33	0.24	1.1	0.8	90	15	1.0	0.25	0.11	0.017	20
TOOLOX 44	0.32	1.1	0.8	90	15	1.3	0.8	0.14	0.017	20

In TOOLOX, titanium has been chosen to control austenite grain size in the different production steps in the steel mill. Furthermore, titanium also gives an effective austenite grain growth control in the heat affected zone (HAZ) during welding.

The steel cleanliness and control of centre-line segregation is of great importance as it has a large influence on properties such as; polishability, etchability, fatigue life length, toughness etc. Traditionally, tool steel production ingots are ESR-remelted when high demands are put on the final product. In contrast, the chemical compositions of the TOOLOX grades are developed for production by the continuous casting of slabs having equal cleanliness and segregation levels as ESR-remelted ones. The steel/slab production process simplified using Controlled Soft Reduction (CSR) during the continuous casting of the very clean liquid steel.

Figure 2 shows a sulphur-print of an uphill teemed tool steel ingot having the dimension 746x1089x1700mm and a chemical composition of 0.48%C, 0.36%Si, 0.88%Mn, 1.49%Cr, 0.009%P and 0.048%S. The sulphur-print shows heavy A- and V-segregates in the equi-axed zone in the central part of the ingot. The peripheral part of the ingot, i.e. the columnar solidified zone, is free from macro-segregations and show relatively short distances between the dendrite arms. It is important to note that smaller ingots are well known to have short solidification times which reduce macro-segregation, and show a columnar zone where solidification has taken place under a relatively high temperature gradient suppressing formation of A- and V-segregates. In large ingots is only the sub-surface zone solidified under such a high temperature gradient.

The same principle with respect to the temperature gradient as for the solidification of small ingots is also comparable to that in continuous casting of slabs. In continuous casting, the steel solidifies under a high temperature gradient creating small distances between the secondary dendrite arms. Furthermore, it can be carried out using full protection of the liquid steel to open air during the time elapsed from BOF tapping until the entire melt is cast.

Lagerstedt and Fredriksson [1] have carried out continuous casting tests using the same chemical composition as was used in the ingot casting trials (see above). The steel was found to solidify under a relatively high temperature gradient, creating a columnar zone from the outer part of the shell all the way into the strand centre-line. A short solidification time was found to suppress formation of both A- and V-type macro-segregations. In essence, the high temperature gradient creates small dendrite arm distances which give low amounts of micro-segregations, see Figure 3. In their work Lagerstedt and Fredriksson [1] clearly show that in a continuous cast structure typical centre-line segregation can be effectively controlled and suppressed by applying a soft reduction to the solidifying slab, thereby eliminating the inter-dendritic flow of liquid steel in the centre region of the solidifying slab. The macro-structures shown in Figure 2 and 3 exhibit large differences in macro-segregation which indicates different solidifying conditions. This difference will also remain in the final product due to the low diffusion rate of alloying elements in their solid state.

Figure 2. Sulphur-print of an ingot of the dimension 746x1089x1700mm [1].

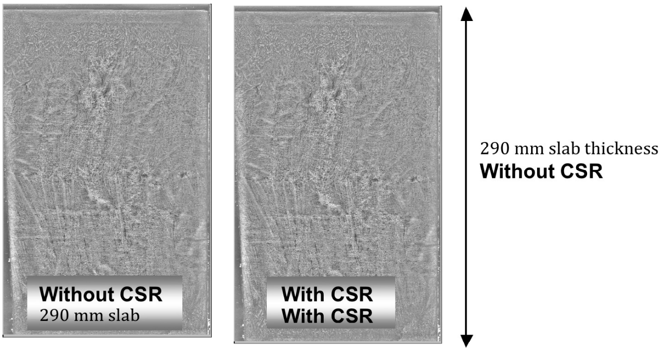

Figure 3. As-cast microstructures in the slabs studied by Lagerstedt and Fredriksson [1].

Steel cleanliness

To gauge the cleanliness of the two newly developed grades, inclusion amounts have been determined in the two new grades and compared against common tool steels. As is shown in Figure 4 and 5, BOF-steelmaking in combination with secondary metallurgy and CSR-casting enables the production of steels having inclusion contents and sizes equal to ingot cast and ESR-remelted steels. The equivalent diameters of the inclusions were established assuming the inclusions to be globular in shape. In plastic moulding a frequently used rule-of-thumb claims that if inclusions on the mould surface are smaller than 25microns are these to be regarded as 'invisible' to the naked human eye, i.e. they will not interfere with the quality of the moulded component. Furthermore, when judging possible influences from inclusions their aspect ratios have to be considered and this value should be kept as low as possible.

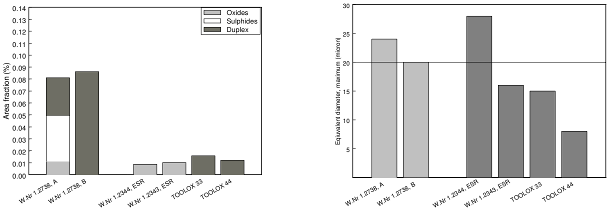

Figure 4. Area fraction of inclusions and their equivalent diameters in steels examined, sub-surface position.

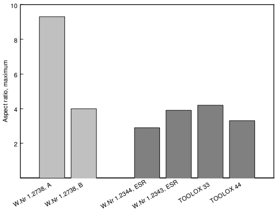

Figure 5. Aspect ratios of inclusions in steels examined, sub-surface position.

Plate and forged bar production

To optimise the toughness in plates, as well as in forgings, it is necessary to effectively control the final austenite grain size. Casting of steel under a high solidification rate gives possibilities to utilise the microalloying technique to control the austenite grain sizes in slab reheating, rolling and any subsequent heat treatment operation.

The results of calculations carried out to predict the austenite grain size after finish rolling of 60mm thick plate, assuming initial slab austenite grain sizes of 400 and 800microns respectively, is shown in Figure 6. The austenite grain size after the last rolling pass (No. 12) is calculated at 25micron. Furthermore, Figure 6 clearly demonstrates that the chosen chemical compositions are insensitive to disturbances in slab reheating temperature before hot deformation in the austenitic state. The grain size differences are levelled out after pass No 7. A comparison between calculated grain sizes and measured is given in Table 2. Good agreement between average measured austenite grain sizes and predicted ones is achieved. No austenite grain growth generally takes place below 880°C in TOOLOX plates when cooled after hot-rolling.

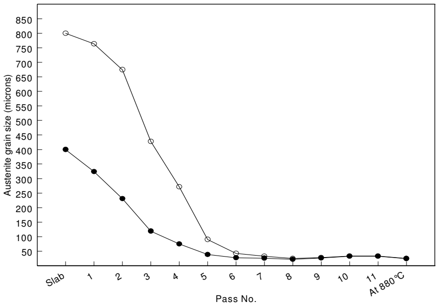

Figure 6. Calculated austenite grain size development during rolling of 60mm thick plate.

Table 2. Microstructures observed in as quenched conditions in TOOLOX plates.

Th. (mm)	**Grade**	**Calc. austenite grain size (micron)**	**Meas. austenite grain size (micron)**
60	TOOLOX 33	25	25
60	TOOLOX 44	25	18

The manufacturing of heavier gauges is through the forging route, where the width of the slab is used as the ingoing thickness, see Figure 7. The slab is forged with a height to width ratio of 6:1 (1700:290mm) using a relatively long length of the anvil, which provides an early through thickness deformation, and opens up the possibility to produce 320x620mm forged bars (thickness x width) that have excellent cleanliness in combination with very good mechanical properties. This forging technology has been tested at three different forging shops and is shown below.

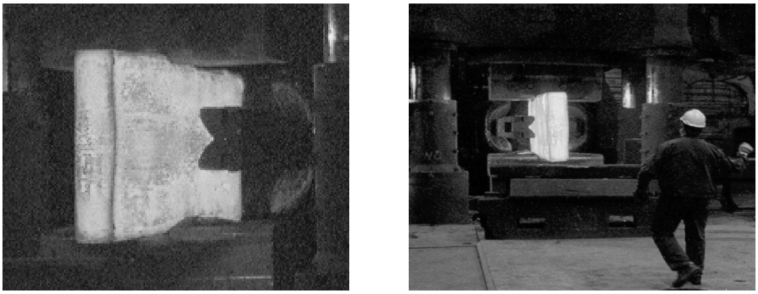

Figure 7. The forging operation.

The austenite grain size evaluation when forging 300mm thick bars has been predicted using MicDel [2]. The bar, see Table 2, has a predicted average austenite grain size and a measured grain size which corresponds very well.

Table 3. Austenite grain sizes in quenched and tempered forged bars of TOOLOX 33.

	Forged thickness (mm)	Bar No.	Pred. grain size (micron)	Measured grain size (micron)
TOOLOX 33	300	1	278	250

Another forged bar that was examined showed a much larger austenite grain size; however, it was forged using a less favourable deformation schedule.

There is a significant difference in austenite grain size, see Table 2 and 3, between plate and forgings which is due to a number of factors:

- Different strain rates in plate rolling ($d\varepsilon/dt \approx 3\ s^{-1}$) and in forging ($d\varepsilon/dt \approx 0.5\ s^{-1}$);
- Differences in time elapsed between individual passes during rolling and forging, and;
- The plate cools much faster, both between deformation steps and after the final deformation as compared to the forging operation.

The main draw-back with forging is the austenite grain growth which takes place during cooling from the last deformation step down to 880°C, below which no austenite grain growth is generally occur in these grades. Despite the large calculated austenite grain sizes, proper use of microalloying elements are shown to be effective.

Impact toughness

The lower carbon and alloy content of the new pre-hardened tool steels, when compared with traditional grades of equal hardness, enables the production of a much tougher tool steel. Figure 8 shows a schematic comparison between typical impact toughness, Charpy-V, of different tool steels.

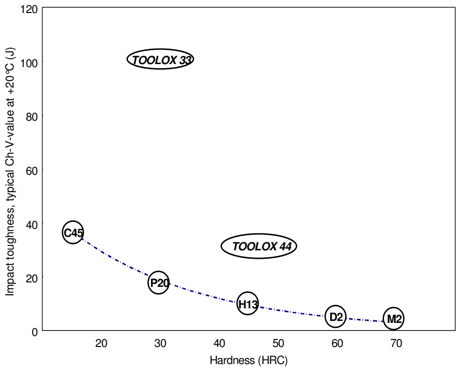

Figure 8. Comparison of typical toughness in different tool steels.

The much higher toughness of TOOLOX 33, when compared with P20, also makes it more resistant to defects than is P20. Table 4 shows examples of differences in maximum acceptable defect size before failure occurs. In this comparison, semi elliptical flaws (a/2c = 0.5 and 0.25) were assumed in a 30 mm thick plate exposed to a uniform tensile stress of 500MPa using BS 7910 [3, 4]. Charpy-V notch impact values, from tests carried out at room temperature, were used in this evaluation. The assessment shows larger tolerable critical flaw sizes in TOOLOX 33, which has a typical toughness of about 100J at RT ($K_{mat} = 113.6MPa\sqrt{m}$) than P20 which has a typical impact toughness of 15J at RT ($K_{mat} = 43.6MPa\sqrt{m}$). Another benefit of the higher toughness of TOOLOX 33 is that it will allow more plasticity in the ligament before an unstable fracture will propagate.

Table 4. Maximum allowable defect sizes [3].

Grade	**a_c (mm) (a/2c = 0.5)**	**a_c (mm) (a/2c = 0.25)**
TOOLOX 33	17.3	12.8
P20 / W.Nr 1.2311	3.9	2.0

Weldability

Traditional tool steels have poor weldability due to their high carbon and alloy contents. Table 5 gives a comparison of the most common tool steels generally used. As is pointed out, these high carbon and alloy contents necessitate high preheat temperatures when welding such grades.

Table 5. Typical chemical compositions and carbon equivalents in traditional tool steels, as well as in the new steels developed.

Grade	**C**	**Si**	**Mn**	**Cr**	**Mo**	**Ni**	**V**	**T_{preh} (°C)**
P20	0.40	0.30	1.45	1.95	0.20	-	-	200 - 250
H13	0.40	1.0	0.4	5.2	1.35	-	1.00	325 - 375
D2	1.55	0.25	0.30	11.5	0.70	-	1.00	~ 400
TOOLOX 33	0.24	1.1	0.80	1.0	0.40	0.2	0.10	min 175
TOOLOX 44	0.31	1.1	0.70	1.3	0.80	0.1	0.11	250 - 300

When judging the weldability with respect to the chemical compositions of the steels given in Table 4 the well-known CE_{IIW}-equivalent should not be used. Dearden and O'Neill [5] in their original published work did not include alloy contents of that amount as are common in traditional tool steels. Furthermore, when welding low alloyed constructional steels, the HAZ hardness has to be limited pertaining to minimize the cracking risk, which in this case means to minimize the martensite amount in the microstructure. In contrast, when welding tool steels the HAZ will be martensitic, as will the weld deposit, to equal the properties of the weld metal and the HAZ to that in the base material.

The TOOLOX grades have much lower alloy contents when compared with the traditional tool steels. As repair welding is often made in tooling these new grades offer much easier welding repair. When comparing P20 and TOOLOX 33, Table 4 shows that the lower alloy content of TOOLOX 33, results in a 50 to 75°C lower preheat temperature. Much larger differences in required preheat temperatures, roughly 100-150°C, are necessary when comparing welding of H13/D2 and TOOLOX 44 respectively. After welding, both TOOLOX grades need to be stress relieve tempered at 580°C to achieve optimum properties.

Tests carried out on welding repair in TOOLOX was undertaken using a solid filler wire, Ø1.6mm, produced from a plate having the same chemical composition as TOOLOX 44. After test welding the test pieces were stress relieved as outlined above.

In the welding repairs of moulds for fabrication of plastic components it is important that no influence of the welding operation can be traced on the surface of the plastic component. A welded sample was therefore prepared to evaluate the weld quality. Half of the sample surface was polished while the second half was photo-etched using a pattern having a smooth surface. No trace from the weld was observed on the photo-etched surface.

Thermal conductivity

Thermal conductivity is one important parameter when designing tool steels. As high thermal conductivities are preferred in:

- Plastic moulds to reduce the cooling time in plastic moulding, and;
- Die casting dies to reduce the heat-checking risk.

The low alloy contents in the new steel grades were chosen with respect to the above mentioned targets. Figure 9 shows a comparison of thermal conductivities between the TOOLOX grades and H13 (quenched and tempered to 45 HRC), all commonly used in plastic moulds. The improved thermal conductivity in TOOLOX when compared with H13 enables shorter production cycles in plastic moulding due to its better thermal conductivity. Calculations carried out by MouldFlow show that approximately 5 % shorter production cycle time can be expected when moulding a detail in Terulan plastic.

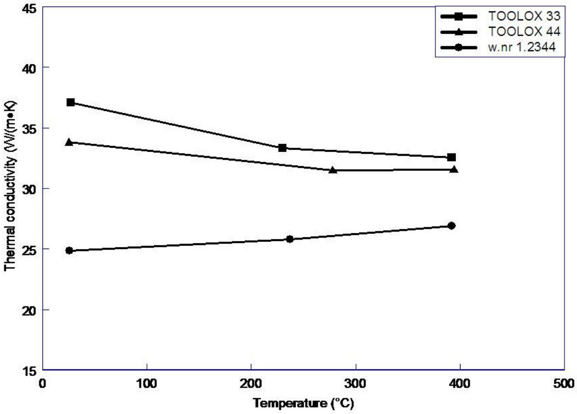

Figure 9. Comparison of thermal conductivities.

Applications

These new tool steels have turned out to show attractive properties in plastic moulding, cold forming and also in hot working applications (die-casting) as well as in engineering/machine steel applications. Figure 10 shows a comparison in mould manufacturing of a mould of standard complexity (note: that the time for heat treatment of the mould made in W.Nr 1.2344 (=H13) is not included in this comparison).

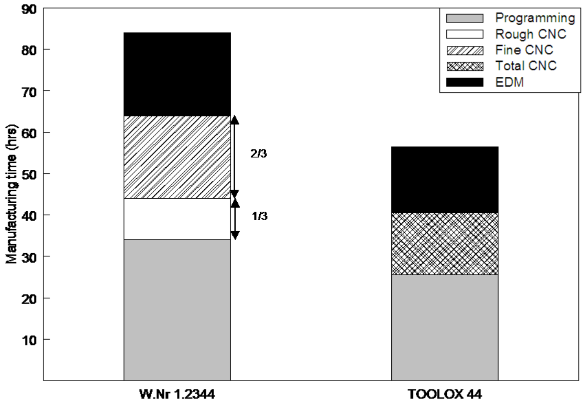

Figure 10. Comparison of mould manufacturing time.

Conclusions

Two new pre-hardened tool steels, eliminating the need for extra heat treatment during mould fabrication, have been developed.

- By a combination of a well performed secondary metallurgy and continuous casting, slabs having equal steel cleanliness as ESR re-melted ingots can be produced. Today the centre-line segregation which may occur in continuous cast slabs can be controlled and also eliminated if the correct combination of casting temperature, casting speed and soft-reduction is used.

- Microalloying can be used to control the austenite grain growth, also in forgings.

- Steels developed have improved impact toughness when compared with traditional tool steels of equal hardness.

- New steels developed have a much lower alloy content than traditional tool steels which gives a better heat conductivity as compared to the traditional H13

References

1. Lagerstedt A., Fredriksson H., Stränggjutning av verktygsstål. ISBN KTH/MG-UND-02/01-SE, TRITA-MG 2002:01. In Swedish

2. Siwecki T., Modelling of Microstructure Evaluation during Recrystallization Controlled Rolling. ISIJ International, vol. 32 (1992), No. 3, p. 368 – 376.

3. Larsson C., Hansson P., Kihlmark P., Toughness of HRC 33/44 Tool Steels Weldments With Yield Strength 1100MPa. 1st Int. Conference Super High Strength Steels, Rome 2005, Ed. Associazione Italiana di Metallurgia, ISBN 88-85298-56-7.

4. BS 7910:1999: (incorporating Amendment No. 1), British Standard Institution, London, 2000.

5. Dearden J., O'Neill H., A Guide to the Selection and Welding of Low Alloy Structural Steels, Institute of Welding Transactions, Oct 1940, p. 203-214.