MODERN PRE-HARDENED TOOL STEELS

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Abstract

Traditional pre-hardened tool steel has been available in the market for decades and is commonly delivered to hardness levels up to approximately 380 HBW (40 HRC). Clean steel manufacturing has seen rapid development during recent decades and has, in combination with improvements in hard machining, provided steel producers the option to design and manufacture very clean pre-hardened engineering and tool steels. This has led SSAB to develop a family of new pre-hardened steels, Toolox, which utilise clean steelmaking practice to minimize inclusion content and continuous casters equipped with soft reduction to control and minimize segregation levels. These modern tool steels are delivered at nominal hardness levels in the range 300 to 450 HBW. The Toolox grades are also microalloyed with niobium to control austenite grain size during heat treatment steps and thereby control and increase the steel impact toughness.

The Toolox grades show very high dimensional stability in machining which enables higher cutting speeds to be used when compared with traditional steels of equivalent hardness and strength. Mould and die making, as well as engineering component manufacturing, are thereby simplified, since there is no need for additional heat treatments which results in reduced lead times and costs.

Additionally, use of effective heat treatment facilities enables the steel producer to choose lean chemistries for the target hardness level. The new chemical compositions provide benefits such as enhanced ductility, high thermal conductivity and improved machinability. Furthermore, such new steels are suitable for surface engineering to develop the desired mould surface properties.

Examples are given in this paper showing the advantages of using the Toolox steels, compared to conventional grades for machining operations, and a model is introduced for determining relative life spans of components subject to wear, depending on the hardness regimes of the interacting bodies. This allows, for example, the determination of the required steel surface hardness to minimize the effect of wear on moulds.

Introduction

Tool steel is essentially a wear resistant steel having a different set of properties compared with grades commonly used in earth moving/mining applications, etc. The main difference is whether the steel grades are developed to possess good welding properties, or developed to have good machinability and very high dimensional stability in the machining operation. Tool steels also require very high cleanliness to enhance their polishing properties. Inclusions have to be kept below 25 microns in size while keeping the area fraction of inclusions as low as possible. Figure 1 gives a summary of different applications/required steel properties.

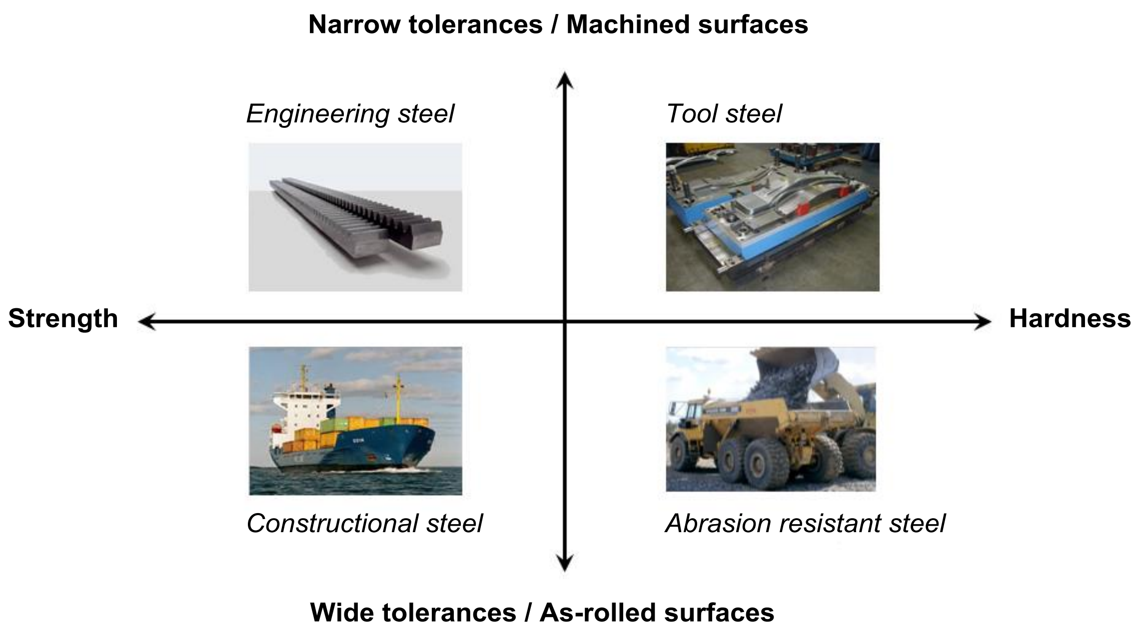

Figure 1. Common steel grade application areas.

Abrasion resistant steels commonly have low alloy contents and are tempered at low/intermediate temperatures to enhance their welding and toughness properties and are usually not suitable in applications exposed to elevated temperatures. However, the newly developed pre-hardened tool steels, Toolox, also offer attractive properties at elevated temperatures. These grades can be used at temperatures up to 590 °C without back-tempering, making them attractive as regular abrasion resistant steels in components which face abrasive wear at elevated temperatures, ie coking plants, slag handling buckets, etc.

When manufacturing, moulds having a surface hardness above approximately 380 HBW/ 40 HRC, soft-annealed tool steels are traditionally the common choice. Depending on which kind of plastic is being moulded, the mould is generally heat treated to a hardness of 45-55 HRC. This heat treatment is not only time consuming, but also generates dimensional distortions due to the phase transformations which take place during the thermal cycle, which have to be corrected after the final heat treatment. Furthermore, the risk for cracks occurring in the mould during quenching must be taken into account.

Modern pre-hardened tool steels, Toolox 33 (300 HBW), Toolox 40 (380 HBW) and Toolox 44 (450 HBW/~45 HRC), offer two major advantages:

- Shorter lead times are possible from ordering of a mould until its delivery;
- The mould has known mechanical properties.

These points arise as there is no need for heat treatment during the mould/die manufacturing and that SSAB issues a certificate showing the exact mechanical properties for each plate produced.

Steel Production and Chemical Composition

Steel shops equipped with effective secondary metallurgy can produce super-clean liquid steel, ie very low levels of tramp elements, in combination with extremely low inclusion contents. The critical part in the steel production cycle is the solidification phase of the liquid steel which needs to be controlled so as not to ruin the steel properties. Continuous casters equipped with integrated controlled-soft-reduction zones, enable very tight control of the steel solidification. The centreline segregation, commonly occurring in conventional casters, can be eliminated when a modern casting machine is used [1]. Figure 2 shows results where slabs of high-sulphur steel have been cast with/without Controlled Soft Reduction (CSR). These trials clearly show the potential of CSR to counter the movement of interdendritic liquid and thus inhibit macro-segregation.

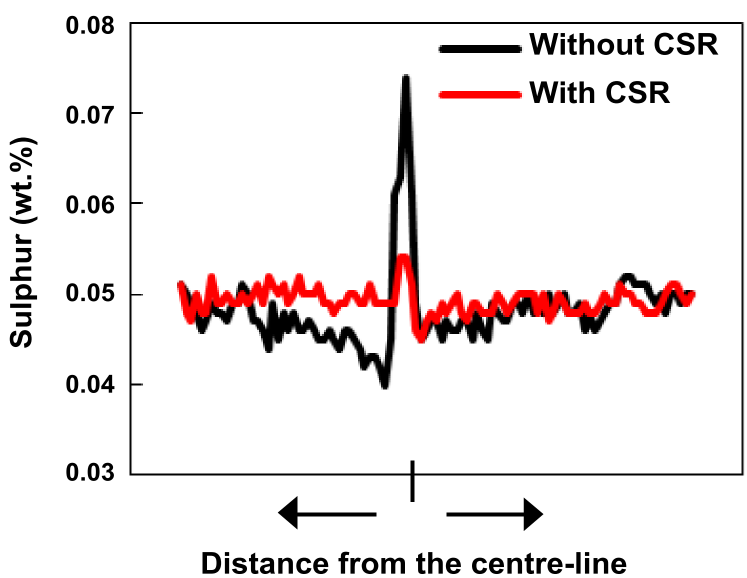

Figure 2. Sulphur segregation at slab centreline.

Furthermore, the steel melting shop has to protect the liquid steel from atmospheric exposure during the casting sequence in order to avoid oxygen pick-up. Protection of the casting is, in this case, by the use of ceramic tubes in the tapping sequence, from ladle into tundish and from tundish into mould, which guarantees an extremely low inclusion content in the solidified steel. The Toolox grades given in Figure 3 are cast with the use of a protected casting system.

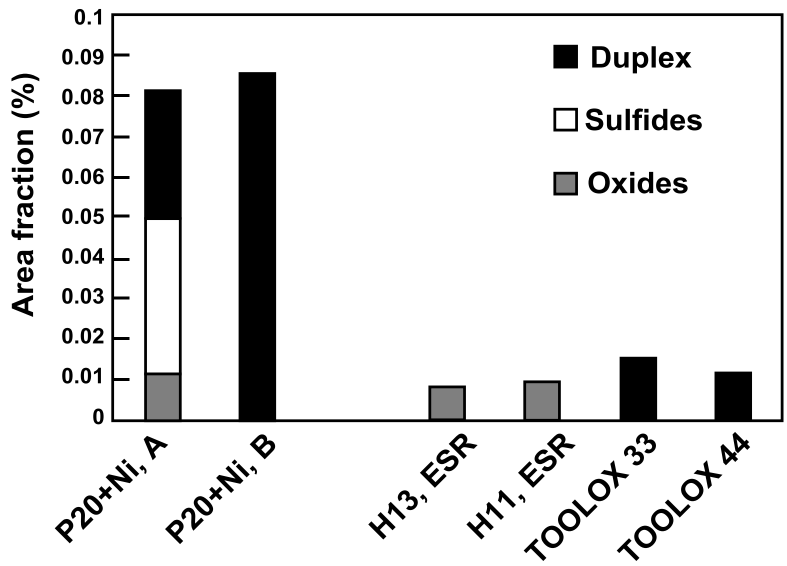

Figure 3. Steel inclusion contents, plate centre position.

Effective heat treatment facilities enable the steel producer to choose leaner chemical compositions when designing pre-hardened steels. When compared with traditional tool steels of equal hardness, P20, P20HH and H13, see Table I and II, the pre-hardened new type steel grades have very lean chemical compositions, which is beneficial to thermal conductivity. In this comparison, the maximum sulphur and phosphorus contents permitted for Superior H13 have been chosen. The Toolox grades are also microalloyed with niobium to control the austenite grain size during the heat treatment steps and thereby control and increase the steel impact toughness. The Superior H13 is normally delivered in the ESR-remelted condition, ie having microsegregation and cleanliness levels comparable with CSR-cast steel, see also Figure 3.

Table I. Typical Chemical Compositions. (wt.%)

	Toolox 33	**Toolox 40**	**P20/P20HH**
C	0.23	0.28	0.38
Si	1.10	1.15	0.30
Mn	0.80	0.60	1.45
S	≤0.002	≤0.002	≤0.035
P	≤0.010	≤0.010	≤0.035
Cr	1.20	1.22	2.0
Mo	0.30	0.50	0.20
Ni	-	0.70	-
Nb	0.015	0.015	
V	0.10	0.12	-

Table II. Typical Chemical Compositions. (wt.%)

	Toolox 44	**H13**
C	0.32	0.40
Si	1.10	1.00
Mn	0.80	0.40
S	≤0.002	≤0.003
P	≤0.010	≤0.015
Cr	1.35	5.30
Mo	0.80	1.30
Ni	0.70	-
Nb	0.015	
V	0.14	0.90

Machining Properties

Pre-hardened tool steels must possess good machining properties in combination with excellent dimensional stability to ensure a straight-forward mould/die manufacturing process. Thereby, the mould/die-maker can exclude the stress relieving step in his manufacturing process and reduce lead time.

The machining properties of steel are partly governed by the carbide contents/distributions in the steel matrix. Chandrasekaran et al. [2] have studied the relationship between carbide amount in the steel matrix and machinability with the use of flat milling tests. The studied grades were Toolox 33 and the European grade W.Nr. 1.2312 (P20+S).

The constants in Taylor’s equation ($Vt^n=C$ where V is the cutting speed, t is the tool life and C and n are constants), see Table III, were established using the following test setup:

- Cutting head, Sandvik Coromill 200 Ø 80 mm;
- Cutting insert, Sandvik GC 1025;
- Feed = 0.15 mm/tooth;
- a_p = 2 mm;
- Cutting width = 60 mm.

The cutting insert edge was defined to be worn out when reaching a flank wear, v_b, of 0.3 mm.

Table III. Constants in Taylor’s Equation Evaluated for the Actual Test Setup

Grade	**n**	**C**
W.Nr. 1.2312 (P20+S)	0.16	476
Toolox 33	0.21	669

The maximum possible cutting speeds for 10, 30 and 45 minutes cutting edge life, calculated using the above data are given in Table IV.

Table IV. Calculated Maximum Cutting Speeds

Grade	**$V_{10\ min}$ (m/min)**	**$V_{30\ min}$ (m/min)**	**$V_{45\ min}$ (m/min)**
W.Nr. 1.2312 (P20+S)	329	276	258
Toolox 33	412	327	301

The costs for each manufacturing step, for a component such as that shown in Figure 4, are compared in Table V. The components were made of Toolox 33 and W.Nr. 1.2312 (P20+S) respectively.

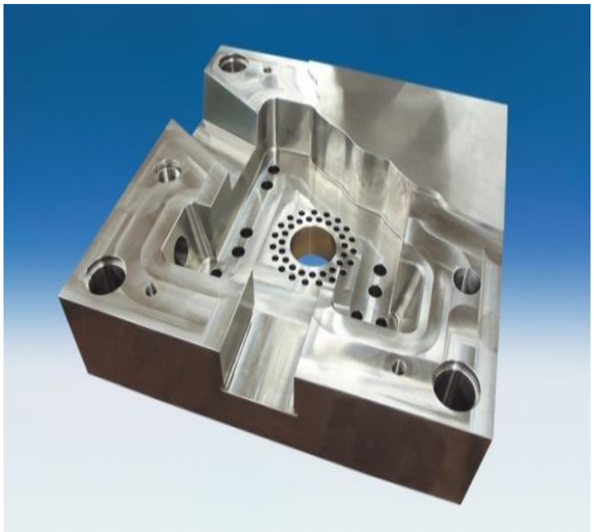

Figure 4. Component made for cost comparison. Size 120 x 1200 x 900 mm.

Table V. Cost Comparison for Manufacture of Component Shown in Figure 4

	W.Nr. 1.2312	**Toolox 33**
Steel cost	719 €	726 €
Machining	4960 €	3930 €
Stress relieving	191 €	-
Grinding	260 €	70 €
Total cost	**6130 €**	**4726 €**

The comparison in Table V shows that a substantial cost reduction, 1404 €/23%, was achieved when choosing Toolox 33 steel to manufacture the component, this was due to:

- faster milling;
- no need for stress relieving;
- machining in only one set-up.

In fact, if the customer had got the W.Nr. 1.2312 blank for free he would still have had a higher total production cost when compared with the total cost of making the component from Toolox 33.

Furthermore, the component manufacturer had to add approximately two days lead time for the stress relief operation when manufacturing the component from W.Nr. 1.2312.

The Hoffmann Group [4] has carried out a comparison which shows the actual time required for each machining step when milling a given cavity in H11 and Toolox 44 respectively, see Table VI. The H11 component was heat treated to a hardness level of 45 HRC in the manufacturing cycle, which in this case required three days lead time.

Table VI. Process Time Required in Each Machining Step

	H11	**Toolox 44**
Roughing	00:53:38	01:21:40
Pre-finishing	01:43:37	-
Finishing	05:14:02	05:14:02
Total	**07:51:17**	**06:35:42**

The study shows a machining time reduction of 16% when choosing a pre-hardened tool steel.

The lead time reduction, thanks to the elimination of heat treatment, needs to be added to the machining time saving, to give an overall picture of the benefit of using the pre-hardened steel.

Mould Service Life Span

Abrasive wear is the dominating wear mechanism in moulding, except for mechanical damage of the moulds/dies. SSAB has developed a wear model [5] pertaining to the description of relative lifetimes of components having different surface hardness levels when subject to abrasive wear. The model is based on two main wear regimes, an aggressive and a soft one. The relative hardness, see Equation 1, is employed to determine the prevailing wear regime.

$$HV_{rel} = HV_{abrasive\ medium}/HV_{mould\ surface} \tag{1}$$

At relative hardness values above 1.6, an aggressive, chip-cutting, wear regime dominates the abrasive wear, resulting in low mould service life length. To obtain a long mould service life, the relative hardness should be well below 1.6 where a soft wear regime, ploughing, prevails. The transition between the wear regimes takes place when the relative hardness equals 1.6. It should be noted that in reality the transition takes place over a hardness range, which depends on the actual wear system. See also Figure 5.

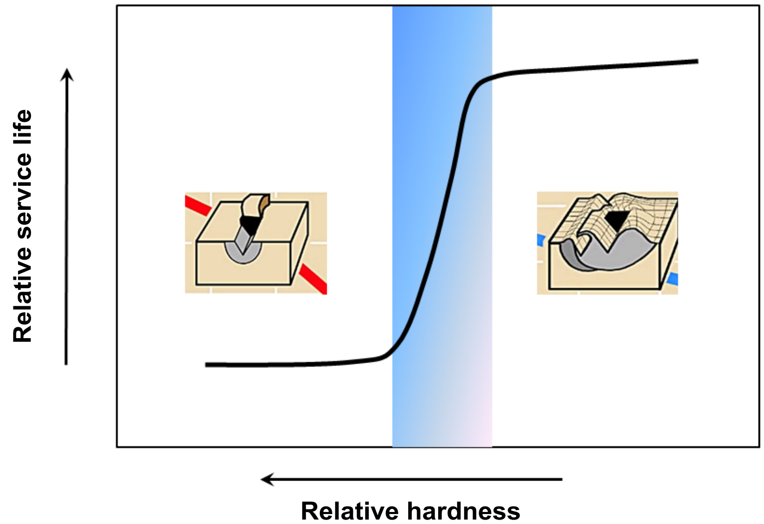

Figure 5. Prevailing wear regimes with respect to the relative hardness.

Using this model, the required mould surface hardness, when moulding a glass-fibre reinforced nylon component, has been determined. The glass-fibre, approximately 1200 HV, governs the actual wear system. The original mould was made of tool steel, W.Nr. 1.2358, heat treated to 55 HRC. This mould, however, showed too short and unpredictable mould lifetimes.

When determining the required mould surface hardness, W.Nr. 1.2311 (300 HBW) was chosen as the reference material and given a relative mould life span of one. The calculated relative service lives for different mould surface hardness levels are given in Table VII. The calculation shows that a minimum mould surface hardness of approximately 660 HV (~60 HRC) is required to ensure the mild abrasive wear mode prevails. A safety margin has to be added and the actual mould surface hardness was chosen to be 65 HRC. An increase in mould surface hardness from 55 HRC to 65 HRC thereby increases mould service life by approximately a factor of six times.

Table VII. Comparison of Relative Mould Service Life

	Relative mould service life
P20 (300 HBW)	1
Toolox 44 (450 HBW)	4
W.Nr. 1.2358 (55 HRC)	6
Toolox 44, nitrided (65 HRC)	35

It was decided to manufacture a new mould in Toolox 44 and to nitride its surface to ensure the soft abrasive wear mode in continuous component production. Directly after mould manufacturing, ie before nitriding, a couple of test runs of ~50-100 components were carried out to check the final product dimensions. The mould was thereafter nitrided and the serial production started. The actual mould was, in this case, used both as a try-out-tool (before nitriding), as well as a serial production mould (when nitrided). Costs and lead times were drastically reduced thanks to elimination of manufacturing of separate try-out-moulds and production moulds.

Die Life Span in Stamping

Die life span is usually governed by adhesive wear in stamping. One of the paramount questions to answer is: which die matrix properties are required in combination with the necessary properties/conditions on the active die/sheet surfaces to achieve long die life span and also to increase the time elapsed between routine maintenance.

Usually, the die steel surface hardness has been the dominant parameter when judging the die performance, while only minor attention has been paid to the die matrix toughness. Modern steel making technology, however, enables steel manufacturing of tool steels with much improved toughness when compared with traditional grades. Traditional tool steels used in stamping dies usually have a toughness of around 5-6 J (Charpy V) at room temperature.

A study was carried out to evaluate the influence of surface-engineered layer properties when stamping Extra High Strength Steel (EHSS) samples, 1.95 mm, DP600. The results are summarized in Table VIII.

Table VIII. Relative Die Life Span

Die steel	Die surface condition	Relative life span
W.Nr. 1.2358	55 HRC/Ra = 0.2	1
Toolox 44	45 HRC/Ra = 0.2	0.9
Toolox 44, plasma nitrided	65 HRC/Ra = 0.2	13
W.Nr. 1.2358, Duplex coated	~70 HRC/Ra = 0.1	>>13
Toolox 44, Duplex coated	~70 HRC/Ra = 0.1	>>13

Ra (µm)

In the actual test set up, the criterion of a successful test was 50,000 stamped samples. Only the duplex coated dies fulfilled this actual criterion. This shows that as long as the die matrix has a sufficiently high yield strength to ensure operation in elastic mode, then the surface engineered layer governs the die life length.

Dies Operating at Elevated Temperatures

Applications where the tool mould/die is exposed to elevated temperatures (die-casting, aluminium extrusion, etc.), put additional demands on the tool steel. In such applications, strength and toughness at elevated temperatures are of interest, in combination with as high a thermal conductivity as possible in the tool steel. High die steel strength and impact toughness properties at elevated temperatures lower the risk for heat checking to occur. Also thermal conductivity influences the heat checking risk. This can be reduced by use of tool steels having high thermal conductivity. The thermal load on the die can be described by the following equation.

$$\sigma = C\alpha E\Delta T \qquad (2)$$

Where E is Young's Modulus, α is mean coefficient of expansion, ΔT is the temperature difference and C is a constant. High thermal conductivity reduces the temperature peak and thereby the thermal load on the die. Furthermore, high thermal conductivity in a die can give higher cooling rates in the solidifying metal, thereby producing smaller dendrite arm spacings and enhanced mechanical properties, notably higher strength, of the cast component [6].

Conclusions

SSAB has developed a family of pre-hardened tool steels, Toolox, which are produced at nominal hardness levels in the range 300 to 450 HBW. These steels are microalloyed with niobium for grain size control and are made with a carefully controlled steelmaking practice to ensure good cleanness and with the use of soft reduction during casting to minimize segregation.

These steels can be used to reduce mould manufacturing time as transport to/from heat treatment and also the heat treatment itself are no longer needed during mould manufacture, giving substantial savings in mould cost and manufacturing lead time.

Surface engineering is an attractive method to optimize the abrasive/adhesive wear properties needed for enhanced mould/die life and Toolox steels are suitable for such processes (nitriding, PVD coating, etc).

A machining trial reported in the current study has shown the benefits of using Toolox grade 33 compared to a European grade W.Nr. 1.2312 in terms of maximum possible cutting speeds and elimination of a stress relieving heat treatment. The study also showed a reduction in overall component cost and a 16% reduction in time to manufacture.

SSAB has developed a wear model to describe the relative life span of components having different surface hardness levels which are subject to abrasive wear. The model can be used to determine the optimum mould hardness level needed, depending on the application, to ensure minimum wear. The model was used to determine the mould hardness required to mould a glass fibre of approximate hardness 1200 HV and a subsequent trial carried out using nitrided Toolox 44 showed very large improvements in mould life.

In some applications the tool steel mould is subjected to elevated temperatures which introduces the risk of heat checking. The Toolox grades with improved strength, toughness and thermal conductivity are suitable for such applications.

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