# TOUGHNESS OF HRC 33/44 TOOL STEELS WELDMENTS WITH YIELD STRENGTH 1100 MPA

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## ABSTRACT

High strength MAG solid welding wires with yield strength above 900 MPa are not to be found in the catalogues of the large consumables manufacturers. One reason is that nowadays small heats of steel cannot be manufactured due to cost consideration and also the need for such wires has not been urgent enough. Instead of a stronger wire it is possible to compensate with a larger leg length where necessary on fillet welds. On butt welding however, such a compensation is difficult to realise. While developing a new tool steel a solid filler wire was produced having equal chemical composition to these new steels enabling repair welding as well as regular welding. This solid wire has yield strength of approximately 1000 MPa, in combination with extremely low sulphur, nitrogen and oxygen contents.

This new high strength steel wire was tested as a TIG welding wire for the new tool steels. Furthermore, the wire was also tested with automatic TIG welding and MAG welding on structural high strength quenched and tempered (QT) steel.

In many structural applications the critical flaw size is the parameter of the largest interest when using such high strength levels. In tool steels the expectations of critical flaws are in general weak. This is explicitly attributed to the inherent low fracture toughness of the traditional tool steels as well as to the high design stress that might be used. The impact of differences in tool steel toughness on critical flaws is shown using the well established BS method for fitness-for-purpose evaluation.

## KEYWORDS

Tool steels, hardness, toughness, welding, TIG, MAG, failure assessment.

## INTRODUCTION

In traditional tool steels, the microstructure usually consists of a tempered martensitic or of a tempered martensitic/bainitic microstructure sometimes together with small amounts of retained austenite. Due to the prior austenite grain size, cooling rate, carbon and alloy content, the as-quenched microstructure in steels can be controlled. The mechanical properties of the tempered martensitic matrix with regard to the proportions of microstructure components, recovered dislocation substructure, amount of carbon in solution and density/size/type of carbides can therefore also be varied. In the tempered martensitic microstructure a high carbon content makes the dislocation mobility more severe (i.e. increases the strain-hardening rate), which consequently has a negative influence on the toughness [1]. High volume fraction of carbides further inhibits the plasticity and also acts as fracture initiations. The tempering effect is strong in martensite, which makes tempering to an important parameter when tuning in the steel properties during manufacturing. However, in the bainitic microstructure the carbon is already precipitated as cementite. The tempering effect of bainite is therefore less than in martensite due to the small quantity of dissolved carbon content that is available to precipitate into carbides and soften the matrix. The bainite laths or plates are, when tempering, also more stable than martensite due to the higher transformation temperature (i.e. closer to equilibrium).

The difference in toughness, and also in strength, between upper and lower bainite is especially interesting. This distinction is caused by the easy initiation of cleavage cracking at the lath boundaries due to cracking of the larger carbides and the inability of low angle bainitic ferrite lath boundaries to impede cleavage propagation in upper bainite and the fine intra-lath carbides in lower bainite obstructing cleavage crack propagation [2]. The complexity of bainite transformation and the terminology of the different steel related microstructures seem however still to be in debate [3, 4], but this subject is out of scope of the present paper.

One way to improve toughness properties in steels and its weldments is to control the grain size [5, 6] via the introduction of second phase particles (AlN, Nb(C,N), VN, TiN) in matrix pinning the austenite grain boundaries. Furthermore, the manufacturing of clean steels having very low sulphur nitrogen and oxygen contents increase the toughness upper shelf energy. Also the improved cleanliness regarding phosphorus has, in combination with grain size control resulted in better tempering embrittlement resistance due to a decreased phosphorus concentration in the prior austenite grain boundaries. When slowly cooled from high temperatures (> 600°C) or soaking at temperatures above >400°C but below 600°C, phosphorus segregates to the prior austenite grain boundaries and causes a tendency to de-cohesion, which makes the steel susceptible to intergranular fracture [7, 8]. Also the risk for martensite tempering embrittlement (250 - 400°C) at room temperature will diminish irrespective of the grain boundary precipitation of fine cementite platelets that are associated with this temperature range and phenomenon. The coarsening and spheroidizing of cementite platelets explain the upper temperature limit of temper martensite embrittlement. Sulphur can be detrimental due to its easy segregation during austenitizing. It is normally tied up as manganese sulphide, but depending on the bulk composition free atoms can still remain for segregation. However, when welding in connection with slow cooling rate sulphur containing compounds can dissolve in the high temperature HAZ and thereafter segregate for further re-precipitation at the austenite grain boundaries, thereby lowering the notch toughness upper shelf energy level. The intergranular fracture associated with this embrittlement is explained by the prior austenite grain boundaries being the only set of high-angle grain boundaries that provide a continuous fracture path [1]. In low carbon steels the fracture mode of temper martensite embrittlement will be transgranular due to insufficient carbon for producing a critical carbide size and/or coverage of the prior austenite grain boundaries [2]. The synergism between various alloy and impurity elements on the grain boundary decohesion tendency must also be emphasized [1, 7, 8].

Since the necessary properties in tool steel, in various degrees, are high strength, hardness and wear resistance the toughness properties generally suffers. Traditional tool steels like P20 and H13 have no toughness guarantees when delivered from the steel producer. In these steels the actual energy absorption is generally about 5-20 Joule at room temperature. NADCA [9] has implemented two toughness levels that have to be fulfilled after heat treatment of H13. When tested at room temperature the Premium Quality and the Superior Quality must guarantee a minimum notch impact toughness of respectively 11 Joule and 14 Joule. The low toughness, if any, specified make commercial tool steels susceptible to failure [10]. Consequently the size of acceptable flaws or the design stress in a specific geometry lowers. The similarities between tool steels and high strength

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structural QT steels in production technique and the possibility to use micro-alloys to control the grain size therefore are emphasized. A decrease in carbon and alloy content improve weldability together with a lowered cold cracking risk [11]. Thereby the preheat temperature should be expected to be lower as compared with traditional tool steels in the same category.

Recently the newly developed tool steels, TOOLOX 33/44, aimed for plastic moulding have been described [12, 13]. These steels have, from the steel user point of view, the benefit of being pre-hardened and not intended to be further heat treated after milling. Problems with distortions have therefore been eliminated. Consequently, this has led to higher productivity for the tool manufacturer. The high steel cleanliness, in combination with low alloy contents, improves both polishability and toughness as compared with conventional tool steels in their respective category (i.e. P20 and H13). The fine-grained microstructure and its influence on toughness (as well as yield strength), due to the Petch effect [14], is shown in Figure 1 [13].

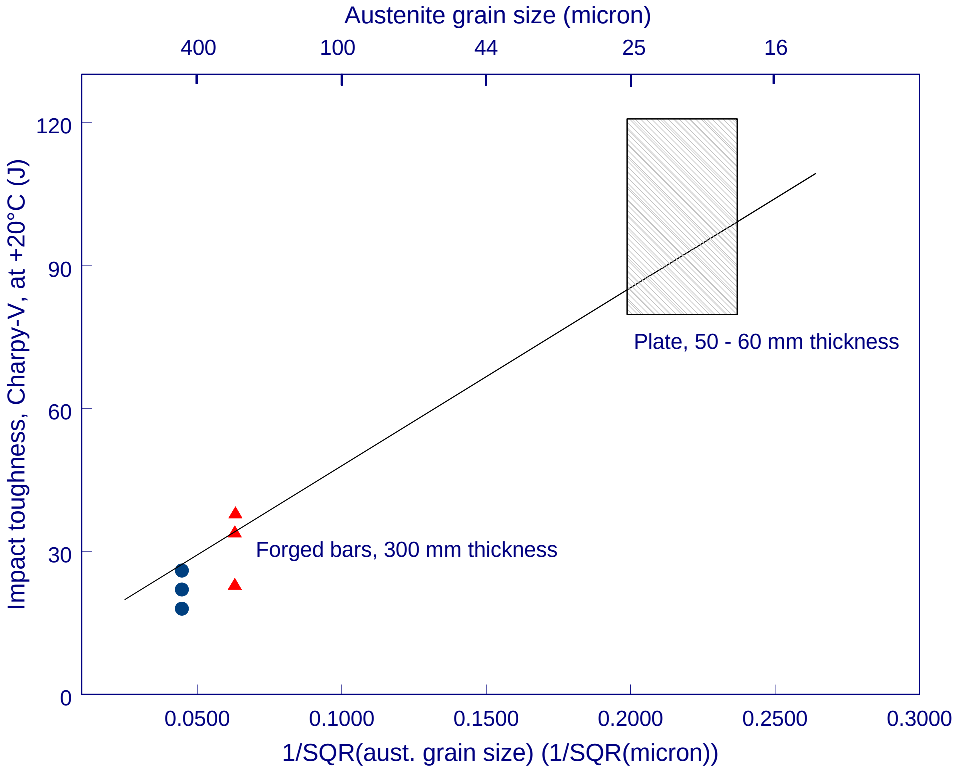

Figure 1. Notch impact toughness, at +20°C, correlated to austenite grain size [13].

TOOLOX 33 and 44 consist of a tempered martensitic microstructure and therefore the toughness properties depend on the austenite grain size, carbon content, size/density of carbides and steel cleanliness.

In the present paper the experimental work with finding a welding procedure and filler material suitable for repairs or modifications of moulds and dies of TOOLOX 33/44 is described. Also a calculation of the size of critical flaws in a simple geometry is made according to BS 7910 [15] superseding PD 6493 [16]. The evaluation is made using results from notch toughness impact tests (CVN). The convenience in using CVN instead of $K_{Ic}/J_{Ic}$ or CTOD for assessing flaws is an advantage. In certain applications, or circumstances, as for fitness-for-purpose reasons (i.e. in existing constructions), surveillance tests [17] or for simple economy reasons this benefit becomes very useful.

## EXPERIMENTAL

For the evaluation of TOOLOX 33/44 weldments billets were cut from a 100 mm TOOLOX 44 plate (Table 1).

Table 1. Chemical composition, weight-%, of the TOOLOX-wire produced
* Oxygen content usually below 10 ppm with the steel-making route used.

| **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Mo** | **V** |
|---|---|---|---|---|---|---|---|---|
| 0.29 | 0.60 | 0.90 | 0.006 | 0.003 | 1.20 | 0.70 | 0.85 | 0.14 |
| **Cu** | **Al** | **Ti** | **B** | **N** | **O** | **$CE_{IIW}$** | **CET** | **$P_{cm}$** |
| 0.10 | 0.035 | 0.02 | 0.002 | 0.004 | * | 0.93 | 0.55 | 0.51 |

The billets were hot rolled to 5 mm wires, and thereafter cold drawn to wires having diameters of 1.0 mm and 1.2 mm. The use of a filler material with a chemical composition similar to the actual tool steel is essential to achieve even hardness and wear resistance as well as tempering resistance and polishability when comparing with the base metal. In repair welding of tool steels also dissimilar filler wires are sometimes used [18].

Two coupons of TOOLOX 33, having chemical compositions and mechanical properties as given in Tables 2 and 3, were welded.

Table 2. Chemical composition, weight-%, of TOOLOX 33
* Se Table 1 (coupon 1 and 2)

| **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Mo** |
|---|---|---|---|---|---|---|---|
| 0.253 | 0.59 | 0.86 | 0.010 | 0.001 | 1.10 | 0.67 | 0.37 |
| **V** | **Al** | **Cu** | **Ti** | **Nb** | **B** | **N** | **Ca** |
| 0.115 | 0.036 | 0.022 | 0.026 | 0.001 | 0.005 | 0.0055 | 0.0005 |
|  |  | **O** | **$CE_{IIW}$** | **CET** | **$P_{cm}$** |  |  |
|  |  | * | 0.76 | 0.45 | 0.44 |  |  |

Table 3. Mechanical properties of TOOLOX 33 base metal
(Average of 3 specimens)

| **$R_{p0.2}$** MPa | **$R_m$** MPa | **$A_5$** % | **CVN (J)** at +20 °C |
|---|---|---|---|
| 885 | 981 | 16 | 109 |

In this evaluation automatic TIG welding was used due to the demands of optimizing the polishability and toughness properties with regard to the inherent cleanliness of the TIG process. Also coupons of structural QT steels were welded. One coupon of WELDOX 900 (Table 4) was TIG welded and two coupons WELDOX 1100 (Table 5) were welded using the MAG process.

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Table 4. Chemical composition, weight-%, of WELDOX 900 (Coupon 3)

| **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Mo** |
|---|---|---|---|---|---|---|---|
| 0.172 | 0.24 | 1.43 | 0.012 | 0.003 | 0.25 | 0.08 | 0.49 |
| **V** | **Al** | **Cu** | **Ti** | **Nb** | **B** | **N** | **Ca** |
| 0.022 | 0.073 | 0.14 | 0.004 | 0.028 | 0.002 | 0.005 | 0.003 |

| **$\mathrm{CE}_{\mathrm{IIW}}$** | **CET** | **$\mathrm{P}_{\mathrm{cm}}$** |
|---|---|---|
| 0.58 | 0.39 | 0.32 |

Table 5. Chemical composition, weight-%, of WELDOX 1100 (Coupon 4 and 5)

| **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Mo** |
|---|---|---|---|---|---|---|---|
| 0.155 | 0.22 | 0.85 | 0.008 | 0.003 | 0.62 | 1.88 | 0.58 |
| **V** | **Al** | **Cu** | **Ti** | **Nb** | **B** | **N** | **Ca** |
| 0.028 | 0.067 | 0.020 | 0.003 | 0.017 | 0.002 | 0.004 | 0.003 |

| **$\mathrm{CE}_{\mathrm{IIW}}$** | **CET** | **$\mathrm{P}_{\mathrm{cm}}$** |
|---|---|---|
| 0.67 | 0.38 | 0.32 |

The evaluation of the new TOOLOX-wire when used in welding structural QT steel is very interesting due to the lack of solid wire filler materials having yield strength above 960 MPa. For productivity reason this also necessitates the evaluation of a more high productive process as MAG with regard to the huge difference in weld running lengths compared with the smaller repairs or modifications expected in tool steels. The demands in toughness properties are however more severe for structural steels due to differences in prioritized properties, design temperatures and estimated failure consequences. The equipments used for the welding procedures are shown in Table 6.

Table 6. Experimental data

| | |
|---|---|
| **Power source** | PROTIG 450; Aristo LUD 450 [ESAB] |
| **Wire diameter** | 1.0 (mm) [TIG]; 1.2 (mm) [MAG] |
| **Shielding gas** | Argon [TIG]; MISON 8 [MAG] |
| **TIG electrode** | WL10 (3.2 mm) |
| **Coupon 1, 2** | 800x400x30 (mm); V (50°); TOOLOX 33 |
| **Coupon 3** | 450x210x35 (mm); V (50°); WELDOX 900 |
| **Coupon 4, 5** | 610x410x30 (mm); X (50°); WELDOX 1100 |

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Each steel type was welded with different cooling times, $\Delta t_{8/5}$, as shown in Table 7.

Table 7. Welding procedures used.

| Coupon No. | Process | Preheat/interpass temperature (°C) | Weld runs | Run | $\Delta t_{8/5}$ (s) |
|---:|---:|---:|---:|:-:|---:|
| 1 | TIG | 200 | 111 | Root | 17 |
| | | | | Filler | 10 |
| 2 | TIG | 200 | 47 | Root | 17 |
| | | | | Filler | 20 |
| 3 | TIG | 200 | 67 | Root | 22 |
| | | | | Filler | 18 |
| 4 | MAG | 175 | 16 | Root | 10 |
| | | | | Filler | 10 |
| 5 | MAG | 230 | 6 | Root | 27 |
| | | | | Filler | 27 |

The cooling times were calculated using WELDCALC, a software made by SSAB Oxelösund AB. It uses algorithms proposed by Uwer and Degenkolbe [19]. For the steels welded control of cooling time is important as the hardness and toughness properties are highly affected by this parameter, to avoid an excessive HAZ softening in the former case, as well as excessive grain coarsening, growth of detrimental precipitations in weld metal/coarse grained HAZ and high volume fractions of un-tempered martensite in the latter are of general concern.

## RESULTS

Impact tests were made according to EN-875. The toughness properties for TOOLOX 33 and WELDOX 900 are shown in Table 8 and Table 9 respectively.

Table 8. Charpy-V results for TOOLOX 33 (10x10 mm test specimens)
F.l. = Fusion line; F.l.+1 and F.l.+3 mm = locations in HAZ

| Coupon No. | Test temp. (°C) | $\Delta t_{8/5}$ (s) | Weld metal (J) | F.l. (J) | F.l.+1 mm (J) | F.l.+3 mm (J) |
|---:|---:|---:|---:|---:|---:|---:|
| 1 | +20 | 10 | 117,119,131 | 121,123,127 | 113,113,115 | 113,113,114 |
| 1 | ± 0 | 10 | 123,123,127 | 123,127,132 | 111,122,130 | 93,105,115 |
| 2 | +20 | 20 | 97,106,126 | 115,119,129 | 111,119,124 | 140,143,156 |
| 2 | ± 0 | 20 | 91,103,119 | 102,103,109 | 101,102,135 | 94,99,137 |

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Table 9. Charpy-V results for WELDOX 900 (10x10 mm test specimens )
F.l. = Fusion line; F.l.+1 mm = location in HAZ

| **Coupon No.** | **Test temp. (°C)** | **$\Delta t_{8/5}$ (s)** | **Weld metal (J)** | **F.l. (J)** | **F.l.+1 mm (J)** |
|---|---|---|---|---|---|
| 3 | -40 | 18 | 64,66,73,164,176,186 | - | - |
| 4 | -40 | 10 | 13,15,18,18,25,33 | 19,25,33 | 25,33,44 |
| 5 | -40 | 27 | 5,17,17,18,18,19 | 13,93,143 | 72,79,121 |

The TIG-welded TOOLOX 33 shows, at test temperatures between 0°C and +20°C, impact properties well above the required transition toughness level (i.e. 27 Joule). The results indicate that when welding TOOLOX 44, using the TOOLOX-wire, equal good properties as for TOOLOX 33 can be expected.

The use of the MAG process and the TOOLOX-wire for joining structural QT steels at the test temperature of -40°C do not fulfil the EN 10 137-requirements of 27 Joule [20]. Welding of structural steels could however be used in connection with TIG welding, but for productivity reason its use is limited to thinner plates. The toughness testing of HAZ in WELDOX 900 is also, to be noticed, not as complete as in TOOLOX 33 due to the extensive research that already has been done in this area [21]. Coupon 3 in Table 10 and 11 shows both the highest average weld metal hardness value and lowest tensile property respectively, which is a contradiction.

Table 10. Hardness tests ($HV_5$)

| **Coupon No.** | **HAZ Min.** | **HAZ Max.** | **Weld metal Max.** | **Weld metal Average** |
|---|---|---|---|---|
| 1 | 280 | 475 | 525 | 470 |
| 2 | 280 | 505 | 490 | 440 |
| 3 | 281 | 339 | 508 | 490 |
| 4 | 320 | 440 | 505 | 430 |
| 5 | 330 | 420 | 450 | 420 |

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Table 11. Longitudinal and transverse tensile tests in weldments (EN 895)
* Rupture in base metal; ** Rupture in HAZ.

| Coupon No. | Long. $R_{p0.2}$ (MPa) | Long. $R_m$ (MPa) | Long. ratio | Trans. $R_{p0.2}$ (MPa) | Trans. $R_m$ (MPa) | Trans. ratio |
|---|---|---|---|---|---|---|
| 1 | - | - | - | - | - | * |
| | | | | - | - | * |
| 2 | - | - | - | - | - | * |
| | | | | - | - | * |
| 3 | 1005 | 1035 | 0.97 | - | - | ** |
| | | | | - | - | ** |
| 4 | 1109 | 1217 | 0.91 | 1088 | 1196 | 0.91 |
| | | | | 1102 | 1203 | 0.92 |
| 5 | 980 | 1156 | 0.85 | 896 | 896 | 1.00 |
| | | | | 987 | 1081 | 0.91 |

Statistical scatter due to differences in laboratory practices most probably explains this. Coupon 3 was evaluated using fewer hardness indentations as compared with the other two coupons. An expected decrease in hardness with longer cooling times is also noticed for both welding processes as well as that the hardness values are lower for the MAG-weldments. These lower weld metal hardnesses are explained by the dilution effect on the weld metal chemical composition from the lower alloyed WELDOX 1100. The mechanical testing hence displays that the TOOLOX-wire is capable of joining TOOLOX 33/44 base metals with regard to its toughness and tensile properties.

## FAILURE ASSESSMENT

Today the use of failure assessment procedures to achieve a safe estimate of tolerable flaws is widespread. When used correctly, a balance between safety and economy due to over-design and unnecessary inspections is possible to achieve. Differences in aims with regard to the industry sector, failure modes and due to being a national regulation/document have led to a number of procedures [22], as for example BS 7910, API 579, and R6. According to the FITNET project an agreed European procedure may possibly become a European standard [23]. The SINTAP project was the first stage in this development and was initiated due to conflicting approaches, i.e different empirical levels of safety and a lack of knowledge of steels with high yield to tensile strength ratios, which describes the new range of HSLA steels [22]. Furthermore, the knowledge of joints with mismatch in strength was important to evaluate. For industrial purposes, several issues are challenging as the use of correct material properties and thermal history, the reliability of Non Destructive Evaluation (NDE), the estimation of residual stresses and applied loads/loading history seem to be of general concern [24]. The above mentioned procedures already include solutions for through thickness variable residual stress distributions and research is still in progress [23]. In the SINTAP procedure guidelines for Non Destructive Testing (NDT) capability have been developed [25]. Also BS 7910, API 579, as well as SINTAP have included opportunities of using Charpy-V data in the failure assessments.

Considering the good toughness properties of TOOLOX 33 the advantage when comparing with similar steels in this steel category, P20, that at +20°C usually has an energy absorption of about 15-20 Joule is shown in Figure 2 and 3.

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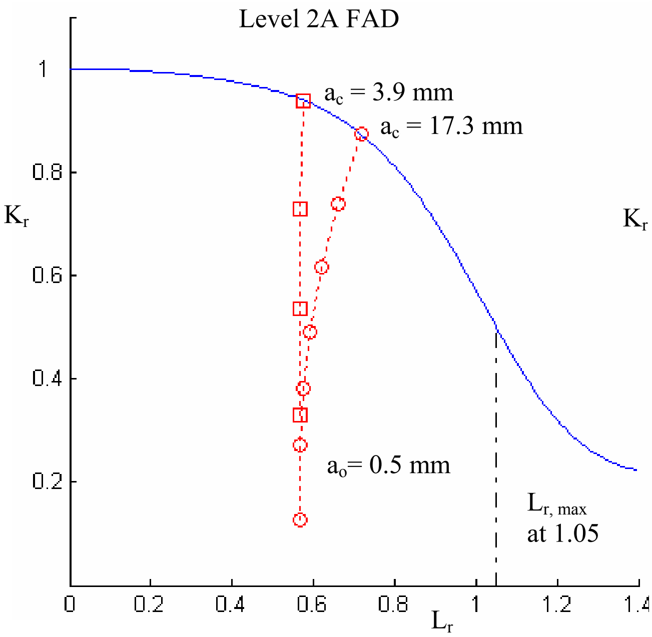

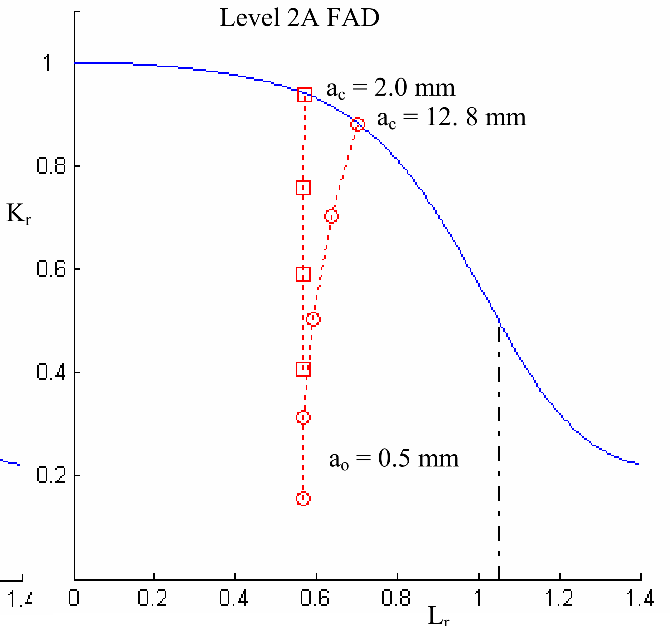

Figure 2. Base material (a/2c = 0.5; t = 30 mm)
Circles = 109 Joule ($K_{mat}$ = 113.6 MPa√m)
Squares = 15 Joule ($K_{mat}$ = 43.6 MPa√m)

Figure 3. Base material (a/2c = 0.25; t = 30 mm)
Circles = 109 Joule ($K_{mat}$ = 113.6 MPa√m)
Squares = 15 Joule ($K_{mat}$ = 43.6 MPa√m)

For the convenience, semi elliptical flaws (a/2c = 0.5 and 0.25) are postulated in a 30 mm thick plate exposed to a uniform tensile stress of 500 MPa using BS 7910. In the assessment the TOOLOX 33 under-matching base material tensile strength is assumed to be valid for the standard P20 steel as well. The difference in critical flaw heights ($a_c$) gives an idea of this benefit (note: partial safety factors = 1.0). Here the actual average TOOLOX 33 base material notch impact value of 109 Joule (se Table 3) is correlated using the BS 7910-algorithm for upper shelf behaviour, $K_{mat}$ = 113.6 MPa√m. An assumed value of 15 Joule is correlated using the algorithm for lower shelf and transitional behaviour, $K_{mat}$ = 43.6 MPa√m. An impact value of 15 Joule could also, according to Annex J, be used with Wallin's "Master curve approach" [26]. Further evaluation of this approach however recommends that estimates of $T_{27J}$ should not be performed below 21 Joule from Charpy results obtained from a single temperature [27].

The assessment when using 15 Joule shows little local yielding before the cracks becomes critical (squares in Figure 2 and 3). This result in critical flaws dominating at the $K_r$ side of the FAD diagram and a brittle fracture is predicted to occur when the cracks are shallow. An improved toughness of 109 Joule allows more plasticity in the ligament before an unstable fracture will propagate. This also shows in the FAD where the critical flaws in this case have turned towards the part of FAD that represents failure by local plastic collapse (circles).

In the present evaluation of TOOLOX 33 the aim was, however, to find a suitable filler material and welding procedure for the use in repair welding or if modifying an existing tool/die. The experimental procedures revealed hence that the TOOLOX-wire well could be suited for this purpose, with regard to its toughness and tensile strengths properties. Here semi elliptical flaws (a/2c = 0.5 and 0.25) positioned parallel with the welding direction are assessed in TOOLOX 33, as shown in Figure 4 and 5.

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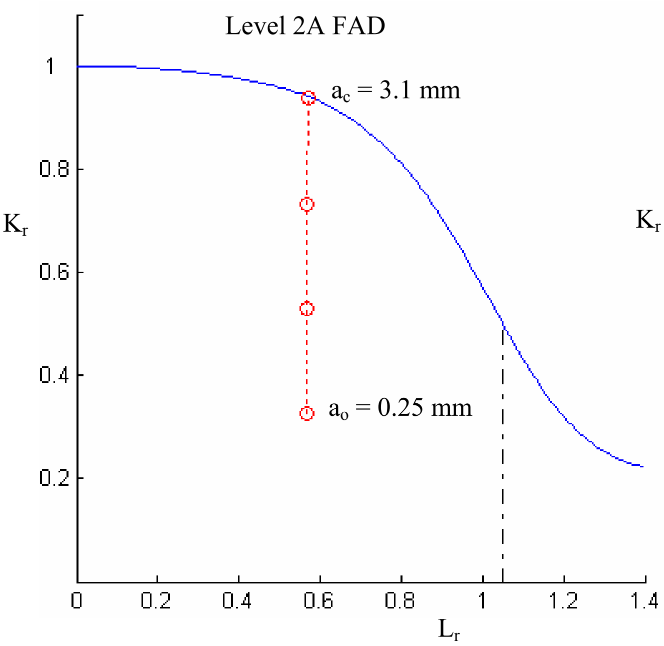

Figure 4. Weldment of TOOLOX 33 (a/2c = 0.5; t = 30 mm); Circles = 97 Joule ($K_{mat}$ = 107.1 MPa√m; Upper shelf behavior)

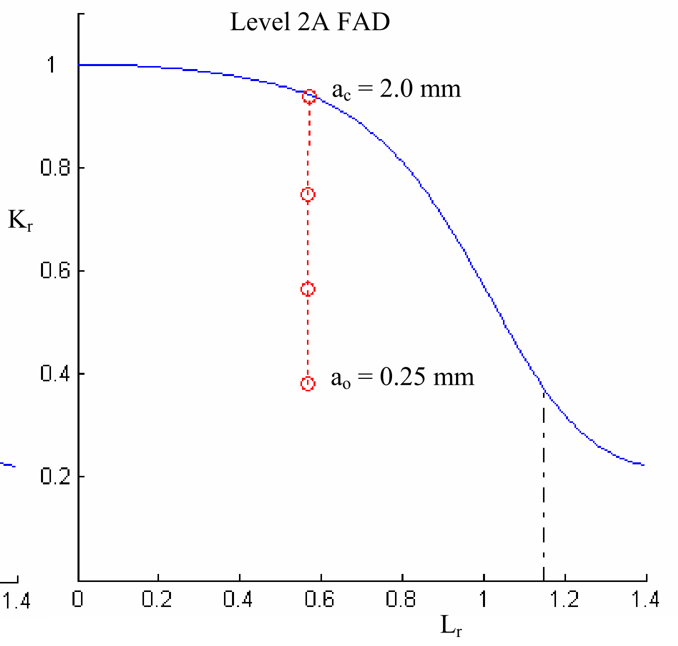

Figure 5. Weldment of TOOLOX 33 (a/2c = 0.25; t = 30 mm); Circles = 97 Joule ($K_{mat}$ = 107.1 MPa√m; Upper shelf behavior)

As shown in Figure 2 and 3 the flaws are exposed to a uniform tensile stress of 500 MPa in a 30 mm thick plate. No stress concentration caused by the toe is assumed, that otherwise would further decrease the critical flaw size. Due to the inhomogeneous microstructure of weldments the lowest impact toughness value of 97 Joule at +20°C is used (Table 8; $\Delta t_{8/5}$ = 20s). With regard to that the energy absorption is somewhat between transitional and upper shelf behaviour a comparison was performed using the algorithms for both behaviours. In this case the difference in critical flaw height becomes very small, but dependent upon the assessed plate thickness the magnitude of this difference will vary. Since the algorithm for upper shelf behaviour gives the smallest critical flaws that value is used in the assessment. Thus, for a/2c = 0.5 the critical flaw height decreases from 17.3 to 3.1 mm in as-welded condition and when a/2c = 0.25 a decrease from 12.8 mm to 2.0 mm occurs. If the fracture toughness value instead would be 43.6 MPa√m (CVN = 15 Joule) then in the as-welded condition the critical flaw heights become 0.5 mm and 0.3 mm for a/2c = 0.5 and a/2c = 0.25 respectively. This is the subsequent consequence of the contribution from residual stresses to the stress intensity that affects the flaw. In BS 7910 the algorithm for through thickness variable residual stress distributions in a plate butt weld is limited to a proof stress of maximum 740 MPa. Therefore a more conservative residual stress distribution is assumed that is correlated with the tensile properties and consequently becomes higher when the steel strength increases. Thus, some improvements of assessed critical flaws in welded tool steels are implied and could therefore be anticipated if these validated proof stress ranges would extend.

The assessments are also conservative with regard to the correlations between Charpy-V and $K_{mat}$. These predicted critical flaw heights for both base metal and weldment would be less conservative if using actual $K_{Ic}$ or critical CTOD/J values. Actually, sound based relationships between upper shelf Charpy-V energy and critical J values that are validated for a wide range of steels [28, 29] have recently been proposed. In the former reference the actual uniform fracture strain is used, which with TOOLOX 33 base metal mechanical properties (see Table 3) gives $J_{0.2}$ = 232 kJ/m$^2$. In the latter reference the uniform fracture strain is conservatively estimated ($A_5$ = 6.8%) that gives

$J_{0.2}$ = 174 kJ/m$^2$. These values give $K_{mat}$ values of 229 MPa√m and 198 MPa√m respectively by using the relationship (1) where E is the Young modulus and ν is the Poisson ratio.

$$K_{mat} = (E \cdot J_{0.2}/(1-\nu^2))^{0.5} \qquad (1)$$

Thus, improvements with regard to the inherent conservatism in the Charpy-$K_{mat}$ upper shelf correlation could well be anticipated if using fracture toughness test.

Besides this dilemma of, in certain cases, being too conservative the expectations are that critical flaws in weldments in general will be smaller when compared with the non-welded parent metal. Therefore when modifying tool steels the importance of a good weld plan that, if possible, to avoid the most stressed areas is of course not to be neglected.

## DISCUSSION

The notch impact tests of TOOLOX 33 base metal show excellent toughness properties at +20°C as well as at ±0°C. This is explained by its fine microstructure, high cleanliness and relatively low carbon content with regard to its effect on lowering the strain-hardening rate of the tempered martensitic matrix. When limiting the carbon content in combination with the amount of carbide forming elements the density and size of carbides will be smaller. This has a large influence on the matrix toughness due to the well-known fact that carbides function as plasticity inhibitors and as fracture initiators.

The notch impact tests of joints of both a tool and structural steel show that the toughness properties are excellent at ±0 °C and +20 °C and adequate at -40 °C when using the TOOLOX-wire in connection with TIG welding. In general when joining steels at this strength level the problem is to achieve a combination of a satisfying weld metal toughness and also strength properties. The reason for achieving this is partly explained by the cleanliness of the used wire with respect to the phosphorus, sulphur and oxygen contents. As with the base metal the relatively low carbon content and small density of precipitates are also advantageous in this respect.

High wire cleanliness gives cleaner austenite grain boundaries in the deposited weld metal, which lowers the risk of decreased grain boundary cohesion strength, and hence the risk for inter-granular fracture. A lower carbon and alloy content will decrease the strain-hardening rate of the matrix. The feature of TIG welding, that gives low contents of oxygen and sulphur inclusions, in combination with small weld beads that give a well tempered martensitic weld metal matrix in connection with a balanced cooling time should also be emphasized.

Although no conclusion based on statistical reasons can be drawn, the result shows that weld metal yield strengths are fairly well predicted by the formula (2) developed by Hart [30].

$$\sigma_Y \leq 2.2 \cdot HV + 90; \quad \leq 1200 \text{ MPa} \qquad (2)$$

Using the test coupon average hardness values (see Table 10), the predicted weld metal yield strengths would for test coupons No. 4 and 5 (WELDOX 900 and WELDOX 1100 respectively) be 1036 MPa and 1014 MPa respectively. These values are 73 MPa below and 34 MPa above the actual values reported. The average hardness value of coupon No. 1 and 2 (TOOLOX 33) is 455 $HV_5$. According to Hart a nominal yield strength value would be 1091 MPa.

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Due to differences in ductility of steels the correlation between hardness and yield strength is however in general seen as less obvious compared with the correlation between hardness and tensile strength. One can in this respect use another convenient approach to reach what is reasonable to expect in TOOLOX 44 weld metal yield strength. The average hardness value of 455 $HV_5$ is extrapolated in Nevasmaa's expressions (3, 4)), which are evaluated from FCAW and FCAW/SMAW weld metals respectively [31].

$$R_m = 2.47 \cdot HV_5 + 93; \quad \leq 365 HV_5 \qquad (3)$$

$$R_m = 2.83 \cdot HV_5; \quad \leq 365 HV_5 \qquad (4)$$

The average tensile strengths then become 1217 MPa and 1288 MPa. Using a yield to tensile ratio of 0.90 gives average yield strengths of 1095 MPa and 1159 MPa. The former value is actually almost the same as when using Hart's formula (2) due to the similarities with the in this case resulted yield strength formula (5).

$$\sigma_Y = 2.22 \cdot HV_5 + 84 \qquad (5)$$

The nominal all weld metal yield strength would then be about $Rp_{0.2} = 1100$ MPa when using the TOOLOX-wire for joining of TOOLOX 33/44 base metal. The validity range in cooling time is in this respect $\Delta t_{8/5} = 10 - 20$s.

The main purpose of the present evaluation was to find a welding procedure for the joining and/or repair welding of TOOLOX 33. However, the use of TOOLOX-wire also showed satisfying impact toughness at -40°C when TIG welding the structural QT steel WELDOX 900. For productivity reason this procedure is limited when joining thicker plates but could be an alternative for automatic TIG welding of thinner plates. When welding WELDOX 1100 with the MAG process the notch impact tests at -40°C showed energy absorption below the requirement of 27 Joule (see Table 9). A combination of higher inclusion content and larger fraction of un-tempered martensite in the as- deposited weld metal explains the difference as compared with the results achieved when using the TIG process.

## CONCLUSIONS

A new welding wire aimed for modifications and repair welding of TOOLOX 33/44 has shown satisfying results. The excellent toughness properties at +20°C and ± 0°C are explained by the interaction of the cleanliness of the wire and for these steel categories low carbon contents as well as the inherent cleanliness of the TIG process. This wire could also be an alternative for TIG welding of structural high strength QT steels of thinner plates.

Using the present wire in the MAG process for welding structural QT steels gave inadequate results with regard to toughness properties.

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