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Properties mismatching and distribution on structural steels welded joints

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ABSTRACT

The paper presents results of combined, conventional and non-conventional, approach for evaluation of mechanical and technological properties of structural steel's welded joints. The selected structural steels are in the range of most common used strength level(s), as well as corresponding various chemical composition concept(s) and processing routes. A short review regarding weldability is presented based on recommendation provided in EN 1011-2, manufacturers recommendation, and own results. However, even it is a well-known fact, mismatching of properties is presented rather to provide sense of its level for particular steel grades. Moreover, the level of under-matching of weakest weld zone (coarse grained heat affected zone), provided by mean of welding thermo-cycle simulation is presented. This is due to the fact that such estimation is not possible with everyday conventional (standardized) testing. The most important design and technological properties of welded joint(s) are considered; e.g. strength, ductility, hardness, microstructure and toughness.

Key words: *Properties, mismatching, distribution, steel, welded joint;.*

1. INTRODUCTION

The main subject of the paper is mismatch and distribution of mechanical properties of the structural steel welded joints. For initial consideration of base metals and its delivery condition and weldability issues, the strength grades from 355 to 890 MPa, yield stress (Y), are considered. Thus, as an introduction to this paper, a review of basic properties, including carbon equivalent (CET), are reviewed and commented, particularly regarding dependence of steels strength (Y) to some basic design and technological properties. It will be shown, that welded joints mismatching of properties can be significant, particularly regarding strength and toughness. However, such analysis may be performed only using rather sophisticated methods of specimen's preparation, prior to final testing. Such methods consist of preparation of "testing ready" specimens, and further simulation of welding thermo-cycles, which can characterize some parts of heat affected zone (HAZ) of welded joints which are well known as weakest one, e.g. coarse-grained heat-affected zone (CG-HAZ).

Initial analysis of base metals (BM), e.g. structural steels, is done based on available data from various sources, including some owns researchers. The major analysis of mismatching and distribution of mechanical properties along perpendicular axis of welded joints is based on particular own research, for 690 and 890 strength grades

2. BASE METALS

While there is a general trend towards use of higher strength steels (such as 460 grade and stronger) for manufacturing of lighter and economically beneficial welded products, there is still some limitations regarding design code's requirements. Thus, 20 years ago, 275 strength grade (such as S275J2) was the norm, and 355 mostly the exception. Nowadays, 355 grade is the norm, and even higher strengths steels are available, up to 890 and 960 grades.
The design limitations are basically set regarding yield stress (*Y*) to tensile strength (*T*) ratio and ductility (elongation at failure) *A* [1].

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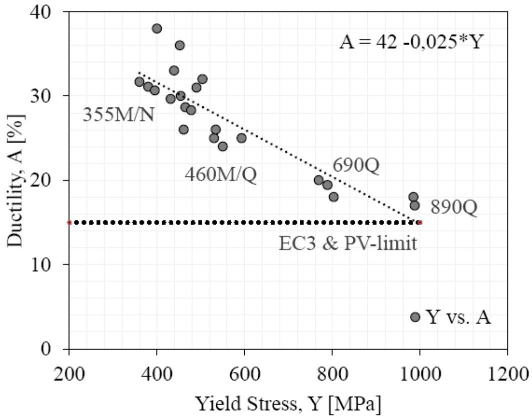


Fig.1 *Dependence of ductility on strength*

2 [4], the *KV* for Impact Toughness at room temperature (*RT*) and the *K* for Fracture Toughness, also at *RT*.

In addition to A and Y/T, there is also a linear trend regarding dependence of hardness on strength (Fig. 3) of BM; while toughness (K) shows significant scatter, mostly depending on strength level and delivery condition (Fig. 4), where 460 grades shows highest level of toughness.

For design purposes, or even structural integrity assessment, of any welded product, the strength and toughness are the most influential design variables; while for a simplified outlook, the carbon equivalent is most important (welding) technological variable of BM(s). Thus the attainment of both strength and toughness is a vital requirement for most structural steels; but unfortunately these properties are mostly and generally mutually exclusive. The same requirement is also applicable for a welded joints, which is clearly defined trough the principles of a welding procedure qualification, particularly where toughness is a major design parameter [9].

Table 1 *Considered steel's grades and basic data [5 -8]*

Nominal Strength Grade	Delivery condition	CET range	Y/T ratio range	A range [%]	BM, HV10 range	KV @ RT range [J]	K_{Ic} @ RT range [MPa*m^{0,5}]
355	N, M	0.225-0.309	0.65-0.82	26-33	148-175	155-204	141-378
390	M+Q	0.235	0.85	31	198	298	-
420	M+ACC	0.221	0.86	36	180	298	-
460	M+Q, M, QT	0.230-0.263	0.81-0.89	24-32	177-277	231-298	255-530
690	QT	0.309-0.374	0.89-0.94	18-20	283-285	196-225	263-306
890	QT	0.283-0.369	0.94	17-18	336-364	157-191	130-147

Actually, depending on design code, such as the API 5L or Eurocode 3 (EC3) [1]-[2]-[3], *Y/T* may be limited to maximum 0.90-0.93, while limits for *A* are as minimum of 10-15% [2]. Also, depending on other essential design requirements a toughness may become demanding property. Thus, there is a well-known facts that with the increase of the strength (Y) there is an almost linear drop of the ductility (*A*) (Fig. 1), as well as tendency of *Y/T* ratio towards 1, which does not provide any plasticity behaviour of very high strength steel (Fig. 2).

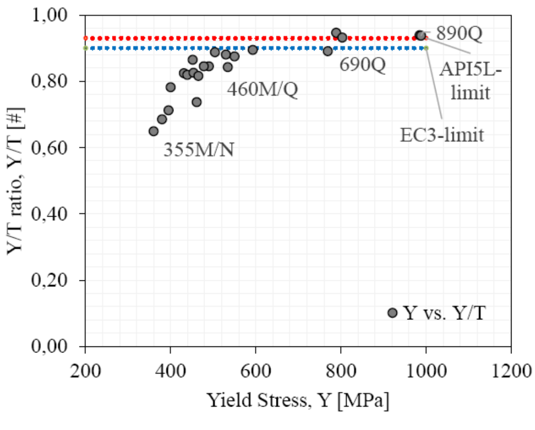


Fig. 2 *Dependence of Y/T ratio on strength*

The considered steel's grades basic data, as shown on Fig. 1 and 2, are shown on Tab. 1. For further analysis, additional basic data are provided; where for delivery condition: *N* stand for normalizing, *M* for thermomechanical treatment, *Q* for quenching, *QT* for quenching and tempering, and *ACC* for accelerated controlled cooling. Furthermore: the HV10 stand for hardness, the CET for Carbon Equivalent as per EN 1011-

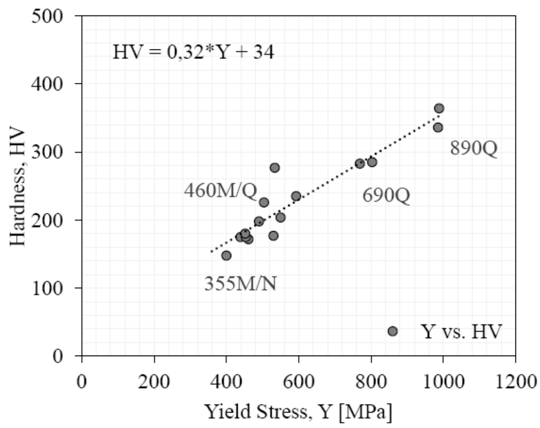


Fig.3 *Dependence of Hardness on Strength*

However, while it is not quite easy and in meaningful manner possible (in everyday engineering practice) to evaluate HAZ toughness, particularly of CG-HAZ, the use of welding thermo-cycles simulation, or simply "simulation" methods become particularly helpful. With such tools and methods, the weldability issue, regarding provision of optimum cooling time form 800 °C to 500 °C, e.g. t, become more feasible [7]-[10]. The problem of extraction of reliable specimen for toughness evaluation is shown on Fig. 5b; where common weld joint preparation, such as V or X groove, may not provide full representative microstructure of HAZ. Actually, the front of crack growth may extends across several and different part of HAZ, and even trough BM.

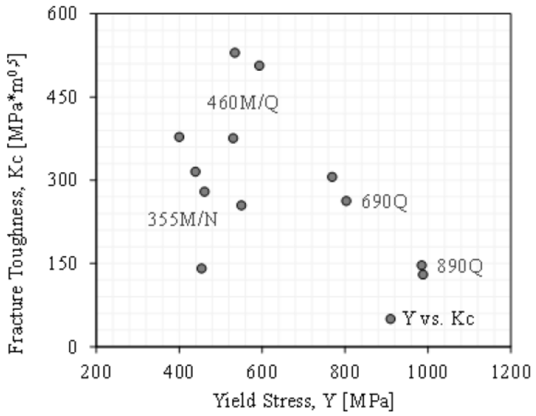


Fig. 4 *Dependence of Toughness on Strength*

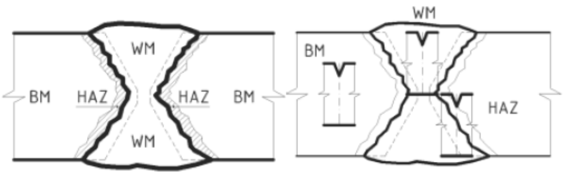


Fig.5 *Welded joint zones and location of toughness specimens: Welded joint zones (left) and position of initial notch for toughness testing (right)*

Therefore, to overcome this problem, as well as to provide detailed introspection into HAZ properties distribution, the more sophisticated method of "welding simulation" become helpful.

3. SIMULATION OF WELDING THERMO-CYCLES

For detailed investigation of HAZ properties and technological (Heat Input, Q, or cooling time, t) influence on the same, it is a common nowadays scientific practice to simulate and further evaluate any zone of interest within HAZ, which is basically determined by its welding thermocycler (s). Number of such studies [7]-[10]-[11]-[12] are performed, where it is shown that the weakest part of HAZ is CG-HAZ, with its peak temperatures around 1300 °C. In addition, grain-refinement effect within fine-grained HAZ (FG-HAZ) with thermo-cycle peak temperature around 900 °C, as well as effect of subsequent passes (for mostly used multy-pass welding) on CG-HAZ is of particular importance (e.g. first cycle to 1300 °C and subsequent to 900 °C; finally FCG-HAZ; Fig. 6). From technological and microstructural perspective, the cooling time, $t_{8/5}$, is of crucial importance.

Such approach may be particularly helpful to evaluate optimum $t_{8/5}$ for selected steel grade, by mean of evaluation of basic design properties, strength, Y, and toughness, KV; and its dependence on technological inputs (Q, $t_{8/5}$). Results of one such study [7] are shown in Fig. 7-9 for one 460M steel grade. The subject steel was micro-alloyed (Nb, Ti, V) and in thermomechanical treated condition, with CET=0,245, and initial Ferite (F, matrix) + Perlite (P) microstructure (Fig. 9a).

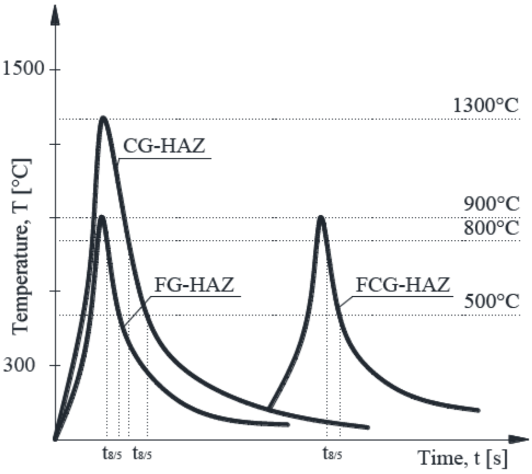


Fig. 6 *Thermo-cycles for HAZ simulation*

Characteristic HAZ zones (CG-HAZ, FG-HAZ and FCGHAZ) where simulated in accordance to thermo-cycles as shown schematically in Fig. 6; with variable cooling time in the range: $t_{8/5}$=5-20 s.

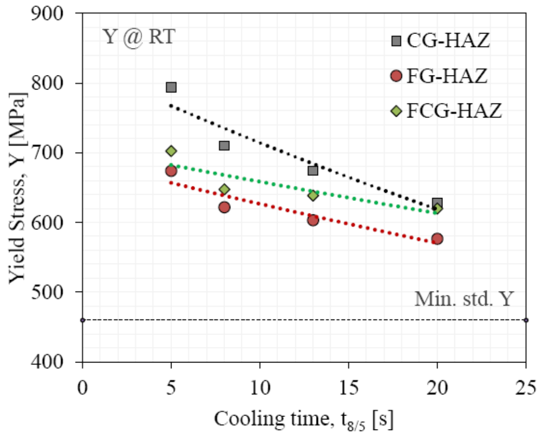


***Fig.** 7 Dependence of HAZ zone's strength on cooling time for 460Mgrade [7]*

From Fig. 7 is obvious linear dependence and drop of strength, Y, with increase of cooling time, $t_{8/5}$All HAZ zones shows sufficient strength level (higher than standardized one, std. Y); and principally allowable level [9] of hardness, cca. 288-295 HV10. Contrary, as shown on Fig. 8, standardized impact toughness requirement of minimum KV=60 J at -40 °C is not achieved at all for CG-HAZ, with high under-matching in comparison to FG-HAZ (cca. UMCG/FG=0.1); and it is obviously dependent on cooling time, $t_{8/5}$. However, it can be seen (Fig. 8) that optimum $t_{8/5}$ range, considering highest toughness values, is 7-14 s.

High decrease of toughness within CG-HAZ, and significant under-matching, in comparison to FG-HAZ and BM is primary consequence of grain size growth (e.g. up to x20 times, or up to 24 µm) and altered microstructure composition (some quenching effect is present, due to the medium content of bainite (B) and small, cca. 10% martensite (M) fraction) as shown on Fig. 9b [7].

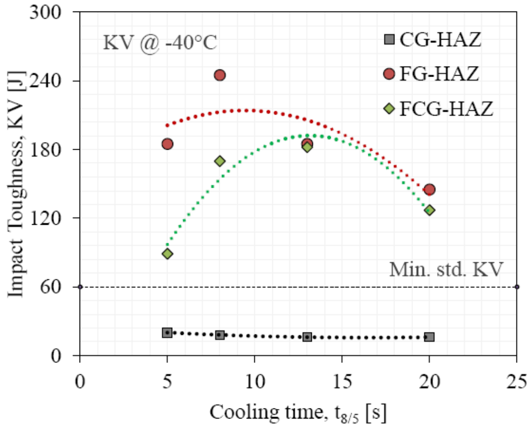
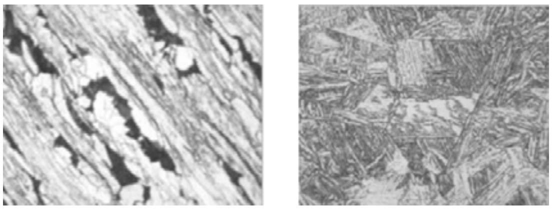


Fig. 8 *Dependence of HAZ zone's toughness on cooling time for 460M grade [7]*



a. BM size 100x100µm, F+P(+B), grain size 2-10µm

b. CG-HAZ, size 100x100µm, F+B+10%M, grain size cca. 24µm

Fig.9 *Dependence of HAZ zone's toughness on cooling time*

4. WELDABILITY

According to EN 1011-2 [4], the weldability of so called "ferritic fine-grained structural steels" are dependent both on design and technological parameters (Tab. 2); without neglecting heat flow - physical properties.

Table 2 *Weldability parameters*

Design	*Technology*
BM, CET	Heat Input, Q
Thickness, d	Use of Preheating, Tp
Joint type / Factor (F2/3)	Achieved t8/5
Optimum t8/5 for BM	HD, residual hydrogen

Here, the most important design, as well as technological variable is $t_{8/5}$. Proper use of optimum $t_{8/5}$ (range) provide optimum combination of mechanical properties; e.g. hardness, strength and toughness; of a welded joint. Therefore, too short $t_{8/5}$ (i.e. fast cooling rates) may cause unallowable increase of hardness and furthermore the risk of cold cracking (RCC); while to high $t_{8/5}$ (longer heating on high temperatures) may cause increase of HAZ microstructure grain size (particularly within CG-HAZ) followed with undesirable toughness loss (Fig. 8 and 9). Helpfully, the optimum $t_{8/5}$ ranges are well known, and mostly provided within manufacturers specifications of BM [4, 13, 14]. Thus, it can be seen that higher strength grades steel are within narrower $t_{8/5}$ range limits; which in addition complicate its weldability, in general (Fig. 10).

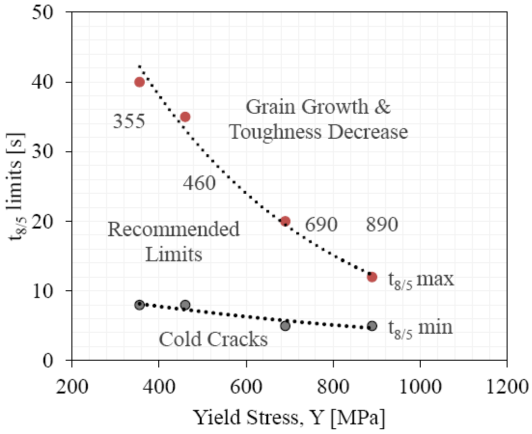


Fig. 10 *Dependence of Optimum $t_{8/5}$ range on Strength [13]-[14]*

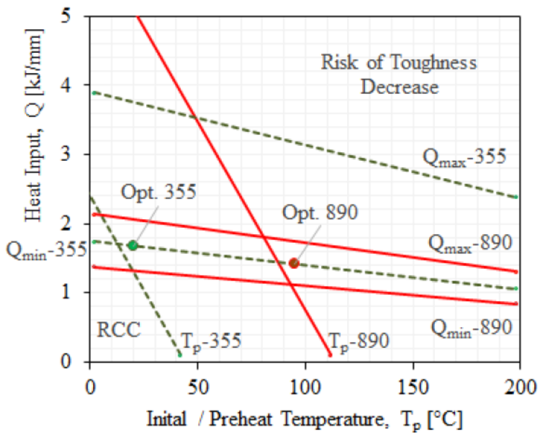


Fig.11 *Selection of optimal Q and T*

For example; if we consider thickness of BM, d=20mm (and 2D heat dissipation), common values of CET for the two "extreme" steel grades (e.g. 0.26 for 355 and 0.36 for 890; from Tab. 1), and GMAW (135) welding process (including HD=5 ml/100g), on butt joint (F=1); the general outlook of weldability requirements regarding welding technology, as per EN 1011-2 [4], can be shown as detailed on Fig. 11.

This is outlook does not neglect a need for the post-weld heat treatment (PWHT) which may be influenced by other design factors.

From Fig. 11 it can be seen already mentioned narrower heat input (Q) limits for grade 890 (which correspond to narrow $t_{8/5}$ range - Fig. 10), as well as the need to use of preheating (at least / minimum on 95 °C), in contrast to grade 355 which provides less conservative heat input limits, as well as possible avoidance of preheating.

5. DISTRIBUTION AND MISMATCHING

The easiest way to present distribution of one mechanical property, and its mismatching along the welded joint axis is hardness measurement (Fig. 12 and 13; for hardness, HV10, results only). Thus, the hardness measurement is considered as one of the standardized requirement within a welding procedure qualification process [9].

In addition, while strength of welded joint is primary evaluated by mean of testing of perpendicular specimen(s) to welded joint axis, with requirement for failure outside welded joint (which means that BM must possess lowest strength); it means that standardized qualification process [9] does not take into account possible evaluation of properties distribution and further mismatching.

However, particular interest may arise regarding distribution of strength and toughness along welded joint. Therefore, for single-pass welding this can be done relatively easily with use of "welding simulation"; but for multi-pass welding it can be more than ambitious. This is due to the fact that single pass welding provide welded joints with characteristic HAZ (such as FG-HAZ, CG-HAZ, etc.) zones along complete BM thickness.

Thus, it may have sense in a case of multi-pass welding to provide distribution, and in relatively conservative way, only along one axis perpendicular to the main welded joint axis. Such approach is provided in Fig. 12 and 13 and Tab.3 and 4; for hardness (HV10), strength (Y) and toughness (KV) for grades 690 and 890.

Table 3 Properties along welded joint for 690 grade [15]

Zone /	HV10	Y	KV @ RT
BM	184-212	745-780	184-212
HAZ	270-421	737-1200	184-187
CG-HAZ	413	1184	85-94
WM	254-274	705	114-171
Used approximation acc. to [15] KV=330-0.56*HV10; and Y=(HV-34)/0.32 acc. to Fig. 1. * Average values are presented ** Shaded cell – approximated values			

Table 4 Properties along welded joint for 890 grade [15]

Zone / Property	HV10 #	Y [MPa]	KV @ RT [J]
BM	327-351	935-962	147-168
HAZ	322-455	900-1420	135-145
CG-HAZ	434	1250	54-59
WM	317-351	897	99-108
Used approximation acc. to [15] KV=330-0.56*HV10; and Y=(HV-34)/0.32 acc. to Fig. 1. * Average values are presented ** Shaded cell – approximated values			

The provided results analysis consist of real specimens from welded joint(s) of BM, WM and HAZ [8], simulated CGHAZ [8], and few approximated strength (Y) values, based on hardness (HV10), in accordance to previously performed studies.

Representative axis for distribution and mismatching of properties is the top side (face) line of hardness measurement (on Fig. 12 and 13; three (3) axis of hardness, HV10, measurement are shown) [15].

Selected steel(s) were in QT delivery condition, welded with qualified procedure and GMAW process, with $t_{8/5}$=6-8 s, and with different BM thicknesses; 30mm for 690 grade and 20 mm for 890; preheated at 200 °C and 150 °C consequently [8-15].

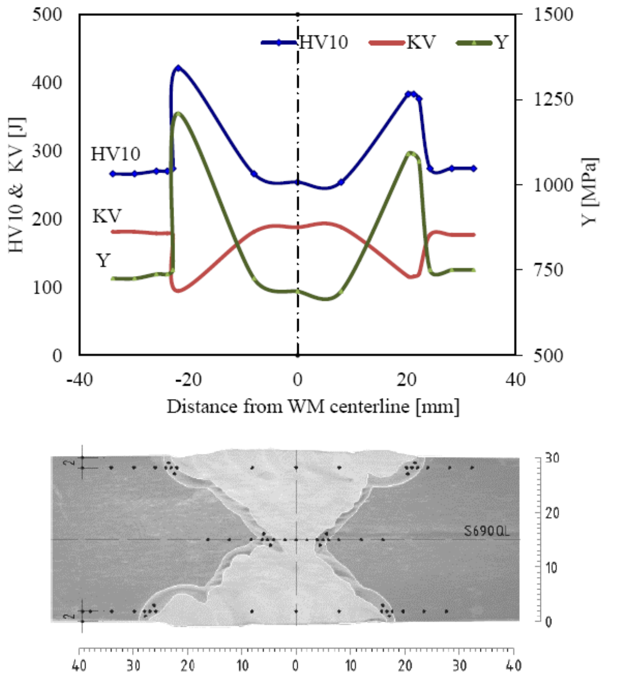


Fig.12 Distribution and mismatch of properties on top side of 690 welded joint

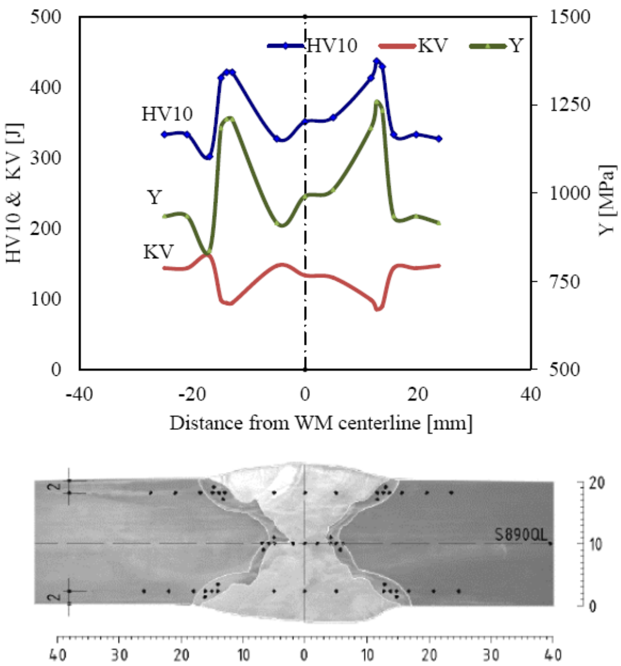


Fig.13 Distribution and mismatch of properties on top side of 690 welded joint

6. FINAL REMARKS

The initial review show well-known fact that the higher is strength one structural steel the lower ductility (Fig. 1) and toughness in general are, where only thermo-mechanical treated steel grades 420 and 460 show remarkably higher toughness level (Fig. 4). A problem of welded joint mechanical properties distribution, regarding level of mismatching effect, in real welds is present, which cannot be evaluated using standardised qualification procedures [9].

Therefore, more detailed and sophisticated approach is required, using welding simulation, particularly for well known weakest zone CG-HAZ.

The final results of evaluation show one ambitious approach, applicable, as show, only for selected grades 690 and 890. Thus, in the case of investigated 690 and 890 grade steel's GMAW welded joints, there is a significant undermatching (UM) of toughness; as well as overmatching (OM) of hardness; within HAZ. Actually, the maximum hardness OM_{max}= 1.52; while contrary, the maximum toughness UM_{max}= 0.37, both within CG-HAZ. Such degraded toughness may have for consequence notable loss of welded joint crack resistance. In addition, while so weakened zone of welded joint may represent cca. 35% (e.g. 1.5-2.0 mm; for 20-30 mm thick BM) of complete HAZ width, it should not be neglected easily. Finally, most influential variable on to the effect of mismatching is technological one - cooling time, $t_{8/5}$ (Fig. 7-8), and therefore it has to be respected and achieved as provided in the available recommendations (Fig. 10).

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