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Modern toughened steels – their properties and advantages

Introduction

For years, metallurgists have been searching for ways of producing structural steels which would have the highest possible mechanical properties and maintain satisfactory plastic properties at the same time. Due to an increase in yield point, it is now possible to manufacture structures consisting of elements of smaller wall thickness, thus lighter and less expensive to transport. A smaller wall thickness requires a smaller amount of filler metals and a shorter welding time. An increase in the mechanical properties of steels may be obtained by an appropriate selection of chemical composition through a classic process of toughening (hardening and tempering) or by means of thermo-mechanical treatment. However, no matter how high its mechanical properties might be, structural steel will only have practical application if it can be welded by means of commonly used arc methods. Toughened steels offer such a possibility. Due to the appropriate selection of chemical composition and proper heat treatment, i.e. hardening and tempering, these steels are characterised by very good mechanical properties as well as good weldability.

Toughened steels

The recent development of structural steels has involved on one hand toughened steels such as S690Q, S890Q and S960Q and on the other hand thermo-mechanically rolled steels of lower mechanical properties but of a higher impact strength (S355M, S460M and S500M). The development of structural steels is presented in chronological order in Figure 1 [1]. The division of toughened steels into sub-groups, in accordance with Technical Report CEN TR ISO 15608 [2], is shown in Table 1.

Toughened steels are fine-grained alloy steels. By selecting a proper chemical composition as well as the conditions of rolling and heat treatment, one obtains steels having different levels of yield point ranging from 460 to 1300 MPa. These steels contain chromium and molybdenum which decrease critical cooling rate and increase hardenability. The presence of niobium or vanadium in these steels guarantees obtaining fine grains of austenite during

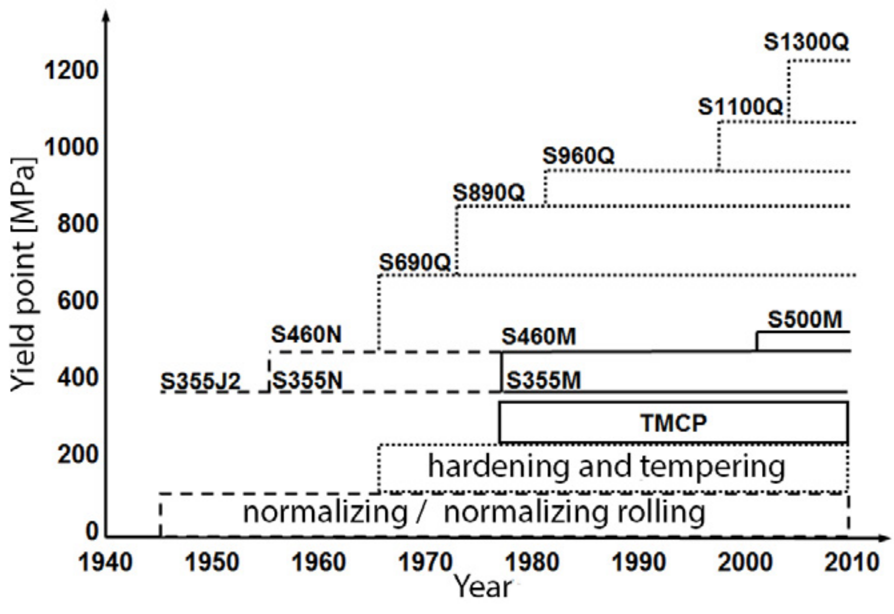

Fig. 1. Development of structural steels (TMCP – Thermo-Mechanical-Control-Process – process of thermo-mechanical rolling) [1]

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Table 1. Division of toughened steels into sub-groups according to Technical Report CEN TR ISO 15608 [2, 3]

Group and sub-group number	Examples of steel designation	
	Steel designation	In accordance with standard:
Toughened steels with a yield point of 360 MPa < Re ≤ 690 MPa		
3.1	S460Q, S460QL, S460QL1, S500Q, S500QL, S500QL1, S550Q, S550QL, S550QL1, S620Q, S620QL1, S690QH, S690QL, S690QL1	PN-EN 10025-6 [4]
	P460Q, P460QH, P460QL1, P460QL2, P500Q, P500QH, P500QL1, P500QL2, P690Q, P690QL1, P690QL2	PN-EN 10028-6 [5]
	C35E, C35R, C40E, C40R, C45E, C45R, C50E, C50R, C55E, C55R, C60E, C60R, 28Mn6	PN-EN 10083-2 [6]
	L415QB, L450QB, L485QB, L555QB	PN-EN 10208-2 [7]
	38Cr2, 46Cr2	PN-EN 10083-3 [8]
	P620Q, P620QH, P620QL	PN-EN 10216-3 [9]
	P420QH	PN-EN 10222-4 [10]
	A420, D420, E420, F420, A460, D460, E460, F460, A500, D500, E500, F500, A550, D550, E550, F550, A620, D620, E620, F620, A690, D690, E690, E690, F690	Regulations PRS, Part IX [11]
Toughened steels with a yield point of Re > 690 MPa		
3.2	34Cr4, 34CrS4, 37Cr4, 37CrS4, 41Cr4, 41CrS4, 25CrMo4, 25CrMoS4, 34CrMo4, 34CrMoS4, 42CrMo4, 42CrMoS4, 50CrMo4, 34CrNiMo6, 30CrNiMo8, 36CrNiMo16, 51CrV4	PN-EN 10083-3
	S890Q, S890QL, S890QL1, S960Q, S960QL	PN-EN 10025-6
Precipitation-hardened steels with the exception of corrosion-resistant steels (stainless steel)		
3.3	S500A, S500AL, S550A, S550AL, S620A, S620AL, S690A, S690AL	PN-EN 10137-3 [12]

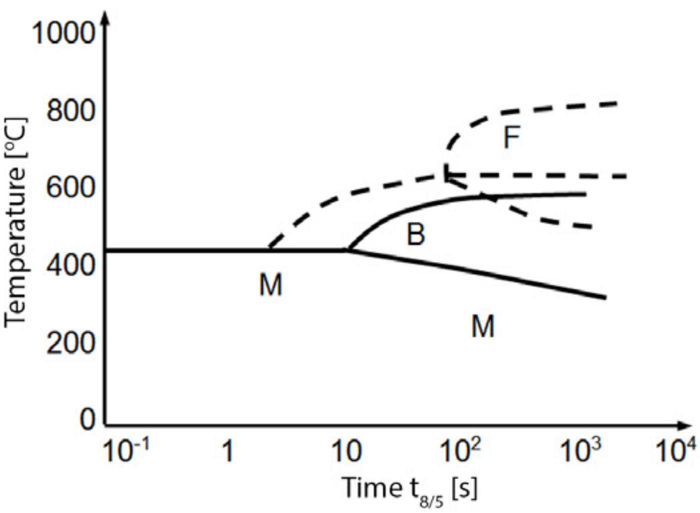


Fig. 2. CCT diagram for welding conditions showing the impact of boron micro-addition on the curves of the beginning of cooled austenite transformations in of Mn-Cr-Mo-Ti steel in the function of time $t_{8/5}$: - - steel without boron, — steel with boron, (0.17% C; 0.85% Mn; 0.005% N; 0.30% Cr; 0.85% Mo; 0.03% Ti; 0.0016%) B [14]

rolling and thus very tiny lamellas of supersaturated ferrite (martensite) after cooling. Tempering at a temperature of about 600ºC results in a high level of mechanical properties and good plasticity. Additionally, the increase in mechanical properties may be caused by precipitation hardening of NbC or V_4C_3. The role of nickel is to improve impact strength [13].

The hardenability of such steels can be improved by introducing a micro-addition of boron below 0.005%. It is effective only in dissolved state in the solid solution. Through segregation on the austenite grain boundaries, it decreases the energy of lattice defects, delays the nucleation in $\gamma \rightarrow \alpha$ decay and decreases the critical cooling rate.

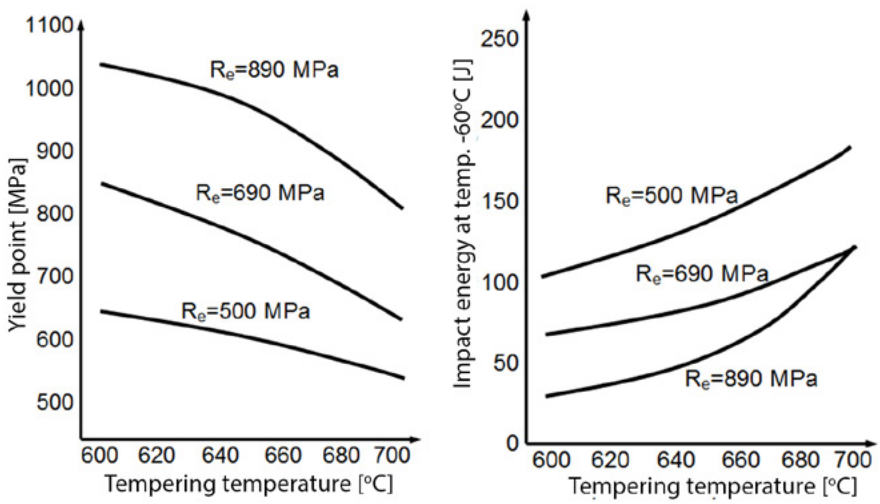


Fig. 3. Impact of tempering temperature on yield point a) and impact strength b) of three toughened steels [13]

A desired effect is obtained only in the case of steel characterised by high metallurgical purity. That is due to the fact that because of a significant affinity for oxygen and nitrogen, this element binds to B_2O_3 oxide in liquid metal passing into slag and, in solid state, into a stable BN nitride. The nitride, however, dissolves in the solid solution, yet this process requires a high temperature of austenitising, at which AlN also dissolves and so does part of MX phases of micro-additions introduced into the steel. This is a typical reason for the disadvantageous growth of austenite grains and worsening of steel ductility.

One may prevent the formation of a BN nitride by introducing into the steel an element of a greater affinity for nitrogen than boron. The most effective protection for boron, without worsening the ductility of steel, is the introduction of titanium into the bath. The amount of titanium should be sufficient to bind nitride in TiN [14].

High strength steels are melted in oxygen converters and then subjected to degassing in vacuum. In order to carry out desulfurization of the bath one introduces into it calcium compounds by means of argon stream as a carrier gas. Apart from considerable desulfurization, it causes the deoxidation and homogenization of the melt. This process also enables controlling the shape of sulphides which remain in the steel. Steels melted in such a way are characterized by high resistance to lamellar cracking. The steels are usually melted in a continuous way. After the typical process of rolling, the sheets/plates are heated up to the temperature of austenitizing and cooled by means of high-pressure spraying devices. The tempering of steel takes place in the next furnace. After the tempering the steel is characterised by a fine-grained structure with dispersive carbides and a favourable combination of strength and impact resistance (see Figure 3) [13].

Table 2. Impact of development of metallurgical processes on the level of impurities in steel [15, 16]

Element [ppm]	**Metallurgical processes in the years 1950/1960**	**Metallurgical processes in the years 1980/1990**	**Metallurgical processes in the years 1990/2010[2)]**
Sulphur	100-300	50-80	60
Phosphorus	150-300	80-140	6
Hydrogen	4-6	3-5	-
Nitrogen	80-150	<60	-
Oxygen	60-80	<12[1)]	-

Note: [1)] technology made it possible to obtain the oxygen content at the amount <12 ppm; however in practice, the oxygen content in steels was higher, [2)] the manufacturers do not indicate the content of hydrogen, nitrogen and oxygen.

Table 3. Examples of designation of toughened steels acc. to their manufacturers

PN EN 10025-6	PN EN 10027-2	Range of thickness [mm]	Steel manufacturer				
			Salzgitter	Thyssen-Krupp Stahl	Dillinger Hütte	FaFer	SSAB
S690QL	1.8928	3-200	Maxil 690	Naxtra 70	Dillimax 690T	Supralsim 690	Weldox 700 E
S890QL	1.8983	4-120	Maxil 890	Xabo 890	Dillimax 890T	Supralsim 890	Weldox 900 E
S960QL	1.8933	4-100	Maxil 960	Xabo 960	Dillimax 965T	Supralsim 960 Q	Weldox 960 E

Table 4. Chemical composition of Weldox type steel [18-22]

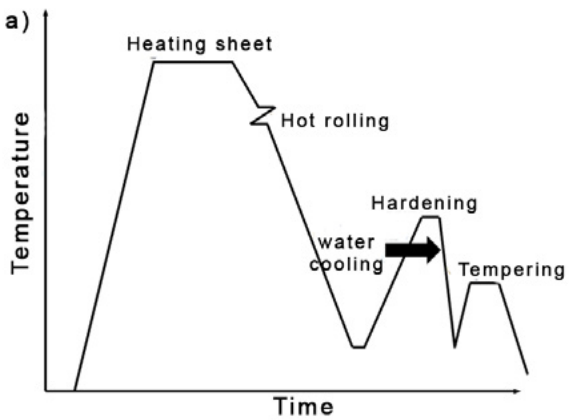
Steel designation[1)]	Chemical composition of steel [%]												
	C	Si	Mn	B	Nb	Cr	V	Cu	Ti	Al	Mo	Ni	N
WELDOX 700	0.20	0.60	1.60	0.005	0.04	0.70	0.09	0.30	0.04	0.015	0.70	2.00	0.010
WELDOX 900	0.20	0.50	1.60	0.005	0.04	0.70	0.06	0.10	0.04	0.018	0.70	2.00	0.010
WELDOX 960	0.20	0.50	1.60	0.005	0.04	0.70	0.06	0.15	0.04	0.018	0.70	1.5	0.010
WELDOX 1100	0.21	0.50	1.40	0.005	0.04	0.80	0.08	0.10	0.02	0.020	0.70	3.00	0.010
WELDOX 1300	0.25	0.50	1.40	0.005	0.04	0.80	0.08	0.10	0.02	0.020	0.70	2.0	0.010

[1)] steel designation by SSAB

The development of steel metallurgical processes aims on one hand at the growth of efficiency (reduction of production costs), and on the other at decreasing disadvantageous impurities in steel (Table 2) which could cause, e.g. lamellar or hot cracking.

Toughened steels may also be manufactured by means of a method of direct hardening of plates/sheets at the temperature of rolling, i.e. in the process of thermo-mechanical treatment. Such a method allows one to obtain, with the same chemical composition, a yield point higher by approximately 130 MPa than the one obtained in a conventional toughening process. By applying this method one can produce steels which have a carbon equivalent lower by approximately 0.05%. Such steels are characterised by better weldability in comparison with steels produced in a conventional way [13]. Approximate diagrams of the production processes of toughened steels are shown in Figure 4.

Global manufacturers of toughened steels (such as SSAB, Salzgitter, Dillinger Hütte and others) introduced their own systems of steel designation. Exemplary designations are presented in Table 3. Tables 4-8 contain steels of HSLA group (High Strength Low Alloy), their chemical composition as well



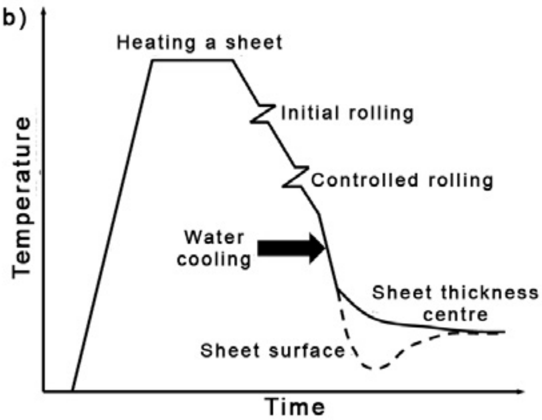


Fig. 4. Diagrams of production processes of toughened steels a) hardening and tempering processes, b) direct hardening process.

Table 5. Designation of high strength steels according to SSAB company [23] and PN EN 10025-6:2009 standard [4]

No.	Designation according to SSAB	Re [MPa]	Meeting KV* criteria	Designation according to standard PN-EN 10025-6:2009
1	Weldox 700 D	700	- 20	S 690 Q
2	Weldox 700 E		- 40	S 690 QL
3	Weldox 700 F		- 60	S 690 QL1
4	Weldox 900 D	900	- 20	S 890 Q
5	Weldox 900 E		- 40	S 890 QL
6	Weldox 900 F		- 60	S 890 QL1
7	Weldox 960 D	960	- 20	S 960 Q
8	Weldox 960 E		- 40	S 960 QL
9	Weldox 1100 E	110	- 40	no equivalent
10	Weldox 1100 F		- 60	no equivalent
11	Weldox 1300 E	1300	- 40	no equivalent
12	Weldox 1300 F		-60	no equivalent

*/ min. 27 J at fracture temperature

Table 6. Mechanical properties of Weldox type steel as well as CE and CET values [18-22]

Steel designation	Mechanical properties			Carbon equivalents	
	Re [MPa]	Rm [MPa]	A_5 [%]	CE* [%]	CET** [%]
WELDOX 700	700	780-930	14	0.43	0.29
WELDOX 900	900	940-1100	12	0.55	0.36
WELDOX 960	960	980-1150	12	0.55	0.37
WELDOX 1100	1100	1250-1550	10	0.59	0.35
WELDOX 1300	1300	1400-1700	8	0.65	0.42

*CE = C+Mn/6+(Cr+Mn+V)/15+(Ni+Cu)/15;
**CET= C+(Mn+Mo)/10+(Cr+Cu)/15+Ni/40

as mechanical and plastic properties on the basis of the requirements of standard PN -EN 10025-6 and SSAB company data. In order to compare these steels, the mechanical properties were referred to sheet/plate thickness up to 10 mm (Fig. 5-7).

Due to difficulty ensuring uniform mechanical properties on the thickness of a finished product made of toughened steel, an increase in mechanical properties (Re) is accompanied by a decrease in the maximum thickness of available sheets. This fact is related to hardening and tempering processes. An example of the maximum thickness of sheets made of Weldox steel (the company SSAB) is presented in Figure 6. It can be expected that a range of available thicknesses will grow along with the development of metallurgical processes.

Taking into consideration the chemical composition of toughened steels (Tables 4 and 7), one can suppose that these steels can cause problems during welding. Figure 7 presents the impact of carbon content and a carbon equivalent CE on the weldability of structural steel according to Graville

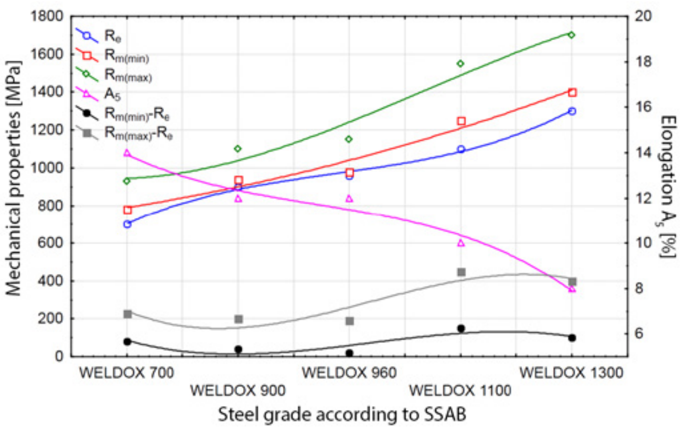


Fig. 5. Mechanical properties of steel Weldox [18-22]

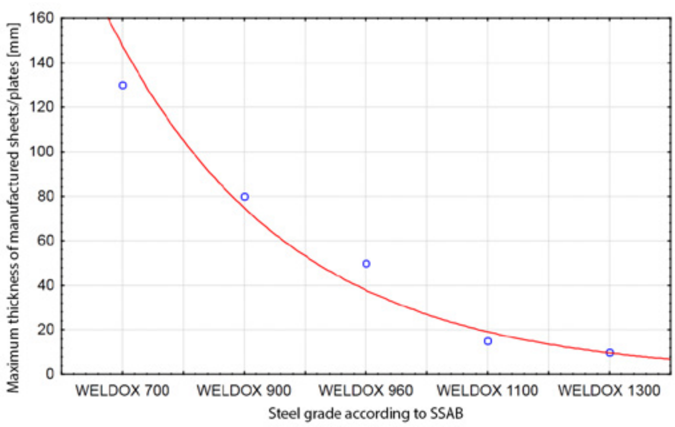


Fig. 6. Maximum thickness of standard sheets made of steel Weldox, other thicknesses available on the basis of individual orders [24-28]

Table 7. Chemical composition of toughened steels according to PN-EN 10025-6 [4]

Steel designation	Steel chemical composition [%] max														
	C	Si	Mn	B	Nb	Cr	V	Cu	Ti	Al	Mo	Ni	N	P	S
S…Q	0.20	0.80	1.70	0.005	0.06	1.50	0.12	0.50	0.05	-	0.70	2.00	0.015	0.025	0.015
S…QL														0.020	0.010
S…QL1														0.020	0.010

[29]. Due to the fact that steels after hardening and tempering are characterised by a carbon equivalent exceeding 0.5% and that carbon content in these steels exceeds 0.1%, they are included in zone III. For this reason it is necessary to use low-hydrogen welding processes and preheating.

Due to very high mechanical properties, steels of a yield point in excess of 1100 MPa have found application in the production of high-loaded elements of car lifts, travelling cranes and special bridge structures.

The advantages of using steels with high mechanical properties are visible as regards the costs of transport, plastic working, cutting, and welding. Table 9 presents the comparison of the relative values of technical parameters in the production of a model element made of steel S235, S700 and S960.

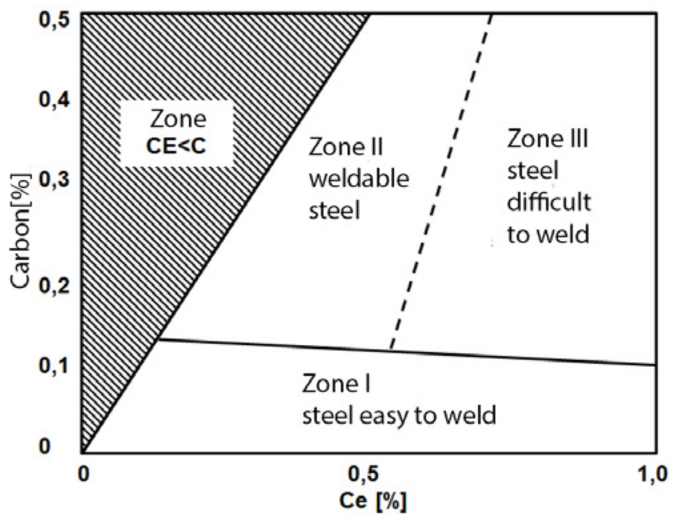


Fig. 7. Impact of carbon content and carbon equivalent CE on structural weldability : I – zone free from susceptibility to cracking, II – zone with susceptibility to cracking depending on welding conditions, III – zone of high susceptibility to cracking independent of welding conditions [29]

Tests conducted at Luleå University (Sweden) have revealed that the use of steel with a higher yield point provides economic benefits for manufacturers of cranes (Table 10) [31].

The redesign of a given crane element and replacing steel Domex 900 with steel Weldox 1100 resulted in the reduction of [31] the following:

- wall thickness from 6 mm to 4 mm, and thus the reduction of the crane weight or an increase in the lifting capacity without increasing the crane weight,
- costs of materials even if the price of Weldox steel is higher, as less Weldox steel was used than Domex steel,
- amount of filler metals and lower costs related to welding time, as sheets of a smaller thickness were used,
- fuel, owing to the smaller weight of the crane.

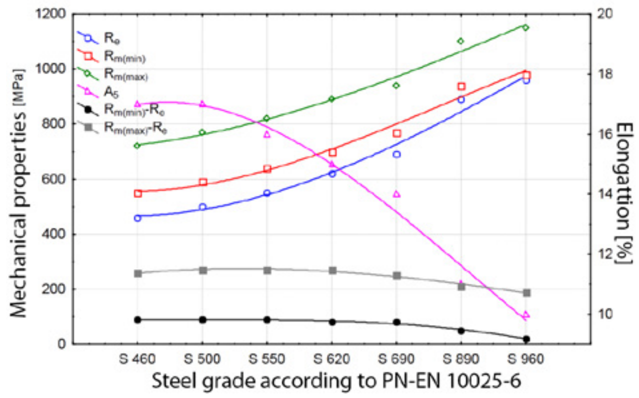


Fig. 8. Mechanical properties of toughened steels [4]

The reference publications contain mainly test results for toughened steels with a yield point of up to 1100 MPa. This is due to the fact that the steels of a yield point of 1300 MPa are relatively new on the market and have not been a subject of intensive research so far.

Even the calculations contained in standard Eurocode 3 [32] do not take into account steels with a yield point of 1100 MPa and higher. This is due to insufficient knowledge about the fatigue strength and the buckling phenomenon related to these steels.

The use of toughened steels of a yield point higher than 1000 MPa in the production of critically important structures exposed to variable loads imposes a necessity of carrying out, among others, fatigue tests. Equally important is the determination of usability of methods increasing fatigue strength, consisting in TIG-remelting, grinding and ultrasonic machining of the welded joint. The results of the fatigue strength tests [33] of the welded joints made of toughened steel grade S700 (steel Domex 700 manufactured by SSAB) reveal that TIG-remelting increases the fatigue strength of joints (100 000 cycles) by 38%, grinding by 31%, and ultrasonic machining makes it possible to increase fatigue strength on the average by 33%. Also in the case of the welded joints made of steels with higher yield points, i.e. 960 and 1100 MPa, subjected to additional surface treatment (TIG remelting and grinding), it was possible to observe an increase in their fatigue strength. The authors [34] obtained results of fatigue tests on the basis of which they suggested changing the class of a joint welded according to Eurocode 3 (fatigue category FAT) to 112 MPa for a joint subjected to grinding and to 140 MPa for a TIG-remelted joint. The welded joint not subjected to machining was classified as 100 MPa.

Table 8. Mechanical properties of toughened steels according to PN-EN 10025-6 [4]

Steel designation	Mechanical properties		
	Re [MPa]	Rm [MPa]	A_5 [%]
S 460	460	550-720	17
S 500	500	590-770	17
S 550	550	640-820	16
S 620	620	700-890	15
S 690	690	770-940	14
S 890	890	940-1100	11
S 960	960	980-1150	10

Table 9. Comparison of relative values of technical parameters depending on steel grade [30]

Steel grade [MPa]	235	700	960
Thickness [mm]	15	6	4
Amount of weld deposit [%]	100	16	7
Time of laser beam cutting [%]	100	40	27
Required bending force [%]	100	32	19
Required bending radius [%]	100	23	30
Weight of element [%]	100	44	30

Note: calculations were made of the closed profile 120×80 mm, V- bevelled butt joint, using a bending moment of 50kNm

Table 10. Costs of producing a crane structural element in case of changing structural material [31]

Costs (euro)	Steel Domex 900	Steel Weldox 1100
Material	353.60	284.28
Cutting	2.45	2.83
Bending	0.013	0.014
Welding	15.24	11.31
Total	371.30	298.43

From a practical point of view, another important phenomenon occurring in steels of a high yield point is buckling – depending, first of all, on the geometry of an element [35], but also on loading conditions, welding imperfections, level of remaining stresses and material properties. The authors [34] demonstrated that currently applied calculation principles allow changing the standard Eurocode and extending it by the steel of a yield point Re = 1100 MPa.

Weldability of toughened steels

While developing a technology for welding steels of high mechanical properties it is of great importance to properly select a filler metal. In order to do so one should take into consideration the following [36]:

- chemical composition, microstructure, mechanical properties (ultimate strength and toughness) of the steel to be welded,
- design requirements related to the minimum ultimate strength and toughness,
- mechanical properties of a filler metal, minimum ultimate strength and toughness,
- chemical composition of the weld deposit; the carbon content should be lower by a minimum of 0.02 percentage by weight than the carbon content in the steel to be welded, and the temperature of the phase transition should be lower by a minimum of 30°C than a transformation temperature in the steel being tested.

The ultimate strength is one of the most important criteria used in selecting a filler metal . A filler metal may have higher or lower ultimate strength than that of the parent metal [36]. The authors [37] investigated the impact of the ultimate strength of a weld deposit on the properties of the whole joint, and demonstrated that for steel S960 one can adopt the dependence: $A_{weld}/A_{sheet} \geq R_{msheet}/R_{mweld}$ deposit, where A is the area of cross-section, R_m – ultimate strength.

While selecting proper welding conditions, one should pay attention not only to choosing a proper filler metal but also to selecting proper welding parameters. The results of the tests conducted on the joints made of steel grade S650 revealed that the use of current parameters ensuring the amount of supplied heat at a level exceeding 32 kJ/cm causes a radical decrease in ultimate strength irrespective of the mechanical properties of a weld deposit [38]. If one compares the welding conditions of three steels of various yield points and subjected to various thermo-mechanical treatment, one can observe that welding toughened steels, if compared with welding thermo -mechanically rolled steels, requires the use of welding conditions of significantly narrower allowed variability limits (Fig. 9) [1].

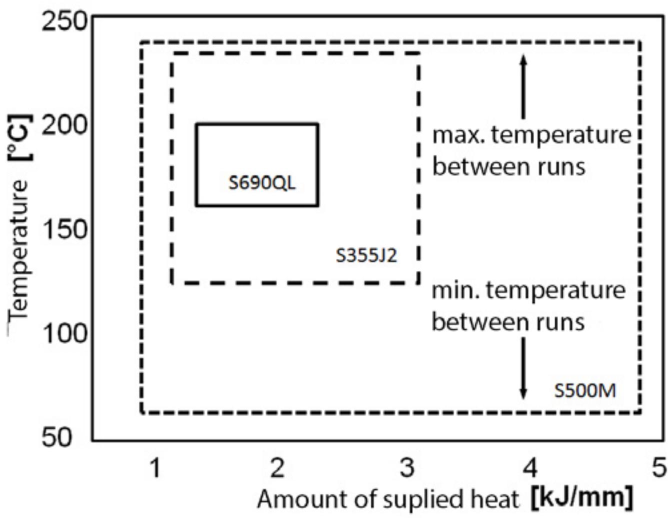


Fig. 9. Typical welding conditions for structural steels (S355J2 – 80 mm, S500M – 50 mm, S690QL – 30 mm) [1]

One should not neglect the fact that steels of high mechanical properties are susceptible to cold cracking and that hydrogen diffusion is a function of time. For this reason it is of crucial importance that NDT should be carried out no earlier than 48 hours after the completion of a welding process [39]. There were cases when toughened steels developed cold cracks after 3-4 weeks [40, 41]. These recommendations are also contained in standards PN-EN ISO 17642-2:2005 [42] and PN-EN 1090:2009 [43]. In some cases it is possible to use post-weld heat treatment in order to prevent cold cracks (stress relief annealing in the range 530 - 580°C). Thanks to this process, hydrogen present in the weld area diffuses towards outside the joint more easily [44], and the susceptibility to cold cracking is less. The tests results obtained so far reveal that an increase in the yield point (Re) or hardness (HV) of a parent metal [44, 45] or weld deposit [46] is accompanied by a decrease in the allowed hydrogen content in a metal, above which once can observe a growing susceptibility to cold cracking. The test results for the parent metal are presented in Figure 10, and for the weld deposit in Figure 11.

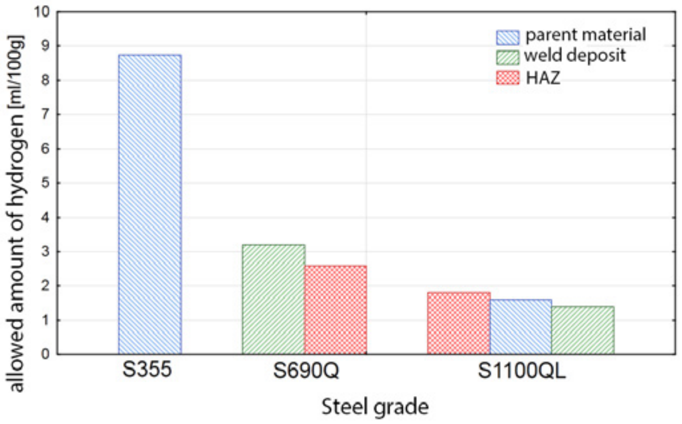


Fig. 10. Allowed hydrogen content in parent metal depending on steel grade (yield point) [44]

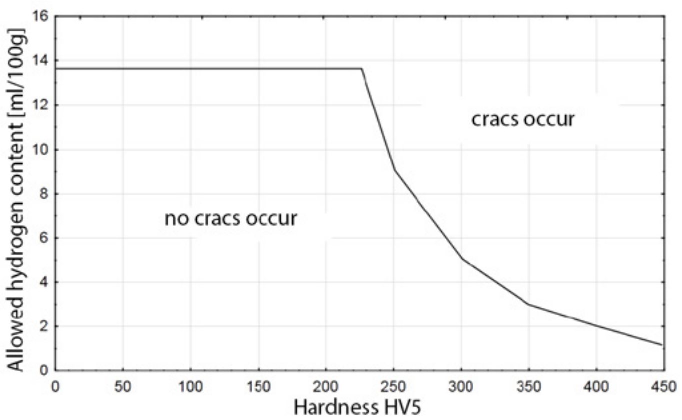


Fig. 11. Allowed hydrogen content in weld deposit depending on the grade of filler metal (weld deposit hardness) [46]

It is important that the content of diffusing hydrogen, while welding with flux cored wires, is in direct proportion to the value of welding current and arc voltage and in inverse proportion to the exposed length of an electrode [47], or more precisely, the distance between the surface of a material being welded and a contact tube. Obviously, the amount of hydrogen also depends on the type of shielding gas, parent and filler metals as well as the weather conditions.

While developing a technology for welding toughened steels characterised by high mechanical properties, one should also focus on, apart from cold crack formation, such phenomena as the following:

- welding-induced HAZ softening (the so-called ”soft layer issue ”),
- failure to obtain a required toughness level in the weld and HAZ (brittleness caused by ageing and precipitation hardening).

Soft layer issue

During welding toughened steels their HAZ develops a softened microstructure area of worse mechanical properties. This phenomenon is particularly visible in steels after rolling and intensified cooling. Figure 12 presents hardness changes in the cross-section of the welded joint made of toughened steel (QT). In the HAZ of toughened steel a hardness decrease is to a little extent caused by phase transitions; much greater in this case is the impact of tempering. Welding with the limited linear energy of an arc makes the layer narrow. In this case, although the hardness of this layer is lower, this fact, due to a narrow softening zone, does not have to result in the deterioration of the mechanical properties of the joint, because of the so called “contact strengthening” phenomenon generated by flat strains triggered in the soft layer [13].

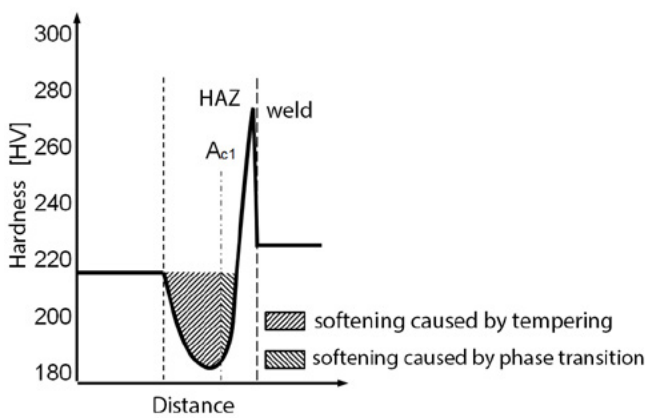


Fig. 12. Hardness distribution HV in welded joint made of toughened steel of Re>500MPa (QT), $t_{8/5}$=30s [13]

Failing to obtain required toughness in the weld and HAZ

An increase in HAZ hardenability due to the dissolution of micro-additions causes a shift of transformation curves in the continuous TTT diagram towards a longer self-cooling time, resulting in an increase in a martensite and bainite content. These structures, combined with a grain size increase, may lead to toughness decrease, particularly if the linear energy of an arc is high. In joints welded with low linear energy, an increase in brittleness is barely visible. In the steels of a yield point over 445 MPa (steel X65) containing Nb, V and Mo, in the HAZ heated to the temperature of Ac3-Ac1 it is possible to observe a decrease in hardness. The decrease is lower with higher welding energy and longer cooling time 8/5 are. According to Tasak [48], the decrease in toughness is caused by the appearance of a ferrite structure with martensitic-austenitic islands (M-A). After reaching the temperature in the range of Ac1-Ac3, the pearlitic areas transform into austenite rich in carbon and alloying elements, which, during (even slow) cooling transforms into hard and brittle martensite and/or partly into retained austenite. The presence of hard and brittle M-A islands is responsible for the fact that during the impact test the martensitic areas crack spontaneously or facilitate the nucleation of cracks on the surface of the division ferrite -MA island, and thus decrease impact energy. For steel X-80 (Re>550 MPa) de Vito [13] determined the dependence between toughness KCV and the amount of the phase M-A: KCVmax=0.52AF+112exp (-0.042M-A), where AF - % content of acicular ferrite, M-A - % content of M-A islands.

Summary

Toughened steels have been produced for many years. For instance, steel S690 had its market introduction 30 years ago. Despite the passage of time, more and more grades of increasingly good mechanical properties have been produced. This process has been accompanied by a constant improvement of metallurgical processes aimed to reduce the level of impurities in steels, i.e. sulphur and phosphorus. As a result, manufactured materials represent relatively good weldability. In consequence, these steels find applications in many welded structures. Obviously, because of their worse plastic properties toughened steels of very high mechanical properties cannot be used in the production of e.g. pressure equipment. It should also be remembered that toughened steels of a high yield point are susceptible to cold cracking which should be taken into consideration while selecting a welding technology. Another limitation during welding hardened and tempered steels is the presence of the so-called softening zone.

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