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Characteristics and Weldability of Toughened Steels Used for Ballistic Shields

Abstract: The article characterises selected toughened steels used in the production of ballistic shields, presents standard requirements in terms of the properties and chemical composition of these steels as well as enumerates and discusses guidance on the welding of such steels. The article also presents the results concerning the comparison of the carbon equivalents (C_e) of selected steels used for ballistic shields and preheating temperatures suggested by steel producers. The analysis of collected information revealed that the above named steels should be welded using low-hydrogen processes ensuring the obtainment of a diffusive hydrogen content below 5 cm^3 per 100 g of the weld deposit. It was also ascertained that sheets having thicknesses above 30 mm should be subjected to preheating and that interpass temperature should not exceed 200°C. In addition, it was determined that welding should be performed using multiple runs and austenitic high-alloy filler metals, preferably G 18 8 Mn and that gas mixture-shielded welding processes should be performed using argon-based mixtures; preferably 82% Ar + 18% CO_2 or 92% Ar + 8% CO_2.

Keywords: ballistic shield, armoured steels, weldability of steels

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Introduction

Recent years have seen a very dynamic development of structural materials used for ballasting and countermine shields. This trend is undoubtedly related to growing demand for such materials, resulting from political instability in many regions of the world or local conflicts, wars and terrorism. Producers of such materials are thus additionally motivated to develop and implement new techniques and production technologies, thus giving rise to the significant technological progress in materials used for ballistic shields.

All materials used for ballistic elements must satisfy requirements specified in NATO – STANAG 4569 (Standardisation Agreement) *Protection Levels for Occupants of Logistic and Light Armoured Vehicles*. Annex A to STANAG 4569 defines 6 various levels of protection against the penetration by shells or artillery shell fragments, including levels of resistance to ordinary gun shells and armour-piercing shells, e.g. calibre 5.56 or 14.5 mm, and levels of resistance to penetration by fragments of artillery shells connected with the distance from the detonation of a calibre 155 mm shell. Annex B to STANAG-u

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4569 defines levels of protection against penetration by grenade and mine shrapnel. Regardless of normative acts valid in individual countries, another standardisation document specifying levels of ballistic resistance is the standard issued by the United States Department of Justice of 1985 NIJ STANDARD 0108.01 "*Ballistic Resistant Protective Materials*", also used by state services and civilian companies [1, 2].

Spectacular progress in this group of materials has led to the development of a wide variety of non-metallic structural materials, which, due to their ballistic properties, are slowly replacing commonly used metallic materials. In addition to resistance/protection levels defined by related standards, another comparative criterion is the *ballistic resistance coefficient* – M [1].

$$M = \frac{E \cdot H_K \cdot R_m \cdot T_t}{\rho}$$

where

M – ballistic resistance coefficient,
E – modulus of elasticity [GPa],
H_K –Knoop hardness [GPa],
R_m – tensile strength [MPa],
T_t – melting point [K]
ρ – density [g/cm^3].

Non-metallic materials used for ballistic shields include armoured ceramics (e.g. hot isostatic pressed (HIP) boron carbide B_4C or titanium diboride TiB_2, ballistic laminates with carbon (T700), glass (Hollex), polymer (Kevlar), aramid (Twaron) and polyethylene (Spectra) fibres decisive for their usability. Taking into consideration the criterion of ballistic resistance M, the above-presented ceramic materials are characterised by 3÷10-fold higher resistance than "typical" armoured steel (see Table 1) [1].

In Table 1 above, armoured steels are characterised by the lowest resistance, yet they continue to be the most popular materials used for ballistic shields because of their advantages including relatively low manufacturing costs, proven effectiveness and possibility of joining with other materials, e.g. laminates reinforced with fibres with polymer shields [3].

Toughened Steels Used for Ballistic Shields

New steel grades, increased purity of heats, innovative extra-furnace treatment methods as well as the possibility and ease of process control enabling the obtainment of specific properties make it possible to produce sheets of increasingly high strength and toughness without compromising good plasticity [3].

Requirements specified for metallurgical products used for elements of ballistic shields are very restrictive. Armoured sheets/plates must be characterised by the following properties [1]:

- low level of non-metallic inclusions determined by volume fraction V_N %,
- uniform arrangement of non-metallic inclusions characterised by the possibly high degree of coagulation,
- fine-grained austenite (above standard 6),
- possibly low contents of gases:
  - oxygen below 30 ppm,
  - nitrogen below 70 ppm,
  - hydrogen below 2 ppm (liquid),
- chemical composition enabling (after quenching) the obtainment of 100% of martensite across the entire crops-section of a finished product.

Steels used for ballistic shields are high strength toughened steels. These steels are classified as

Table 1. Ballistic resistance coefficient M of selected non-metallic materials in comparison with "armoured steels" [1]

Material	Ceramics				Steel
Type of material	B_4C	TiB_2	SiC	Al_2O_3	Armoured steel*
M·[(GPa·m)^3 K/kg]	$5.3 - 10^3$	$5.0 - 10^3$	$1.8 - 10^3$	$1.5 - 10^{3}3$	$0.5 - 10^3$
* averaged values were used for the calculation of the index					

Table 2. Chemical compositions of steel S960QL, Armstal 500 (30PM) and Armox 500T [7, 8, 9]

Steel	Chemical composition [max. content in %]														
	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	Al	B	Nb+V	Ti	Zr	N
S960QL	0.2	1.7	0.8	0.01	0.02	1.5	2.0	0.7	0.5	-	0.005	0.11	0.05	0.15	0.015
30PM	0.3	1.2	0.5	0.01	0.015	0.9	1.1	0.25	0.2	0.04	0.003	0.12	0.05	-	-
ARMOX	0.3	1.2	0.4	0.01	0.015	1.0	1.8	0.7	-	-	0.005	-	-	-	-

low hardness steels (300÷380 HB) as well as high and very high hardness steels (500÷600 HB and even 650 HB). Chemical compositions of these steels correspond to low-alloy and medium-alloy steels. Table 2 presents chemical compositions of steel S960QL, Armstal 500 (30PM) and Armox 500T [3].

In accordance with presently valid standards, steel producers enjoy a certain degree of freedom as regards the selection of chemical compositions and manufacturing technologies. Standards require the obtainment of certain minimum mechanical properties, which, as a result, makes it possible to use a wide range and number of alloying elements in production. Standard MIL-DTL-46100E (MR), i.e. the primary document being the basis for the specification of required technical acceptance criteria in terms of steels used for ballistic shields, in cases of key steel components, does not restrict the minimum content of alloying elements (see Table 3) but defines the minimum requirements as regards the properties of sheets/plates used for shields as to their hardness (Table 4).

Table 3. Allowed contents of alloying elements in ballistic steels according to standard MIL-DTL-46100E (MR) [10]

Element	Maximum permissible content in %
C	0.32
Mn	unlimited
Si	unlimited
P	0.02
S	0.01
Ni	unlimited
Cr	unlimited
Mo	unlimited
B	0.003
Cu	0.25
V	unlimited
Ti	0.1
Zr	0.1
Al	0.1

Microagents enable the obtainment of high mechanical properties. Chemical elements such as manganese, nickel, molybdenum, chromium, niobium, vanadium, boron or titanium enable the obtainment of high hardenability and required plastic properties as well as reduce the critical cooling rate during the formation of martensite and bainite. Hard and very hard weldable steels are produced as dead steels having fine-grained structures obtained after tempering and composed of low-carbon martensite (up to 14% in steels S690 and up to 100% in steels S1100). Figure 1 presents the martensitic structure of steel Armox 440T [5].

Toughened steels used for ballistic shields are delivered in the form of sheets/plates having thicknesses of 3÷150 mm, where $R_{po.2} \leq$ 690 MPa, 3÷100 mm for $R_{po.2} \geq$ 890 MPa and thicknesses of 3÷50 mm, if $R_{po.} \geq$ 960 MPa.

Table 4. Minimum required properties of sheets used for ballistic shield according to standard MIL-A-12560H (MR) [11]

Parameter	Hardness [HB]			
	370÷430	420÷480	480÷540	≥ 550
R_m [N/mm^2]	min. 1250	1250÷1550	1450÷1750	> 1600
$R_{p0.2}$ [N/mm^2]	min. 1000	min. 1100	min. 1250	> 1250
A_5 [%]	min. 10	min. 10	min. 8	min. 8
Charpy-V (-40°C) [J]	min. 45	min. 30	min. 20	min. 15

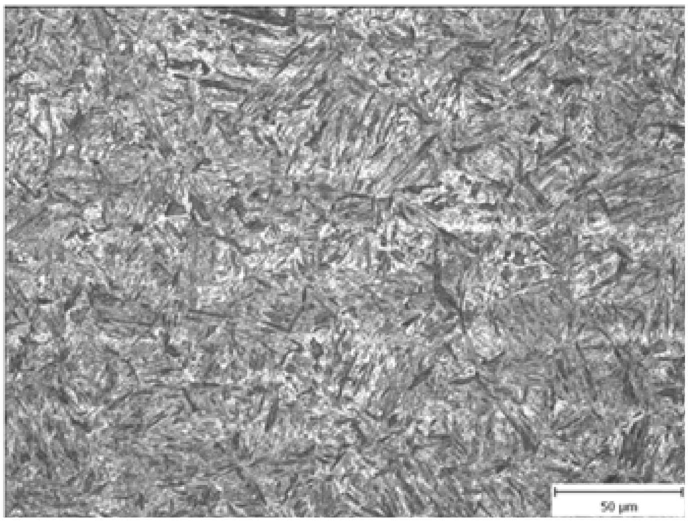

Fig. 1. Microstructure of steel Armox 440 – tempered lath martensite [16]

These steels can be classified in accordance with designations of European standards, yet apart from steel S960QL, also used in other industries, they are usually known under names given to them by their producers. Exemplary mechanical properties of the most popular steels used for ballistic shields are presented in Table 5 [5, 6, 7]. As stated in publication [1], after processing, steels used for ballistic shield must satisfy the following requirements:

- high hardness on the surface and in the core; differences in the hardness in the sheet/plate or an element after heat treatment are specified in technical acceptance conditions or standards MIL-DTL-46100E (MR) and MIL-A-12560H (MR); usually, a spread of 10% in relation to required hardness is allowed,
- relatively high yield point $R_{p01.02}$ without compromising high maximum strength,
- good plastic properties determined by the relative elongation A% of strength specimens or the result of a bend test using a probe having a specific diameter "*d*", aimed to obtain a specific angle,
- low anisotropy of mechanical properties in the longitudinal and transverse direction in

Table 5. Mechanical properties of selected steels used for ballistic shields [1]

Steel grade *Producer*	Sheet/plate thickness [mm]	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	Toughness ISO-V -40°C	HB
XH 129 *Thyssen Stahl AG*	4÷25	1400	1700	-	14	477÷534
Armox 500T *SSAB Oxelosund AB*	6.13, >13	1300 1300	1600 1600	8	10 20	min. 480 min. 450
Hardox 500 *SSAB Oxelosund AB*	up to 50	1300	1550	8	25	450÷530
Weldox 900F *SSAB Oxelosund AB*	4÷50	900	1100	12	30	-
CP 50 *CP Steel Processing Ltd*	up to 25	1350	1640	8	-	470÷530
S960QL *Masteel Ltd*	up to 50	960	980÷1150	10	27	-
2P *(according to GOST)* *HSJ S.A.*	up to 20	1400*	1500*	8*	20*	363÷514
ARMSTAL 450 *HSJ S.A.*	up to 20	1100	1200	9	30	min. 450
SECURE 500 *ThyssenKrupp AG*	3÷50	1300	1600	9	25	480÷530
Ramor 500 *Ruuki Metals Oy*	2÷20	1450	1700	7	20	480÷560
ARMALLOY 500HH *EVRAZ Group N.A.*	4÷34	1310	1655	10	27	477÷534

*declared values

relation to the direction of rolling,
- lowest possible temperature of transition into the brittle state, determined by the toughness at a test temperature of -40°C or -50°C,
- uniform structure of tempered martensite or sorbite without precipitates and structural constituents deteriorating mechanical properties (e.g. ferrite or bainite),
- good weldability of sheets used for armoured vehicle bodies.

Toughened steels characterised by low hardness are subjected to quenching in water (by immersing or spraying), less frequently in oil, followed by tempering at a temperature from a range of 180÷300°C or 500÷600°C [3]. In order to obtain the highest possible hardness, according to publication [1], 3 principal manners of obtaining required mechanical properties for armoured steels are used:
- quenching in presses with the low-temperature tempering of alloy and low-alloy steels leading to the obtainment of the highest hardness (500÷600 HB),
- quenching in presses with the high-temperature tempering and using the secondary hardness of alloy and low-alloy steels, usually with nickel additions (hardness of 450÷500 HB),
- quenching of sheets/plates from the controlled final rolling temperature with tempering in a production line and using tension in order to avoid the deformation (curvature) of sheets/plates.

Figure 2 presents the exemplary production of toughened steel Armstal 500 (30PM). This steel is melted in an electric furnace, subjected to refining in a ladle furnace and to vacuum degassing. Afterwards, the steel is cast using a continuous steel casting facility and a stream shield against re-oxidation and electromagnetic mixing. Sheets made of this steel grade are delivered in the toughened state, i.e. subjected to quenching in water, in a quenching press with low tempering.

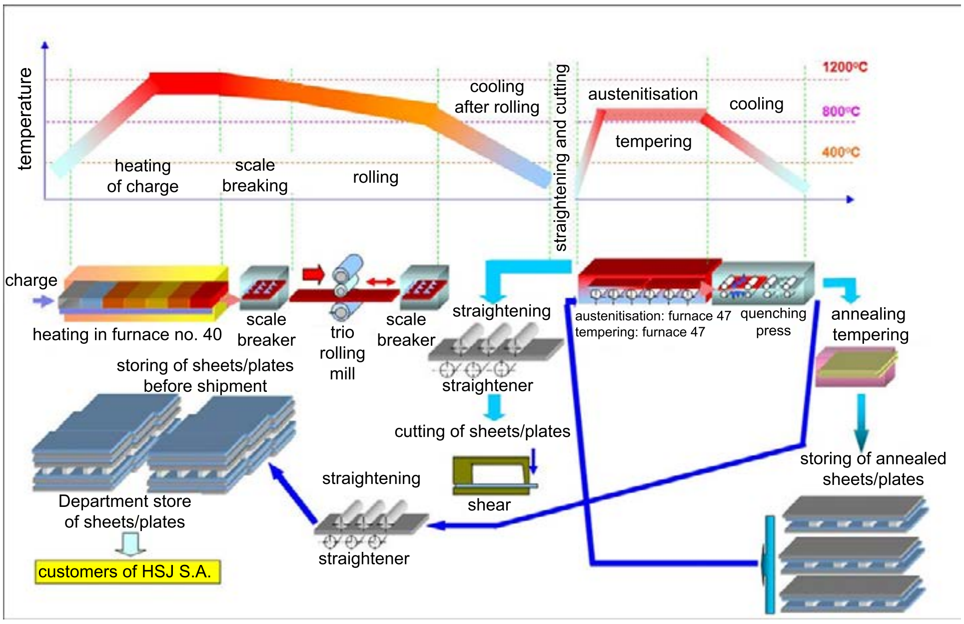

Fig. 2. Production of toughened steels at HSJ S.A. [8]

The chemical composition and heat treatment methods depend on the specific use of steel as well as on operating conditions and further processing allowing for ballistic resistance, sheet thickness, hardness and weldability. The development of methods of single and double-sided quenching in presses to obtain a required depth followed by low tempering enabled the obtainment of different hardness in the cross-section of sheets/plates, which significantly contributes to the continuous use of metallic materials for ballistic shields [3].

Weldability of Steels Used for Ballistic Shields

Toughened steels having structures composed of fine-grained tempered martensite are characterised by the highest strength and yield points. All these steels are considered to be weldable, yet their carbon equivalents C_e presented in Table 6 (as well as preheating temperatures) can vary significantly. Producers of steels used for ballistic shields recommend welding without preheating if filler metals used during welding have an austenitic structure. If welding is performed using low-alloy filler metals, producers recommend preheating to temperatures not exceeding those specified in Table 6. Figure 3 presents a CCT diagram for welding conditions for steel S960QL.

The very high tolerance in terms of chemical compositions makes the selection of welding procedures and the adjustment of welding parameters difficult. In addition, sometimes the strength of welded joints is by approximately 30% lower than that of initial materials. Therefore, the maintaining of technological conditions during welding works is very important.

Table 6. Carbon equivalents C_e of selected high strength steels [9, 12, 13, 14, 15]

Steel *Producer*	C_e [%]	As-delivered state	Preheating
XH 129 *Thyssen Stahl AG*	~ 0.81	Q + T	up to 180°C
Armox 500T *SSAB Oxelosund AB*	0.67÷0.75	Q + T	up to 200°C
Hardox 500 *SSAB Oxelosund AB*	~ 0.6	Q	up to 175°C
S960QL *Masteel Ltd.*	0.72÷0.82	Q + T	up to 150°C
ARMSTAL 450 *HSJ S.A.*	~ 0.83	Q + T	up to 150°C
SECURE 500 *ThyssenKrupp AG*	~ 0.93	Q + T	up to 200°C
Ramor 500 *Ruuki Metals Oy*	~ 1.07	Q	up to 180°C
ARMALLOY 500HH *EVRAZ Group N.A.*	~ 0.86	Q + T	up to 225°C

Q – quenching; Q + T – quenching + tempering

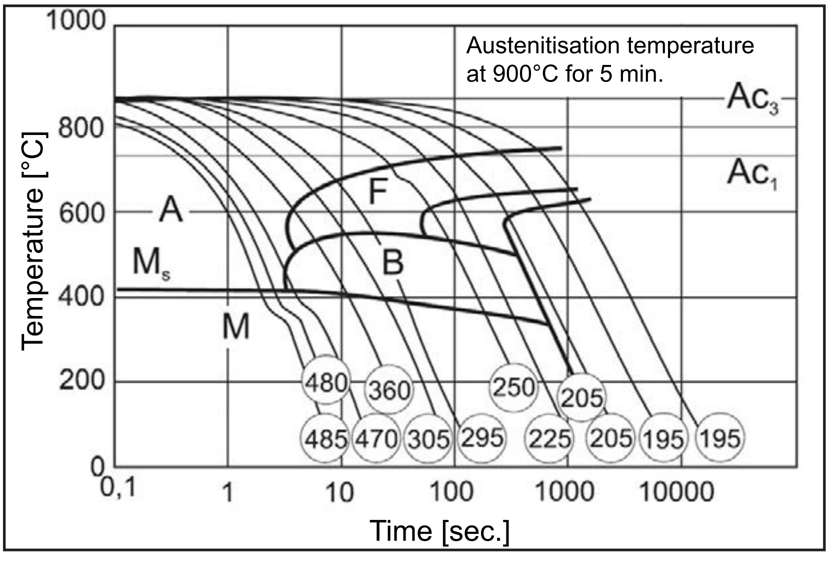

Fig. 3. CCT diagram for welding conditions for steel S960QL [14]

For steels characterised by higher strength or greater thickness, producers have developed certain recommendations to minimise the loss of properties in joint areas. Primarily, sheets/plates thicker than 30 mm should be subjected to preheating in order to ensure appropriate cooling time, yet it is important not to exceed a specified range as this could lead to the loss of welded joint properties, particularly hardness. Excessively high preheating temperature and excessively high welding linear energy could result in the formation of coarse-grained upper bainite precipitates (less plastic than fine-grained tempered martensite) in the HAZ and in the weld. In addition, in order to prevent cracks and material overheating, specific sheet thicknesses require appropriately adjusted welding current and welding linear energy [4, 16, 17, 20].

Toughened steels tend to have the quenched HAZ, demonstrated by a high parameter C_e amounting to 0.7÷1.1 (see Table 6) and increasing the risk of cold crack formation. It is important to use a low-hydrogen joining process, where the content of diffusive hydrogen should not exceed 5 cm^3 per 100 g of weld deposit. In order to prevent the formation of lamellar cracks in crosswire joints, sheets/plates used when making such joints should contain the lowest possible amount of sulphur [4, 17, 18].

The multilayer welding of toughened steels is highly desirable as it has a positive effect on the toughness of joints, allows reducing the HAZ area where grain growth has occurred and increases the area processed by welding heat. If possible, the last run should be made in the middle of the weld and not adhere to the base material [18, 19, 20].

As regards welding positions, producers have not specified any limitations, yet the vertical down position (PG) is not recommended. When MMA welding, it is recommended to use electrodes having basic covers. In submerged arc welding, it is necessary to remember about reducing linear energy to 15-20 kJ per running centimetre of a weld. Regardless of a welding procedure, it is recommended that linear energy be lower by 5÷6 kJ/mm than the upper limit. Gas-shielded welding should be performed using argon-based mixtures, preferably 82% Ar + 18% CO_2 of 92% Ar + 8% CO_2, and a shielding gas flowrate of 12÷16 l/min. It is recommended to use high-alloy austenitic filler metals, grade G 18 8 Mn. This, however, deteriorates joint properties in comparison with the base material. In special cases, ferritic filler metals (e.g. for grades Armstal or Ramor) are allowed. When welding the above-presented steel grades, interpass temperature cannot be high as it could lead to the grain growth in the fusion line. In addition, if the HAZ or welds are heated above austenitisation temperature, cooling times are extended, thus leading to the formation of unfavourable coarse-grained structures and the deterioration of properties. Therefore, it is recommended that interpass temperature not exceed 200°C in order to not to increase the risk of cold crack formation [9, 12, 13, 19, 20].

Summary

Toughened steels used in the production of ballistic shields are characterised very good mechanical properties obtained through appropriate heat treatment involving quenching in hydraulic presses followed by tempering. Although toughened steels are considered weldable, their average carbon equivalent (C_e) of approximately 0.72% is excessively high. Standards governing chemical compositions are not very restrictive, hence the selection of welding procedures and parameters is not easy. Producers do not impose any specific requirements, yet the analysis of scientific reference publications leads to the conclusion that when welding these steels, it is necessary to:

- use low-hydrogen processes, i.e. the content of diffusive hydrogen should not exceed 5 cm^3 per 100 g of weld deposit,
- use multi-run welding, interpass temperature should not exceed 200°C,
- use high-alloy filler metals having austenitic structures, preferably grade G 18 8 Mn; when performing gas-shielded welding, use argon-based shielding gas mixtures, preferably 82% Ar + 18% CO_2 or 92% Ar + 8% CO_2; a flowrate of 12÷16 l/min.

Preheating is recommended for plates having thicknesses exceeding 30 mm.

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