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EXPERIMENTAL EVALUATION OF THE TENSILE PROPERTIES OF DIFFERENT TYPES OF ARMOUR STEEL AND THEIR WELDED JOINTS

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Abstract: *This paper presents the results of an experimental investigation into the mechanical properties and quality assessment of welded joints and their corresponding base materials. The study focuses on high-strength armour steels, a class of steel that due to their high hardness and toughness under dynamic impact loads, are utilized in specialized protective structures. The primary objective was to evaluate the performance of the welded joints produced by a specific welding technology and MAG welding process and to compare their characteristics with those of the unaffected base metal. Tensile testing was conducted on a universal testing machine equipped with appropriate instrumentation for precise measurement of force and elongation. A total of 27 specimens were tested, including both transverse welded samples and base metal reference samples, ensuring a comprehensive dataset. The tests allowed to determine key mechanical parameters, including yield strength, ultimate tensile strength, percentage elongation after fracture, and reduction of area. Beyond the numerical results, a fractographic analysis was performed, with particular attention given to the location and morphology of the fracture. The fracture surfaces were examined to determine whether failure occurred in the weld metal, the heat-affected zone (HAZ), or the base material, providing critical insights into the weakest link of the joint. The obtained results were analysed to assess the efficiency of the welding MAG procedure.*

Keywords: *welded joints, tensile testing, mechanical properties, armoured high-strength steels, fracture analysis, heat-affected zone (HAZ)*

1. INTRODUCTION

The modern development of Infantry Fighting Vehicles (IFVs) stemmed from the continuous effort to enhance tank operational efficiency and battlefield survivability. This evolutionary requirement presented a major metallurgical and design challenge: developing armour systems capable of defeating small-arms fire and anti-tank projectiles while simultaneously maintaining optimal tactical, technical, and operational performance. Meeting these stringent criteria necessitated the development of specialized ultra-high-strength steels, commonly referred to as armour or ballistic steels, which continue to undergo active technological refinement [1-3]. Prominent among these materials is the commercial ARMOX series produced by the Swedish manufacturer SSAB Oxelösund, manufactured under strictly controlled production protocols [4]. Their primary function is to defeat kinetic energy threats such as small arms fire, armour-piercing projectiles, and explosive shrapnel while maintaining minimum structural weight to preserve vehicle mobility and operational efficiency. The superior ballistic and mechanical characteristics of ARMOX steels result directly from their tailored chemistry and manufacturing processes: ultra-low carbon content (C<0.3%) formulated specifically to improve field weldability and minimize cold-cracking susceptibility. Thermomechanical processing (TMP): utilized to achieve exceptionally high yield and ultimate tensile strengths [5,6]. However, despite these superior properties, joining armour steel plates into a coherent hull structure introduce localized material degradation. The intense heat input during the welding process inevitably alters thermo-mechanically processed microstructure, creating a localized softening zone or microstructural mismatch in the heat-affected zone (HAZ). Consequently, these welded joints represent potential critical structural vulnerabilities when exposed to dynamic or ballistic loading conditions. To address this

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challenge, this study presents a comprehensive experimental investigation into the mechanical properties, fracture behaviour, and overall quality assessment of ARMOX welded joints compared directly to the base metal.

2. MATERIALS AND METHODS

The objective of this research is to determine fundamental mechanical parameters (Re, Rm, percentage elongation A, and reduction of area Z) for different welded samples using specific welding technology. Based on obtained results, researchers investigated how welded joints perform under tensile loads, assess the technological efficiency of the applied welding procedure, and provide key insights into the structural integrity of armoured vehicles when subjected to severe mechanical stress. Testing was done by using a universal testing machine equipped with precise force and elongation instrumentation. A total of 27 specimens, comprising both transverse welded samples and base metal reference standards were tested to destruction. For testing and welding two different armour (ballistic) steels were used as well as one structural steel:

1. ARMOX 500T,
2. SWEBOR 500,
3. S355J0.

Besides armour steels, S355J0 steel was tested because in common military use the armour steels are often welded directly to structural steel, so the authors wanted to test the properties of that welded joints too.

In tables 1 and 2 the chemical composition and mechanical properties are given.

Table 1. Chemical composition of ARMOX 500T, Swebor 500 and S355J0

Steel type	Chemical composition, %									
	C	Si	Mn	Cr	Mo	P	S	Mo	Ni	B
ARMOX 500T	0.32	0.5	1.3	1.0	0.7	0.01	0.005	0.7	1.8	0.005
Swebor 500	0.30	0.5	0.4	NS	NS	0.015	0.005	NS	/	/
S355J0	0.22	0.55	1.6	/	/	0.035	0.035	/	/	/

*NS – not specified.

Table 2. Mechanical properties of G42CrMo4 cast steel [8]

Steel	R_m, MPa	$R_{p0.2}$, MPa	A, %	Z, %	Impact energy, J
ARMOX 500T	1650	1300	7-10	/	25 (R)
Swebor 500	1670	1200	9.5	/	25 (-40°C)
S355J0	510-680	355	14-18	/	27 (-20°C)

After materials selection, we approached to samples preparation. Samples were prepared in company Zastava TERVO, Kragujevac, Serbia.

For the purposes of testing and analysing the obtained results, base material samples of the selected steels were prepared, as well as test specimens for welded joints with all possible combinations. For initial testing purposes, a total of twenty-seven samples were prepared (shown in Fig. 1), according to standard SRPS EN ISO 6892-1 [7] and drawing given in Fig. 2, consisting of 9 different series with 3 samples in each series:

- Series 1 - Base material samples of S355 structural steel – 3 pcs.
- Series 2 - Base material samples of Swebor 500 high-strength steel – 3 pcs.
- Series 3 - Base material samples of Armox 500 high-strength steel – 3 pcs.
- Series 4 - Welded samples of S355 structural steel – 3 pcs.
- Series 5 - Welded samples of S355 structural steel and Swebor 500 high-strength steel – 3 pcs.
- Series 6 - Welded samples of S355 structural steel and Armox 500 high-strength steel – 3 pcs.
- Series 7 - Welded samples of Swebor 500 high-strength steel – 3 pcs.
- Series 8 - Welded samples of Armox 500 high-strength steel – 3 pcs.
- Series 9 - Welded samples of Swebor 500 and Armox 500 high-strength steels – 3 pcs.

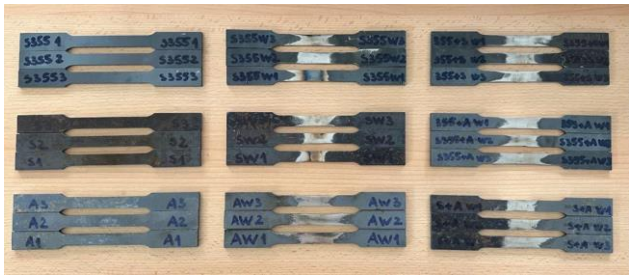


Figure 1. Prepared samples

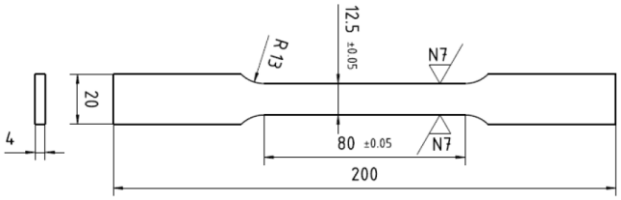


Figure 2. Drawing for samples preparation

Before testing the specimens to determine the mechanical properties of dissimilar steel welded joints, the mechanical properties of the base metals of the selected steels were determined.

The specimens for determining the mechanical properties

of dissimilar steel welded joints for all tested series were prepared through a sequence of manufacturing operations. The test specimen parts were first prepared for the welding process. Following laser cutting, the edges were bevelled so that the specimen parts could be welded. Each specimen was welded using the same method and with identical welding parameters.

Welding was performed with a runoff tab (backing tab) to prevent the formation of defects during the strike and extinction of the electric arc over such a short distance. After welding, the specimen was ground smooth at the joint location (Fig. 3). The welding was carried out using the MAG process with MIGWELD 307Si austenitic filler wire (diameter 1.0 mm) and M12 shielding gas (Ar + 0.5% CO_2). This filler wire was selected to prevent brittle fracture in the weld metal, as recommended by both the manufacturer [4] and other authors [6]. The chemical composition and mechanical properties of the filler wire are given in Table 3.

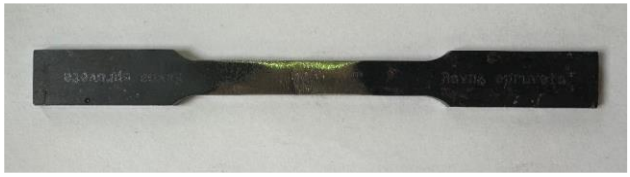


Figure 3. Appearance of welded sample

Table 3. Chemical composition of filler metal MIGWELD 307Si

Chemical composition, %				
C	Si	Mn	Cr	Ni
0.08	<1.0	7.0	18.5	9.0
Mechanical properties				
Rm, MPa	Rp0,2, MPa	A, %	KV, J	
560-660	>380	>35	32 (-196°C)	

For tensile testing, the Shimadzu servo-hydraulic testing machine (pulsator) (Fig. 4) and the MFA25 extensometer (MF Mess & Feinwerktechnik GmbH, Velbert, Germany) with a gauge length of 50 mm (Fig. 5) were used. Direct integration with the Servo 4830 controller and software enables automated data acquisition and real-time graphical visualization throughout each test. Following specimen mounting, the extensometer was positioned at the midpoint of the gauge length to measure real deformation. The device was carefully attached to prevent slippage during testing..

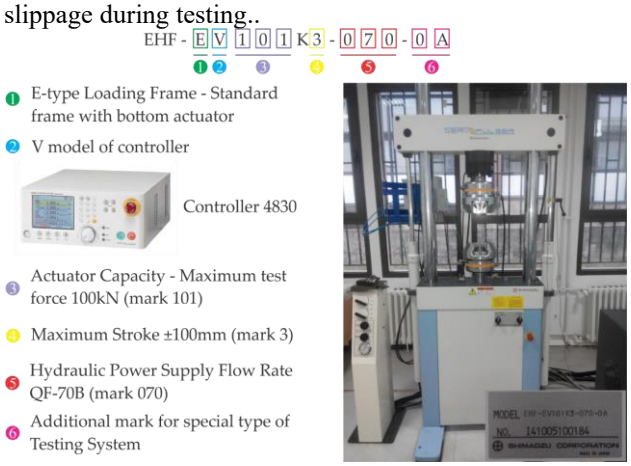


Figure 4. SHIMADZU servo-hydraulic machine



Figure 5. MFA25 extensometer

Tensile testing of the specimens was conducted at room temperature (23±5°C) at a constant displacement rate of 0.9 mm/min (Fig. 6). Prior to each test, zeroing of all measurement channels on both the testing machine and within the Servo 4830 software was carried out to ensure the accuracy and reliability of the recorded data.



Figure 6. Sample during testing

3. RESULTS AND DISCUSSION

Based on the tests performed on the specimens, an analysis of the obtained results was conducted. Following data processing using the DataViewer 4830 software, engineering stress–displacement curves were generated for each uniaxial tensile test. Furthermore, engineering stress–engineering strain curves along the A50 extensometer gauge length can also be plotted, as extensometer opening—and thus strain—was recorded continuously throughout all experiments.

For result analysis and comparison, engineering stress–displacement curves are presented for each tested specimen (Fig. 7). This approach was adopted because fracturing and necking did not consistently occur within

the extensometer gauge length. As can be clearly seen from the figure, the specimens fabricated from the S355 structural steel baseline material exhibit the highest elongation. Conversely, the high-strength steels, Swebor 500 and Armox 500, demonstrate high yield strength and tensile strength values, accompanied by lower elongation compared to the S355 structural steel.

To facilitate tracking and evaluation of the obtained mechanical properties across all tested specimens, the complete set of results is summarized in Table 3.

Analysis of the obtained results revealed that the mechanical properties of the welded joints significantly depend on the base metal type. For the S355 structural steel, relatively uniform plastic deformation was observed, with fracture occurring primarily in the base metal or in the immediate vicinity of the heat-affected zone (HAZ). Conversely, due to their higher hardness and specific microstructure, the armour steels exhibited reduced plastic deformation prior to failure, alongside a more pronounced localization of stress and fracture within the weld zone.

The test results indicate that the proper selection of welding parameters and filler material plays a vital role in determining the quality and load-bearing capacity of the welded joint, particularly for high-strength steels. Furthermore, it was confirmed that the heat-affected zone (HAZ) represents a critical region of the welded structure, as it undergoes substantial microstructural alterations and degradation of mechanical properties.

The conclusions made by this analysis is mostly aligned with the conclusions of other authors which find that superior ballistic and mechanical properties of ARMOX steels to a fully tempered martensitic microstructure, which simultaneously imposes inherent limitations regarding ductility and strain hardening capacity [1]. Under tensile and dynamic loading, these materials are particularly prone to stress localization and premature failure driven by stress triaxiality and local plastic instability [3]. When joining such ultra-high-strength steels, thermal cycles during welding inevitably induce structural heterogeneity across the joint zones, leading to localized variations in mechanical resistance. To mitigate the risk of brittle failure within the weld metal—a critical drawback highlighted in high-hardness steel joining—austenitic or ductile filler metals are routinely implemented [6]. Consequently, the observed reduction in overall elongation and the stress concentration within specific joint regions for example HAZ/weld metal, align with literature findings, confirming that the soft austenitic weld matrix absorbs plastic strain while protecting the joint against catastrophic brittle fracture.

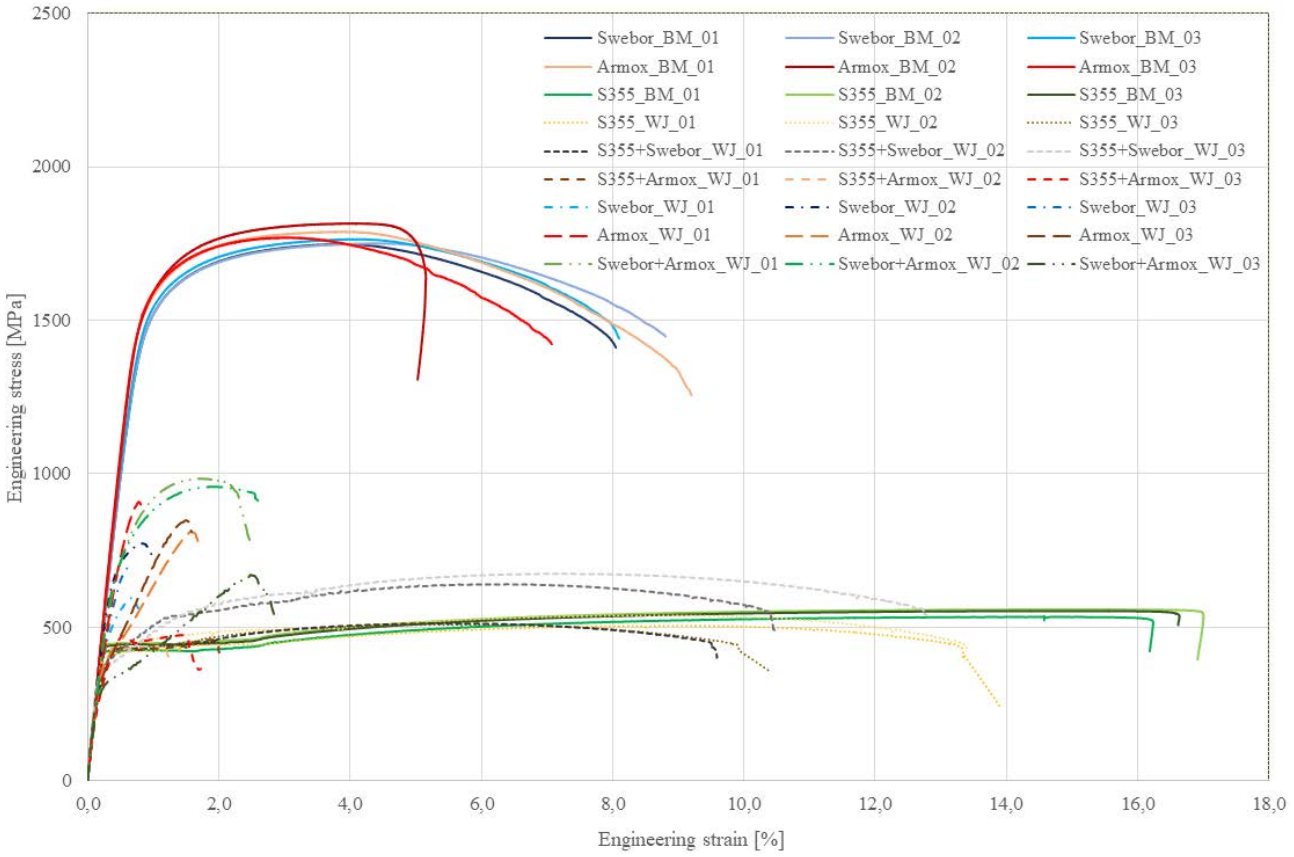


Figure 7. Stress-strain diagrams for tested specimens

Table 3. Results obtained by tensile testing

Sample no.	Elasticity modulus E, MPa	Yield stress, $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Fracture location
Swebor_OM_01	204273	1484.4	1748.7	-
Swebor_OM_02	203203	1487.0	1751.0	-
Swebor_OM_03	204054	1509.6	1764.6	-
Armox_OM_1	217619	1541.4	1788.8	-
Armox_OM_2	215319	1555.2	1816.2	-
Armox_OM_3	221284	1553.0	1770	-
S355_OM_1	176623	422.08	535.28	-
S355_OM_2	182713	447.02	558.13	-
S355_OM_3	180622	441.79	553.05	-
S355_ZS_1	182192	415.33	504.01	HAZ
S355_ZS_2	181723	427.21	536.98	HAZ
S355_ZS_3	186641	428.8	510.41	HAZ
S355+Swebor_1	182963	441.03	511.05	Welded joint
S355+Swebor_2	200073	359.26	414.01	Welded joint
S355+Swebor_3	191195	429.07	511.19	HAZ
S355+Swebor_4	207138	401.37	640.53	HAZ
S355+Swebor_5	219892	379.93	673.67	HAZ
S355+Armox_1	199375	439.74	459.86	Welded joint
S355+Armox_2	192213	426.11	442.8	Welded joint
S355+Armox_3	183336	445.41	473.65	Welded joint
Swebor_ZS_01	192244	547.68	594.15	Welded joint
Swebor_ZS_02	204824	724.21	772.16	Welded joint
Swebor_ZS_03	190049	677.57	693.26	Welded joint
Armox_ZS_01	196462	828.23	910.5	Welded joint
Armox_ZS_02	189000	776.57	813.56	Welded joint
Armox_ZS_03	190255	665.86	781.45	Welded joint
Armox_ZS_04	198142	435.81	809.08	Welded joint
Armox_ZS_05	206256	426.02	850.07	Welded joint
Swebor+Armox_01	194510	764.65	983.91	Welded joint
Swebor+Armox_02	190867	547.41	562.89	Welded joint
Swebor+Armox_03	186946	764.32	958.21	Welded joint
Swebor+Armox_04	179842	331.85	669.12	Welded joint
Swebor+Armox_05	180418	375.16	741.96	Welded joint

5. CONCLUSION

Based on the experimental investigations and the analysis of the results, several key conclusions can be drawn regarding the mechanical behaviour of dissimilar welded joints under tensile loading. The tests were performed on welded joints made of S355 structural steel and two types of armour steels (Armox 500 and Swebor 500), aiming to evaluate the influence of the base metal on the load-bearing capacity, plastic deformation capability, and fracture behaviour of the welded joint.

The experimental results demonstrated that the mechanical properties of the welded joints significantly depend on the mechanical and metallurgical characteristics of the base metal. For the S355 structural steel, a relatively uniform stress distribution was observed during tension, along with a pronounced plastic deformation capacity prior to fracture (Fig. 7). In the majority of tested cases, fracture occurred in the base metal or in the immediate vicinity of the heat-affected zone (HAZ), indicating that the weld metal quality was not the critical weakness of the structure.

The results for the armour steels revealed a specific mechanical behaviour resulting from their high hardness and strength. These materials exhibited reduced plastic deformation capacity alongside pronounced stress localization within the heat-affected zone (HAZ), specifically in the coarse-grained HAZ adjacent to the fusion line. Such behaviour can lead to earlier fracture initiation, particularly in regions subject to microstructural alterations induced by the welding heat input.

A critical aspect of the analysis concerns the heat-affected zone (HAZ), where significant microstructural and mechanical changes take place. The findings confirm that the HAZ represents one of the most critical regions in welded structures, particularly for steels with high mechanical properties.

Consequently, it can be concluded that welded joints fabricated from S355 steel display favourable mechanical behaviour and good ductility, making them suitable for structural components subjected to static loads. Conversely, armour steels—despite their high strength and resistance to mechanical damage—require stringent control of welding parameters due to their heightened sensitivity to microstructural changes.

Test specimens comprised both similar joints (same base metals) and dissimilar joints (combinations of the aforementioned steels). Particular attention was devoted

to the preparation of the weld zone to ensure the representativeness of the results and to minimize the influence of geometric imperfections.

Acknowledgement

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