10th INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2022
Belgrade, Serbia, 13 – 14 October 2022

# CHARACTERIZATION AND HEAT TREATMENT OF ARMOUR STEEL OF NEW GENERATION

JURE BERNETIČ, MATJAŽ MARČETIČ
SAAT, d.o.o., C. na Lipce 4, 4260 Bled, Slovenia, jure.bernetic@saat.si, matjaz.marcetic@saat.si

DOMEN P. KOSEC, MIRKO SOKOVIĆ
University of Novo mesto, Faculty of Mechanical Engineering, Na Loko 2, 8000 Novo mesto, Slovenia, domenpk@gmail.com, mirko.sokovic@gmail.com

BORUT KOSEC, BLAŽ KARPE, ALEŠ NAGODE
University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva cesta 12, 1000 Ljubljana, Slovenia
University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva cesta 6, 1000 Ljubljana, Slovenia, borut.kosec@ntf.uni-lj.si, blaz.karpe@ntf.uni-lj.si, ales.nagode@ntf.uni-lj.si

ZIJAH BURZIĆ, IGOR RADOSAVLJEVIĆ
Military Technical Institute, (MTI), Ratka Resanovića 1, 11030 Belgrade, Serbia, zijah.burzic@vti.vs.rs; igor.radosavljevic@vti.vs.rs

GORAZD KOSEC
SIJ ACRONI, d.o.o., C. B. Kidrica 44, 4240 Jesenice, Slovenia, gorazd.kosec@acroni.si

***Abstract:*** *Armour steel plate is intended for ballistic protection of military and civilian vehicles and structures, parts of machines and devices.*
*The work includes heat treatment and characterization of mechanical, microstructural and thermal properties of new generation of armour steel with internal code SA600.*
*Steel is the result of the development and knowledge of firm SAAT, d.o.o. in collaboration with scientific institutions and industry partners, produced in an industrial environment. The results of the research confirmed that the optimal austenitization temperature for steel SA600 is 870 °C, and the tempering temperature is 150 °C. Under these conditions, the hardness of the steel is 632 HV10, which means that it is suitably high. The yield strength is 1640 MPa and the tensile strength is 2052 MPa. The ratio* $Rp_{0,2}/Rm$ *is equal to 0.799 and is correspondingly low.*
*The thermal conductivity increases with temperature and is equal to 28.33 W/mK at ambient temperature (approx. 22 °C) and 39.67 W/mK at 400 °C.*

***Keywords:*** *armour steel, protection, heat treatment, characterization, production, testing.*

## 1. INTRODUCTION

Steel armour plates are intended for ballistic protection of military and civilian vehicles and structures, parts of machines and devices. When selecting or developing the appropriate materials for the armour it is necessary to achieve the best possible compromise between the required mechanical properties of materials, its density and the final price of the product [1]. With the appropriate production technology, which includes casting, hot forming, heat treatment, etc. [2], high strength low alloy steel of good functional properties at affordable prices can be produced. By improving the strength and toughness of the steel, the required thickness and the weight of the armour can be reduced.

New steel for ballistic protection with internal code SA600 belongs to the group of high strength low alloy (HSLA) steels [3]. Steel is the result of the development and knowledge of SAAT, d.o.o. in collaboration with scientific institutions and industry partners, produced in an industrial environment of VOEST Alpine GmbH. Table 1 shows the mass percentages of the elements that make up SA600 steel in addition to iron. The optimal chemical composition enables the achievement of the desired mechanical and physical properties and the planned microstructure.

The relevant mechanical properties are achieved by quenching and tempering [4].

**Table 1**. Indicative chemical composition of SA600 steel (in m.%)

| | |
|---|---|
| C | 0.43 |
| Si | 0.80 |
| Mn | 0.70 |
| Cr | 0.80 |
| Ni | 0.30 |
| P | 0.015 |
| S | 0.003 |
| B | 0.005 |
| Fe | rest |

The first and most important purpose of SA600 steel is resistance to the penetration of projectiles from small arms. The resistance depends mainly on the following mechanical properties: hardness, yield strength, tensile strength, plastic deformation capabilities, impact and fracture toughness, and stretching [5].

With the alloying elements silicon, chromium, molybdenum and boron, the appropriate manufacturing technology and heat treatment, all the desired mechanical properties can be achieved.

Table 2 shows the approximate values of the mechanical properties of SA600 sheet steel.

**Table 2.** Mechanical properties of SA600 steel

| | |
|---|---|
| Hardness | 590 – 640 HB |
| Yield strength | 1600 MPa |
| Tensile strength | 2050 MPa |
| Elongation | 7.5 % |
| Impact toughness (at -40°C) | 15 J |

## 2. EXPERIMENTAL

The experimental work includes heat treatment and characterization of new generation armour steel with internal code SA600.

In Figure 1 is testing SA600 steel plate from which samples were cut to perform heat treatment, mechanical tests, microstructure analysis and thermal properties description.

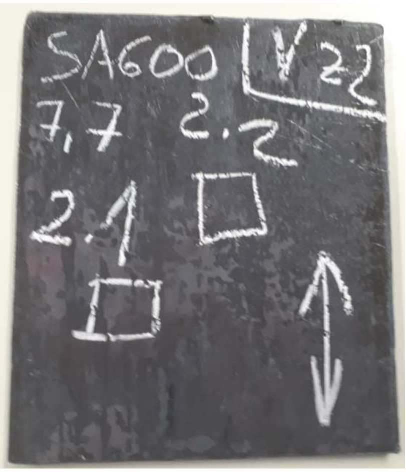


**Figure 1.** Testing SA600 steel plate

Samples from the supplied plates with a water jet for heat treatment and investigations of microstructure and mechanical properties (Figure 2) were cut.

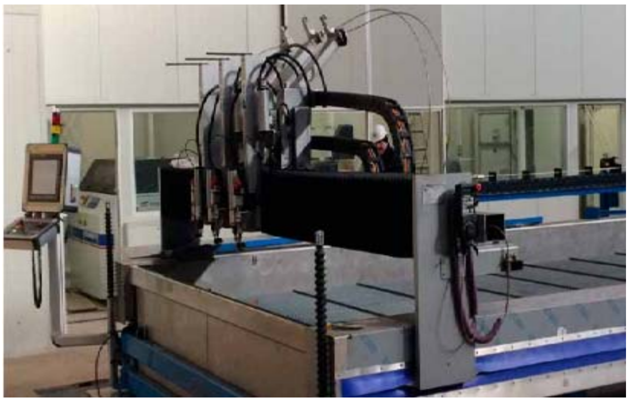

**Figure 2.** Water jet cutting machine Water Jet NC 2525 D in SIJ ACRONI d.o.o.

We performed heat treatment of steel SA600 in the delivered state, which consisted of hardening and tempering.

Based on experience and previous preliminary research, we determined a temperature of 870 °C for the optimal austenitization temperature, i.e. the temperature at which the original crystal grains of austenite do not grow more noticeably, and at which high hardness is obtained after quenching. The tempering was performed at temperatures of 150, 200, 300 and 400 °C.

In the Metallographic Laboratory of the Department of Engineering Materials, Faculty of Natural Sciences and Engineering, University of Ljubljana, samples cut from SA600 steel in the supplied and heat treated state were examined and analyzed with an OLYMPUS BX61 optical microscope, and a scanning electron field emission microscope Thermofischer Quattro S (Figure 3).

**Figure 3.** Scanning electron field emission microscope Thermofischer Quattro S

For the optimal austenitization temperature 870 °C was determined, i.e. the temperature at which the original austenite crystal grains do not yet grow more noticeably and at which high hardness is obtained after quenching. When examining the microstructure, the size of the original austenite crystal grains was measured.

Hardness measurements were performed with an instrument dynaTESTOR 10, and a load of 100 N was used. Hardness was measured on all four samples heat treated samples, and on the fifth sample immediately after the first phase of heat treatment - quenching. Hardness with tempering temperature decreases from initial (immediately after quenching) hardness of 671 HV, to 632 HV at tempering at 150 °C / 1 h, and up to 455 HV at tempering at 400 °C / 1 h. Based on the results of hardness measurements, the temperature of 150 °C was chosen as the optimal temperature for the tempering.

The tensile tests were performed on a universal tensile testing machine INSTRON 1255 in accordance with the standard ISO 6892-1: 2009 [6].

## 3. RESULTS AND DISCUSSION

At temperature 150 °C temperature, SA600 steel achieves the most suitable combination of mechanical properties for armour steels.

Microstructure of SA600 steel hardened from 870 °C and hardenend and tempered are shown in Figures 4 and 5.
The grains grow more noticeably at temperatures above 870 °C (Figure 4).

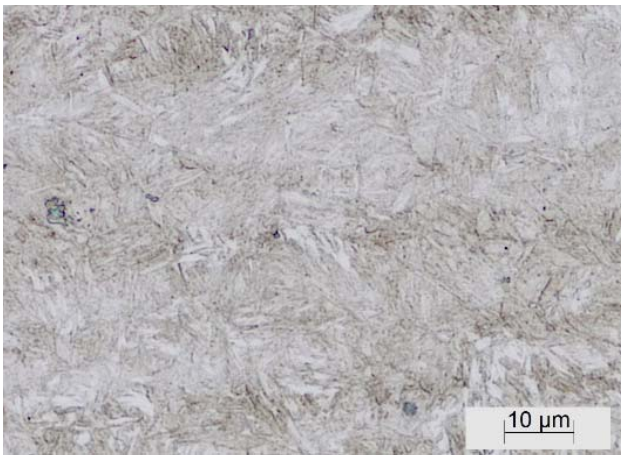


**Figure 4**. Microstructure of SA600 steel hardened from 870 °C; (OM)

Figure 5 shows the microstructure after tempering at 150 °C. At this tempering temperature, the first stage of tempering takes place, which involves the elimination of i.e. transition ε-carbides of formula $Fe_{2,4}C$. Elimination takes place by lowering the carbon content of martensite to form low-carbon martensite. In Figure 5, these carbides are very fine and in the form of thin needles. At this magnification, they are barely noticeable. They are excreted on the cubic planes of the martensite nut and on dislocations [3].

The hardness in our case is high and amounts to 632 HV (580 - 640 HV is prescribed).

Results of tensile tests are presented in Figure 6. The $Rp_{0.2}/Rm$ ratio is the lowest at this temperature (0.7992). A low $Rp_{0.2}/Rm$ ratio means higher resistance to local steel flow and thus better armour protection. The elongation at this temperature is 7.5% and thus reaches the required elongation value for armour steel.

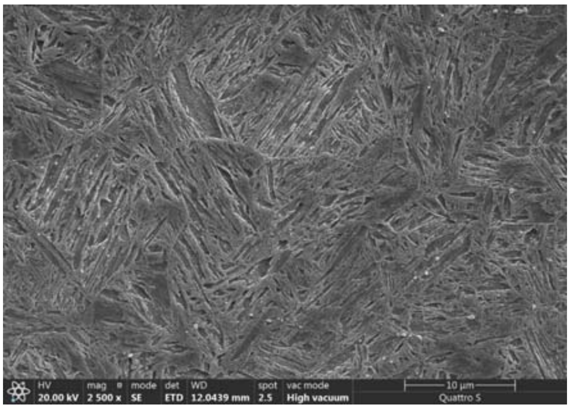


**Figure 5.** Microstructure of SA600 steel, hardened at 870 °C and tempered at 150 °C/ 1h; etched with Nital, (SEM).

sij acroni

SIJ ACRONI d.o.o. - Služba Kakovost
Cesta Borisa Kidriča 44 SI - 4270 Jesenice

**Poročilo o Nateznem Preizkusu / Test report**

Obrazec/Form : OB 10.25.04a(14)
Št./No. : AHP_EN_BPC-F0600_2019-08-02_29642
Dat. Prevzema : [illegible]
Nar./Custom. : Predelava Debele Plocevine
Stroj/Machine : BPC-F0600.R09
S. št:171877-2006
Merilo/Measure : Klj. mer:7001398

Vrsta vz./Spec type : Prop. type D
Test Standard : SIST EN ISO 6892-1:2017 B6
Temp./Test temp, : Sobna/Room
E-Modulus speed : 60 MPa/s
Yeld point speed/hit. do ReH : 60 MPa/s
Yeld range speed/hit. ReH-ReL : 0,0025 1/s
Test speed/ hit. pr. : 0,008 1/s
Automatic force zeroing : Yes
Calc. of str. Ax to ISO 2566- 1/2 : Yes

| LOT | Vzorec | Material | Dn mm | $a_0$ mm | $b_0$ mm | $L_0$ mm | Rp0,2 MPa | Rp1,0 MPa | Reh MPa | $R_m$ MPa | $A_{5,65}$ % | A50 % | Z % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] |  | [illegible] | 9,50 | 9,8 | 14,8 | 100 | 1565 | 1918 | - | 2040 | 7,0 | 7,0 | 27 |
| [illegible] |  | [illegible] | 9,50 | 9,7 | 14,7 | 100 | 1691 | 1964 | - | 2060 | 7,0 | 7,5 | 21 |
| [illegible] |  | 600 | 9,50 | 9,7 | 14,6 | 100 | 1654 | 1939 | - | 2054 | 8,0 | 8,5 | 29 |
| [illegible] |  | [illegible] | 9,50 | 9,7 | 14,6 | 100 | 1651 | 1938 | - | 2054 | 6,5 | 7,0 | 25 |
| [illegible] |  | [illegible] | 9,50 | 9,7 | 14,6 | - | - | - | - | - | - | - | - |

**Figure 6.** Results of tensile test

Measurements and analysis of thermal properties of testing samples from the steel SA600 were performed in accordance with the standard ISO 22007-2 [7,8] For determining the thermal properties, one of the most advanced instruments Hot Disk TPS 2200 (Figure 7), a product of Hot Disk AB company, Gothenburg, Sweden [9] was used.

**Figure 7.** Instrument Hot Disk TPS 2200

In Figure 8 are presented results of thermal properties measurements and determination at ambient temperature.

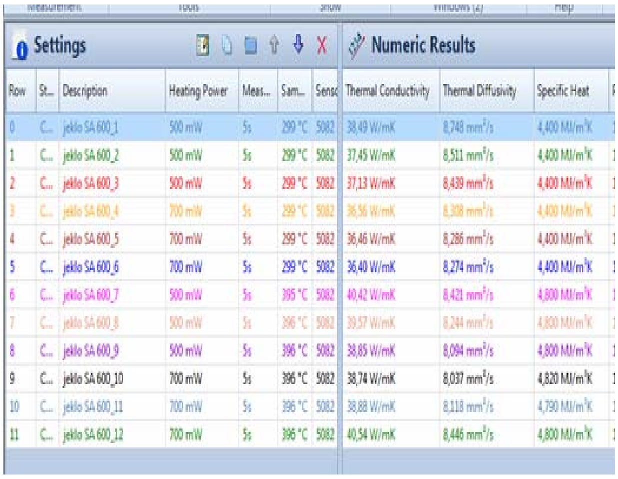


**Figure 8.** Results of thermal properties measurements

In Table 3 are presented thermal properties (thermal conductivity, specific heat and temperature diffusivity) of steel at ambient temperature (approx. 22 °C). The thermal conductivity increases with temperature, and is equal to 28.33 W/m·K at ambient temperature, and 39.67 W/m·K at 400 °C.

**Table 3.** Thermal properties of steel SA600 at ambient temperature (approx. 22 °C)

| Steel SA600 | |
|---|---|
| Thermal conductivity | 28.33 W/m·K |
| Specific heat | 4.44 MJ/m$^3$K |
| Temperature diffusivity | 6.37 mm$^2$/s |

## 3. CONCLUSIONS

The work includes heat treatment and characterization of mechanical, microstructural and thermal properties of new steel for armour protection with internal code SA600. Steel is the result of the development and knowledge of firm SAAT, d.o.o. in collaboration with scientific institutions and industry partners, produced in an industrial environment.

The results of the research carried out as part of the investigation confirmed that the optimal austenitization temperature for SA600 steel is 870 °C and the tempering temperature is 150 °C. Under these conditions, the hardness of the steel is 632 HV10, which means that it is suitably high. The yield strength is 1640 MPa and the tensile strength is 2052 MPa. The $Rp_{0,2}/Rm$ ratio is equal to 0.7992 and is correspondingly low.

The thermal conductivity increases with temperature and is equal to 28.33 W/m·K at abmient temperature, and 39.67 W/m·K at 400 °C.

## ACKNOWLEDGEMENT

The authors want to thank dr. Slavko Ažman+ (SIJ ACRONI d.o.o.), professor Ladislav Kosec (University of Ljubljana), professor Franc Vodopivec+ (Institute of Metals and Technology, Ljubljana), dr. Milenko Rimac (Metallurgical Institute K. Kapetanovic, Zenica), and professor Anton Smolej (University of Ljubljana) for mentorship at study armoured steels.

### References

[1] *CROUCH, I. G.:* The Science of Armour Material. Amsterdam*: Elsevier, 2017.*

[2] DOBRZANSKI, L.A.: *Technical and Economical Issues of Materials Selection*, Silesian Technical University, Gliwice, 1997.

[3] TOTTEN, G. E.: *Steel heat treatment: equipm- ent and process design.* Boca Raton: CRC Press, Taylor & Francis Group, 2006.

[4] BERNETIČ, J.: *Development of model for predicting hardenability of high strength low alloy steels:* (B. Kosec, A. Smolej), Doctoral Thessys, University of Ljubljana, Ljubljana, 2013.

[5] BERNETIČ, J., KOSEC, G., KOSEC, B.: *Steel of new generation PROTAC 500,* IRT 3000, 8 (2013) 48, 30-31.

[6] Slovenian standard SIST EN ISO 6892-1:2010: Metal Materials – Tensile Testing Part 1: *Testing Methods at Room Temperature* (01 – march- 2010).

[7] International standard ISO 22007 (2009). Plastics – Determination of thermal conductivity and thermal diffusivity – Part 1: *General principles*. Reference: ISO 22007:2009(E).

[8] BERNETIČ, J., KOSEC, B., KOSEC, G., GOJIĆ, M., BURZIĆ, Z., NAGODE, A., SOKOVIĆ, M., BIZJAK, M.: *A new generation of armoured steel plate*. Contemporary materials, 7 (2016) 2,137 – 141.

[9] KOSEC, B., KARPE, B.: Instrument for the thermal properties analysis Hot Disk TPS 2200, IRT3000, 1 (2017), 67.