XIII Scientific/expert symposium with international participation
”METALLIC AND NONMETALLIC MATERIALS“ Zenica, BiH, 27th May 2021.

THERMAL PROPERTIES OF ARMOUR STEEL

Borut Kosec, Tjaša Kranjec, Blaž Karpe, Aleš Nagode, Milan Bizjak
University of Ljubljana, Faculty of Natural Sciences and Engineering
Ljubljana, Slovenia

Jure Bernetič
SAAT d.o.o. & Swebor Stahl Svenska AB
Bled, Slovenia Lule, Sweden

Mirko Gojić
University of Zagreb, Faculty of Metallurgy
Sisak, Croatia

Zijah Burzić
Military Technical Institute
Belgrade, Serbia

Milan Rimac
University of Zenica
Zenica, BiH

Gorazd Kosec
SIJ ACRONI d.o.o.
Jesenice, Slovenia

Keywords: armour steel, thermal properties, measurements, temperature

ABSTRACT

The presented investigation work investigates thermal properties of the ultra-high hardness (UHH) armour steel. Steel is distinguished with high hardness and strength. It is sold in the quenched or tempered state, because achieving planned hardness which has to be between 590 HB and 640 HB.

In the frame of the investigation work the analysis of thermal properties of the steel was carried out on the device Hot Disk TPS 2200, which works according to the method of transient plane source (TPS) method. Measurements were carried out according to the standard ISO 22007. In addition to thermal properties we measured hardness and analyzed the microstructure of the steel.

The study aimed to determine thermal properties at ambient and at elevated temperatures. The results have shown that thermal conductivity increases up to the temperature of 400 °C. Analyzed steel can be classified as medium thermal conductive steel with an average value of thermal conductivity of 27.17 W/mK at ambient temperature.

1. INTRODUCTION

The selection of the appropriate armoured material is crucial to ensure the adequate safety and mobility transport systems. 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, minimizing the density and the final price of the product [2].

With the appropriate production technology, which includes synthesis, hot forming, heat treatment, etc. [3] ultra-high hardness 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 steel shell iarereduced. Such steels are competitive to other materials for the armour [4].

Steel SWEBOR Armour 600 can be used in most protection applications i.e. civil armoured vehicles, CIT-vehicles, police cars, security doors and walls, bank counters, shoot catches, etc.. Steel can be used as the base material for protection or as add-on armour for most demanding applications. Regardless of higher hardness steel SWEBOR Armour 600 remains easy to handle in the workshop with good bending and welding properties regardless of its ultra-high hardness [5].

The development of steel armour plate is a complex process. Although guidelines are indicating the chemical composition, alloying and heat treatment parameters, the correlation between mechanical properties and ballistic protection is still unknown. In the initial stage of development, it is necessary to define the main purpose of the use of steel, ie resistance to penetration of firearms. An appropriate combination of the following mechanical properties plays an important role in achieving this property: hardness, yield stress ($Rp_{0.2}$), tensile strength (Rm), $Rp_{0.2}$ / Rm ratio (plastic deformation ability), impact and fracture toughness and elongation (A_5). When exposed to missiles, the armor can absorb kinetic energy. This means that the projectile can deflect or deform it. There are three ways of absorbing the kinetic energy of a missile [3,6]:

- by elastic deformation of the material,
- by plastic deformation of the material, and/or
- by transferring the kinetic energy of the projectile to the target material.

The total energy absorbed by the projectile is the product of the energy absorbed per unit volume and the volume involved in the deformation.

The response of materials and structures to intense loading is quite complex. Under load conditions that cause vacuum stress, the materials behave elastically and Hook's law applies. The behavior of the material in plastic deformations involves large deformations along with localized heating. The influence of hardness in projectile penetration depends on the deformation rate and the thickness of the plate. The modes of failure on the plates can be divided into six mechanisms: penetration with brittle fracture, penetration with plastic deformation, flexible, radial fracture, penetration with punching of the plug, penetration with crushing of material on the back and penetration with twisting (folding) [6].

2. BASIC MATERIAL PROPERTIES

Steel SWEBOR Armour 600 is an ultra-high hardness (UHH) armour steel with extreme hardness. Advance alloying system with silicon, nickel, chromium, molybdenum and boron with carefully managed production from the melt, rolling to heat treatment sequence give the steel the extreme combination of hardness, high strength, weldability and one of the most advanced ballistic performance properties on the World market [5].

The basic material properties of the armour steel SWEBOR Armour 600 are still well known. The chemical composition of the armour steel SWEBOR Armour 600 is represented in Table

1, mechanical properties are collected in Table 2, and microstructure is represented in Figure 1 [5].

Table 1. Chemical composition of steel SWEBOR Armour 600

Element	Mass %
C	0.40
Si	0.80
Mn	0.60
Cr	1.30
Ni	3.00
B	0.004
P	0.015
S	0.003

Table 2. Mechanical properties of steel SWEBOR Armour 600

Hardness	590 – 640 HB
Yield strength R_{P02},	1550 MPa
Tensile strength R_m	2100 MPa
Elongation A_5	7 %
Impact toughness (at testing temperature -40 °C)	13 J

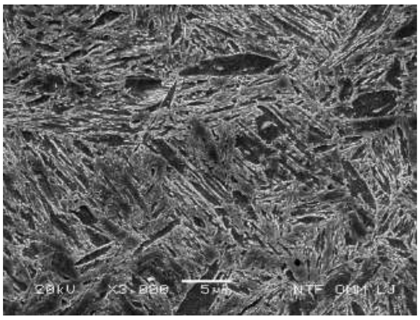


Figure 1. Martensitic microstructure of steel SWEBOR Armour 600 (SEM).

3. THERMAL PROPERTIES

In the frame of the presented research one of the most advanced instruments for determining thermal properties, Hot Disk TPS 2200, a product of Hot Disk AB company, Sweden (Figure 2) [7] was used.

Figure 2. Instrument Hot Disk TPS 2200.

The instrument can be used for determining thermal properties of various materials including pure metals, alloys, minerals, ceramics, plastics, glasses, powders and viscous liquids with thermal conductivity in the range from 0.01 to 500 W/mK, thermal diffusivity from 0.01 to 300 mm^2/s, and heat capacity up to 5 MJ/m^3K. Measurements can be performed in a temperature interval between -50 °C up to 750 °C.

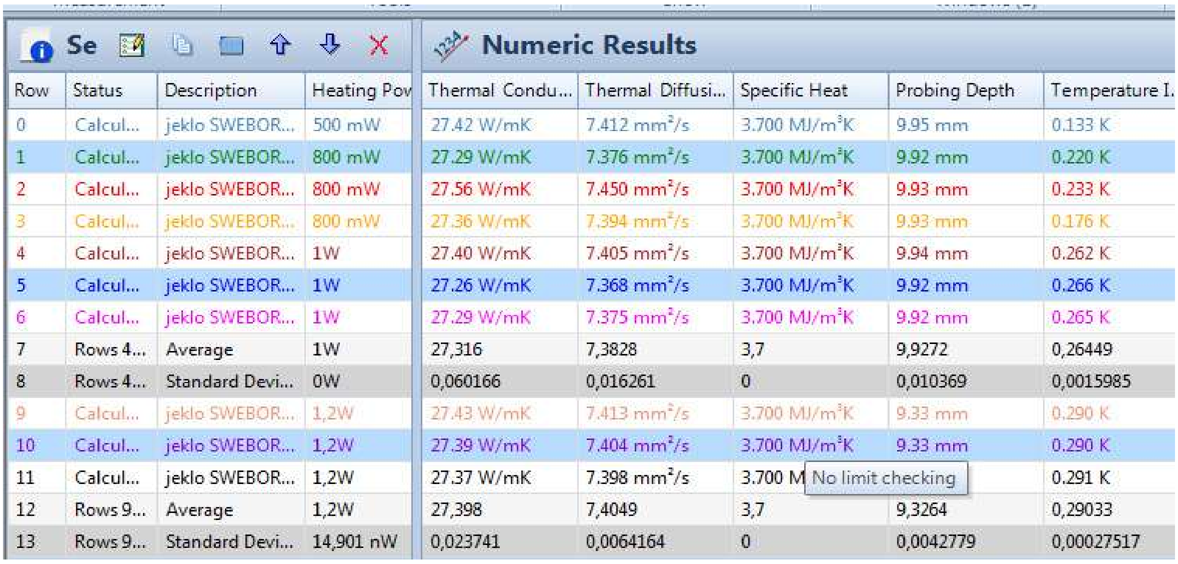
Figure 3. Measuring sensor sandwiched between two halves of a sample during measurement.

The hot disk measuring method is a transient plane source technique (TPS). Based on the theory of TPS, the instrument utilizes a sensor element in the shape of a 10 µm thick double spiral, made by etching from pure nickel foil. Spiral is mechanically strengthend and electrically insulated on both sides by thin polyimide foil (Kapton ®Du Pont) for measurements up to 300 °C or mica foil for measurements up to 750 °C.

Sensor acts both as a precise heat source and resistance thermometer for recording the time dependent temperature increase. During measurement of solids, encapsulated Ni-sensor is sandwiched between two halves of the sample and constant precise pre-set heating power is released by the sensor, followed by 200 resistance recording in a pre-set measuring time, from which the relation between time and temperature change is established. Based on time dependent temperature increase of the sensor, the thermal properties of the tested material are calculated [8]

4. EXPERIMENTAL WORK

Measurements and analysis of thermal properties of testing samples from the steel SWEBOR Armour 600 (40 x 40 x 10 mm) were performed by standard ISO 22007-2 [9] in the Laboratory for Thermotechnical Measurements, Faculty of Natural Sciences and Engineering, University of Ljubljana. In Figure 4 are presented results of thermal properties measurements with the instrument Hot Disk TP 2200.



Row	Status	Description	Heating Pov	Thermal Condu...	Thermal Diffusi...	Specific Heat	Probing Depth	Temperature I.
0	Calcul...	jeklo SWEBOR...	500 mW	27.42 W/mK	7.412 mm^2/s	3.700 MJ/m^3K	9.95 mm	0.133 K
1	Calcul...	jeklo SWEBOR...	800 mW	27.29 W/mK	7.376 mm^2/s	3.700 MJ/m^3K	9.92 mm	0.220 K
2	Calcul...	jeklo SWEBOR...	800 mW	27.56 W/mK	7.450 mm^2/s	3.700 MJ/m^3K	9.93 mm	0.233 K
3	Calcul...	jeklo SWEBOR...	800 mW	27.36 W/mK	7.394 mm^2/s	3.700 MJ/m^3K	9.93 mm	0.176 K
4	Calcul...	jeklo SWEBOR...	1W	27.40 W/mK	7.405 mm^2/s	3.700 MJ/m^3K	9.94 mm	0.262 K
5	Calcul...	jeklo SWEBOR...	1W	27.26 W/mK	7.368 mm^2/s	3.700 MJ/m^3K	9.92 mm	0.266 K
6	Calcul...	jeklo SWEBOR...	1W	27.29 W/mK	7.375 mm^2/s	3.700 MJ/m^3K	9.92 mm	0.265 K
7	Rows 4...	Average	1W	27,316	7,3828	3,7	9,9272	0,26449
8	Rows 4...	Standard Devi...	0W	0,060166	0,016261	0	0,010369	0,0015985
9	Calcul...	jeklo SWEBOR...	1,2W	27.43 W/mK	7.413 mm^2/s	3.700 MJ/m^3K	9.33 mm	0.290 K
10	Calcul...	jeklo SWEBOR...	1,2W	27.39 W/mK	7.404 mm^2/s	3.700 MJ/m^3K	9.33 mm	0.290 K
11	Calcul...	jeklo SWEBOR...	1,2W	27.37 W/mK	7.398 mm^2/s	3.700 M		0.291 K
12	Rows 9...	Average	1,2W	27,398	7,4049	3,7	9,3264	0,29033
13	Rows 9...	Standard Devi...	14,901 nW	0,023741	0,0064164	0	0,0042779	0,00027517

Figure 3. Results of thermal properties measurements.

In Table 3 are presented thermal conductivity and temperature conductivity of steel SWEBOR Armour 600 at ambient temperature (approx. 23 °C), and elevated temperatures (300 and 400 °C).

Table 3. Thermal conductivity and temperature conductivity

Temperature	23 °C	300 °C	400 °C
Thermal conductivity	27.17 W/mK	33.18 W/mK	36.37 W/mK
Temperature conductivity	7,55 mm^2/s	8.51 mm^2/s	8.87 mm^2/s

4. CONCLUSIONS

Steels from the group SWEBOR Armour are distinguished by good mechanical properties and excellent armour properties even at small thicknesses.

The mechanical properties of steel are relatively well known, while data on thermal properties were not available, so in the frame of this work its thermal properties were determined.

Measurements of thermal properties were performed by with the standard ISO 22007-2 at ambient and evaluated temperatures with the instrument Hot Disk TPS 2200.

The results have shown that thermal conductivity increases up to the temperature of 400 °C. Analyzed steel can be classified as medium thermal conductive steel with an average value of thermal conductivity of 27.17 W/mK at ambient temperature, and 36.37 W/mK at 400 °C.

5. REFERENCES

[1] Hu, C.J., Lee, P.W., Ballistic performance and microstructure of modified rolled homogeneous armor steel, Journal of the Chinese Institute of Engineers, 25 (2002) 1, 99 – 107.
[2] Thelning, E.K., Steel and its Heat Treatment, Butterworths, London, 1984.
[3] Crouch, I., The Science of Armour Materials : WP Woodhead Press, Amsterdam, 2017.
[4] Kasonde, M. Optimising the mechanical properties and microstructure of armoured steel plate in the quenched and tempered condition: master of engineering. University of Pretoria, 2005.
[5] Swebor Armor 600 Datasheet, Swebor Stal Svenska AB, Lulea, 2019.

[6] Børvik, T., Dey, S., Clausen, A.H., Perforation resistance of five different high-strength steel plates for ballistic perforation resistance, International Journal of Impact Engineering, 36 (2009) 7, 948–964.

[7] Kosec., B., Karpe, B., Instrument for the thermal properties analysis Hot Disk TPS 2200, IRT3000, 1 (2017), 67.

[8] Bernetič, J, Kosec, B., Kosec, G., Gojić, M., Burzić, Z., Nagode, A., Soković, M., Bizjak, M.. A new generation of armored steel plate. Contemporary materials. 7 (2016) 2, 137-141.

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

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, and professor Anton Smolej (University of Ljubljana) for mentorship at study armoured steels.*