Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 14th International Scientific and Practical Conference. Volume 3, 24-35

Thermal Characteristics of Materials in Modelling of Welding Processes

Valentin Anguelov
Center of welding (IMSETCHA) "Acad. A. Balevski"
Bulgarian Academy of Sciences
Sofia, Bulgaria
valentin.anguelov@ims.bas.bg

Abstract. **The application of welding processes during manufacturing of metallic products result in changes of the properties of the base materials. Process simulation enables evaluation of the effect of heat application in proximity to the weld seam. The availability and use of input data, relevant for the specific material, is essential for the reliability of the results. The thermal characteristics of the materials, required for the heat modelling were identified. Their dependency on the material temperature was investigated and the formulas were presented. Particular values were found in existing data sources, for specific structural steels, stainless steels, nickel and titanium alloys. The values of the thermal characteristics were represented and in graphical and tabulated formats, facilitating direct implementation in calculations, assessment of variation trends and applicability for specific purposes.**

Keywords: thermal characteristic, modelling, welding process.

I. INTRODUCTION

The properties of the welded joints could not be assessed in full after the completion of the structures manufacturing. Welding is a special process [1] and control before, during and after the completion of the works is necessary, if comprehensive quality requirements are to be met [2]. In fusion welding a heat source or sources are applied to the material, melting and joining the neighbouring parts. The increase of the temperature from an initial value (T_0) is very fast, and the decrease of the temperature is slower, depending on variable conditions, process and material characteristics. Standard recommendations regarding the process variables [3], [4] are issued for the most common materials, like ferritic steels, and information is provided by the manufacturers of advanced materials [5]. The common evaluation is based on calculation or estimation of the cooling time in the temperature range between 800 and 500 °C, the t8/5 time.

The calculation of the cooling time is possible according to standard formulas, valid under limited range of values of essential variables, defines by the standards [4], [6]. For example, a three-dimensional heat dissipation the equation was formulated:

$$t_{8/5} = (6700 - 5 \cdot T_0) \cdot Q \cdot \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0}\right) \cdot F3 \qquad (1)$$

where:

T0 – initial temperature of the material,

Q – heat input,

F3 – seam geometrical factor.

The properties of the materials are not considered in (1), and the formula is only valid for ferritic steels.

The cooling time t8/5 is calculated in the immediate proximity to the weld seam, where the cooling rate is the highest. This area is considered as the most vulnerable to base material properties deterioration.

During the welding process, the t8/5 is regulated by controlled application of heat at specified initial temperature. At process qualification, the resulting material properties are checked by non-destructive and destructive tests on sample pieces.

This simplified approach is applicable to limited range of standard conditions. The zone of the base material, affected by the heat (HAZ) is of complicated three dimensional shapes. The properties in the volume of the HAZ vary in each direction. More detailed analysis is necessary in the cases of welding conditions outside of the limits defined by the standard [3]; for materials of chemical composition outside the defined limits; of special properties obtained by a manufacturing treatment, that could be influenced by the heat; in cases of significant importance of the structure built and in all cases when the standard approach results should be additionally verified.

Print ISSN 1691-5402
Online ISSN 2256-070X
https://doi.org/10.17770/etr2023vol3.7202

The modeling of the welding requires reliable data in order to achieve simulations in close agreement to the real process results.

II. MATERIALS AND METHODS

A. Overview

The simulation of the temperature profile includes building of appropriate model of the heat source (e.g. welding arc, laser beam), simulation of the heat flow within the base materials volume, as well as to and from the surrounding ambience.

The execution, validation and verification workflow of the numerical welding simulation was standardized in [7]. The application of the models and the methods used were described in a significant number of scientific papers, including [8], [9] and [10].

The simulation of the temperature profile includes building of appropriate model of the heat source (e.g. welding arc, laser beam), simulation of the heat flow within the base materials volume, as well as to and from the surrounding ambience.

The heat transfer equation,

$$\nabla^2 T = \rho \cdot \frac{C_p}{k} \cdot \frac{\delta T}{\delta t} \tag{2}$$

was initially solved for the welding processes as in [11]. It was developed in [12] as

$$C_p \cdot \rho \cdot \frac{\delta T}{\delta t} = k \cdot \left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2}\right) + q \tag{3}$$

Formulation for FEA solution was presented in [13] and depending on the welding process, developed in order to represent the specific heat source in the best way (e.g. in [14] and [15]).

B. Modeling Input Data

In all solutions, the required input data includes:

- Process parameters, including power (i.e. welding current and voltage of arc welding), movement speed and process efficiency.

The process parameters are measured during the process or values of the parameters are decided, in order to create simulation of the changes influence. Initial values of the process efficiency could be obtained in [6]. The value of the process efficiency is used for process calibration.

- Heat source parameters, including shape and power distribution.

Multiple solutions of the heat source characteristics were developed, as described in [16]. The values of the heat source parameters are used for process calibration.

- Geometry parameters, including size of the work-piece, distance of the heat application from the edges of the material, distance of the FEM points from the heat source.

The geometry parameters are measured or variations of the values are decided, in order to create simulation of the changes influence.

- Material characteristics, including:

  Cp – specific heat capacity at constant pressure,

  k - thermal conductivity and ,

  ρ - material density.

C. Material Characteristics

The specific heat capacity of a material is the amount of heat required to rise the temperature of 1 kg of mass by 1 K (°C) [21]:

$$Q = m \cdot C \cdot (T_2 - T_1) \tag{4}$$

where Q is the amount of heat, m is the mass, T_1 and T_2 are the initial and final temperatures.
C is the commonly used symbol for the heat capacity, or Cp if considered at constant pressure, with unit of measurement (J/(kg·K)) ≡ (J/(kg·°C)).

The thermal conductivity coefficient is regarded in [17]. Fourier's law defines the quantity of heat diffusing through a unit surface during a unit of time within a material subjected to a temperature gradient:

$$q = -k \cdot \nabla T \tag{5}$$

where k is the commonly used symbol for thermal conductivity, with unit of measurement W/(m·K) ≡ W/(m·°C).

The density of the materials is commonly represented by the symbol ρ □□in units of kg/m^3.

The above characteristics are specific to each material, according to the chemical composition and internal structure and depending on the temperature value and heating rate [18].

The present investigation was targeted at the thermal characteristics of weldable metallic materials, in range representing temperatures of the base material and the heat affected zone in the period of time preceding and successive to the application of heat by a moving source. Commonly used grades of structural, low alloyed and stainless steel, nickel and titanium alloys were investigated. The range between -100 °C to 1400 °C was considered.

D. Data sources of thermal characteristics of the metallic materials

Limited information regarding the thermal characteristic of specific metallic material is readily available. The following types of data sources were identified:

- Regulatory specifications, including EU and USA standards and codes [19], [20]. The data includes empirical formulas of the structural carbon and stainless steel thermal characteristics at temperature ranges. The data provided in the specifications is compulsory to be considered, when calculating the properties of materials, used in construction.

- Data bases of the modelling software. The welding processes modelling software [21], [22] allows for definition of the material properties as constant, as dependent variable defined by the user, or as a data to be obtained from built-in data bases. The data in the bases built in the modelling software is limited to their material libraries.

- Data, provided by educational and research institutions [23], [24]. The data is limited to specific materials that were subject to research. In cases of different results obtained by different researchers, both results were presented in [25].

- Data provided by material manufacturers [26]. The data is limited to the materials of each steel producer.

- Other public data bases. Multiple public data bases are available online, providing information about the materials thermal characteristics. Some of the data bases provide general information, like in [27] and [28], other provide specific information, according to referenced sources [29], while some of the data was false [30].

III. RESULTS AND DISCUSSION

A. Relations of material density, specific heat capacity and thermal conductivity to temperature

In data sources [19], [22], [27] and [29], the values of the material properties are presented as constants or by use of empirical formula calculations, depending on the temperature, as in Table 1, Table 2 and Table 3.

TABLE 1 CONSTANTS AND EMPIRICAL FORMULAS OF MATERIAL DENSITY

Material	**Temperature range, °C**	**Density ρ (T) , kg/m^3**	**Source**
S 355 J2, S 690 QL	All	Constant, 7850	[19]
	All	Constant, 7800	[27]
	(-100) to 704	$7911.3 - 0.01678428 \cdot T - 8.018711 \cdot 10^{-4} \cdot T^2$ $+1.172796 \cdot 10^{-6} \cdot T^3 - 1.015971 \cdot 10^{-9} \cdot T^4 + 3.677737 \cdot 10^{-13} \cdot T^5$	[22]
	704 to 788	$7116.994 + 0.5195388 \cdot T$	
	788 to 871	$8166.523 - 0.4696497 \cdot T$	
	871 to (1400)	Constant, 7630	
	All	Constant, 7850	[29]
X5CrNi18-10 (304)	All	Constant, 7850	[19]
	All	Constant, 7800	[27]
	(-100) to 1427	$7945.333 - 0.1981948 \cdot T - 3.713764 \cdot 10^{-4} \cdot T^2$ $+2.213069 \cdot 10^{-7} \cdot T^3 - 5.128456 \cdot 10^{-11} \cdot T^4$	[22]
	All	Constant, 8000	[29]
X2CrNiMoN22-5-3 (2205)	All	Constant, 7850	[19]
	All	Constant, 7800	[27]
	(-100) to 20	Constant, 7790	[22]
	20 to 400	$7871.9 - 0.1918817 \cdot T - 2.088029 \cdot 10^{-4} \cdot T^2 + 8.9339 \cdot 10^{-8} \cdot T^3$	
	400 to (1400)	Constant, 7675	
	All	Constant, 7800	[29]

TABLE 1 (CONT.) CONSTANTS AND EMPIRICAL FORMULAS OF MATERIAL DENSITY

Material	**Temperature range, °C**	**Density ρ (T) , kg/m^3**	**Source**
NiCr22Mo9Nb (Inconel 625)	All	Constant, 8600	[27]
	(-100) to - 20	$8308.627 + 0.0376521 \cdot T - 0.001256698 \cdot T^2 + 1.529227 \cdot 10^{-6} \cdot T^3$	[22]
	- 20 to 927	$8339.072 - 0.3000351 \cdot T + 2.796812 \cdot 10^{-6} \cdot T^2 - 5.001998 \cdot 10^{-8} \cdot T^3$	
	927 to (1400)	Constant, 7900	
	All	Constant, 8440	[29]
NiCu30Fe (Monel 400)	All	Constant, 8600	[27]
	(-100) to 1093	$8886.029 - 0.2533148 \cdot T - 1.860111 \cdot 10^{-4} \cdot T^2 + 4.094544 \cdot 10^{-8} \cdot T^3$	[22]
	1093 to (1400)	Constant, 8300	
	All	Constant, 8440	[29]
Titan 99.8 (Titan Grade 1)	All	Constant, 4500	[27]
	(-100) to 871	$4534.619 - 0.1176636 \cdot T + 2.570905 \cdot 10^{-6} \cdot T^2 - 1.218339 \cdot 10^{-8} \cdot T^3$	[22]
	871 to (1400)	Constant, 4385	
	All	Constant, 4500	[29]
TiAl6V4 (Titan Grade 5)	All	Constant, 4450	[27]
	(-100) to 27	$4452.817 + 0.02869485 \cdot T - 6.448869 \cdot 10^{-4} \cdot T^2$ $+9.646377 \cdot 10^{-7} \cdot T^3 - 1.720215 \cdot 10^{-11} \cdot T^4$	[22]
	27 to 760	$4467.094 - 0.119171 \cdot T - 1.275079 \cdot 10^{-5} \cdot T^2$	
	760 to (1400)	Constant, 4330	
	All	Constant, 4430	[29]

TABLE 2 CONSTANTS AND EMPIRICAL FORMULAS OF SPECIFIC HEAT CAPACITY

Material	**Temperature range, °C**	**Specific heat capacity at constant pressure Cp (T) , J/(kg °C)**	**Source**
S 355 J2, S 690 QL	(-100) to 20	Constant, 443	[19]
	20 to 600	$425 + 0.773 \cdot T - 0.00169 \cdot T^2 + 2.22T \cdot 10^{-6} \cdot T^3$	
	600 to 735	$666 + \left(\frac{13002}{738 - T}\right)$	
	735 to 900	$545 + \left(\frac{17820}{T - 731}\right)$	
	900 to (1400)	Constant, 650	
	All	Constant, 470	[27]
	(-100) to 20	Constant, 500	[22]
	20 to 575	$-215.730638 + 6.0184999 \cdot T - 0.0183429321 \cdot T^2$ $+2.414973 \cdot 10^{-5} \cdot T^3 - 1.07882432 \cdot 10^{-8} \cdot T^4$	
	575 to (1400)	Constant, 840	
	All	Constant, 470	[29]

TABLE 2 (cont.) Constants and Empirical formulas of specific heat capacity

Material	**Temperature range, °C**	**Specific heat capacity at constant pressure Cp (T) , J/(kg °C)**	**Source**
X5CrNi18-10 (304)	All	$450 + 0.280 \cdot T - 2.91 \cdot 10^{-4} \cdot\ T^2 + 1.34 \cdot 10^{-7} \cdot T^3$	[19]
	All	Constant, 470	[27]
	(-100) to 37	$270.215 - 1.210511 \cdot T + 0.02151566 \cdot T^2$ $-7.511841 \cdot 10^{-5} \cdot T^3 + 8.136796 \cdot 10^{-8} \cdot T^4$	[22]
	37 to 1038	$109.2073 + 2.571775 \cdot T - 0.006528099 \cdot T^2$ $+7.787524 \cdot 10^{-6} \cdot T^3 - 4.167913 \cdot 10^{-9} \cdot T^4 + 8.090613 \cdot 10^{-13} \cdot T^5$	
	1038 to (1400)	Constant, 630	
	All	Constant, 470	[29]
X2CrNiMoN22-5-3 (2205)	All	Constant, 480	[27]
	(-100) to 20	Constant, 482	[22]
	20 to 400	$429.285931 + 0.130317584 \cdot T + 1.56721552 \cdot 10^{-4} \cdot T^2$	
	400 to (1400)	Constant, 587	
	100	Constant, 530	[29]
NiCr22Mo9Nb (Inconel 625)	All	Constant, 440	[27]
	(-100) to 20	Constant, 410	[22]
	20 to 700	$337.05099 + 0.247120722 \cdot T$	
	700 to (1400)	Constant, 580	
	All	Constant, 410	[29]
NiCu30Fe (Monel 400)	All	Constant, 439	[27]
	(-100) to 315	$-100.987409 + 4.83633162 \cdot T - 0.0170401517 \cdot T^2$ $+2.74397264 \cdot 10^{-5} \cdot T^3 - 1.63381644 \cdot 10^{-8} \cdot T^4$	[22]
	315 to (1400)	Constant, 477	
	All	Constant, 427	[29]
Titan 99.8 (Titan Grade 1)	All	Constant, 540	[27]
	(-100) to 27	$-167.746811 + 7.08658306 \cdot T - 0.0297849253 \cdot T^2$ $+6.04477124 \cdot 10^{-5} \cdot T^3 - 4.76258862 \cdot 10^{-8} \cdot T^4$	[22]
	27 to 627	$464.052042 + 0.152465588 \cdot T + 2.12593015 \cdot 10^{-4} \cdot T^2$ $-1.72017085 \cdot 10^{-7} \cdot T^3$	
	627 to 883	$-33066.629 + 136.77383 \cdot T - 0.204810858 \cdot T^2$ $+1.335041 \cdot 10^{-4} \cdot T^3 - 3.17182178 \cdot 10^{-8} \cdot T^4$	
	883 to (1400)	$352.825758 + 0.123047884 \cdot T + 6.65722934 \cdot 10^{-5} \cdot T^2$	
	200	Constant, 560	[29]
TiAl6V4 (Titan Grade 5)	All	Constant, 523	[27]
	(-100) to 30	$-167.173226 + 6.75429814 \cdot T - 0.0235237743 \cdot T^2$ $+2.95625708 \cdot 10^{-5} \cdot T^3$	[22]
	30 to (1400)	$383.351385 + 0.670881806 \cdot T - 5.35234016 \cdot 10^{-4} \cdot T^2$ $+1.63517247 \cdot 10^{-7} \cdot T^3$	

TABLE 3 Constants and Empirical formulas of thermal conductivity

Material	**Temperature range, °C**	**Thermal conductivity k (T) , W/(m °C)**	**Source**
S 355 J2, S 690 QL	(-100) to 20	Constant, 53.35	[19]
	20 to 800	$54 - 0.0333 \cdot T$	
	800 to (1400)	Constant, 27.3	
	All	Constant, 51	[27]
	(-100) to 20	Constant, 53	[22]
	20 to 800	$56.38699 - 0.00728786 \cdot T - 1.988814 \cdot 10^{-5} \cdot T^2$	
	800 to 1200	$-82.99624 + 0.1669461 \cdot T - 6.125136 \cdot 10^{-5} \cdot T^2$	
	1200 to (1400)	Constant, 30	
	All	Constant, 52	[29]
X5CrNi18-10 (304)	(-100) to 0	Constant, 14.6	[19]
	0 to 1200	$14.6 + 0.0127 \cdot T$	
	1200 to (1400)	Constant, 30	
	All	Constant, 16	[27]
	(-100) to 20	$-1.031521 + 0.1813807 \cdot T - 1.088656 \cdot 10^{-3} \cdot T^2$ $+3.411681 \cdot 10^{-6} \cdot T^3 - 3.988389 \cdot 10^{-9} \cdot T^4$	[22]
	20 to (1400)	$6.742253 + 0.02864915 \cdot T$	
	100	16.2	[29]
	500	21.5	
X2CrNiMoN22-5-3 (2205)	(-100) to 0	Constant, 14.6	[19]
	0 to 1200	$14.6 + 0.0127 \cdot T$	
	1200 to (1400)	Constant, 30	
	All	Constant, 27	[27]
	(-100) to 20	Constant, 14.24	[22]
	20 to 400	$7.134798 + 0.02746063 \cdot T - 1.233173 \cdot 10^{-5} \cdot T^2$	
	400 to (1400)	Constant, 20	
	100	16	[29]
	300	18	
	400	20	
NiCr22Mo9Nb (Inconel 625)	All	Constant, 10	[27]
	(-100) to 982	$5.482405 + 0.01380594 \cdot T + 1.678069 \cdot 10^{-6} \cdot T^2$	[22]
	982 to (1400)	Constant, 25.5	
	All	Constant, 9.9	[29]
NiCr22Mo9Nb (Inconel 625)	All	Constant, 23	[27]
	(-100) to 982	$14.14109 + 0.02732033 \cdot T + 2.257259 \cdot 10^{-6} \cdot T^2$	[22]
	982 to (1400)	Constant, 52	
	All	Constant, 21.8	[29]

TABLE 3 (CONT.) CONSTANTS AND EMPIRICAL FORMULAS OF THERMAL CONDUCTIVITY

Material	**Temperature range, °C**	**Thermal conductivity k (T) , W/(m °C)**	**Source**
Titan 99.8 (Titan Grade 1)	All	Constant, 20	[27]
	(-100) to 53	$58.17412 - 0.4851624 \cdot T + 0.00288092 \cdot T^2$ $-8.255595 \cdot 10^{-6} \cdot T^3 + 8.903946 \cdot 10^{-9} \cdot T^4$	[22]
	53 to 704	$41.95804 - 0.1227486 \cdot T + 2.33331 \cdot 10^{-4} \cdot T^2$ $-1.937431 \cdot 10^{-7} \cdot T^3 + 6.191111 \cdot 10^{-9} \cdot T^4$	
	704 to (1400)	$15.13513 + 0.004158454 \cdot T + 1.376649 \cdot 10^{-6} \cdot T^2$	
	All	Constant, 26	[29]
TiAl6V4 (Titan Grade 5)	All	Constant, 7.11	[27]
	(-100) to 38	$0.1560505 + 0.07648919 \cdot T - 2.883179 \cdot 10^{-4} \cdot T^2$ $+3.68138 \cdot 10^{-7} \cdot T^3$	[22]
	38 to 538	$8.114005 - 0.01485211 \cdot T + 4.468662 \cdot 10^{-5} \cdot T^2$ $-2.273481 \cdot 10^{-8} \cdot T^3$	
	538 to (1400)	Constant, 13.32	

B. Graphical presentation of the physical properties of the materials

The presentation of the physical properties values allow for the visual perception of the range of deviations in the material properties data, as well as for visualization of the values development with temperature changes, as well as transition points and extremes.

In all graphics, the data sourced were represented in the following styles:

————————	[22]
—·—·—·—·—	[19]
—··—··—··—	[27]
— — — — —	[29]

- S 355J2 structural steel, acc. to EN 10025-2.

Similar to: 1.0577, ASTM A572 gr.50, GB Q355D

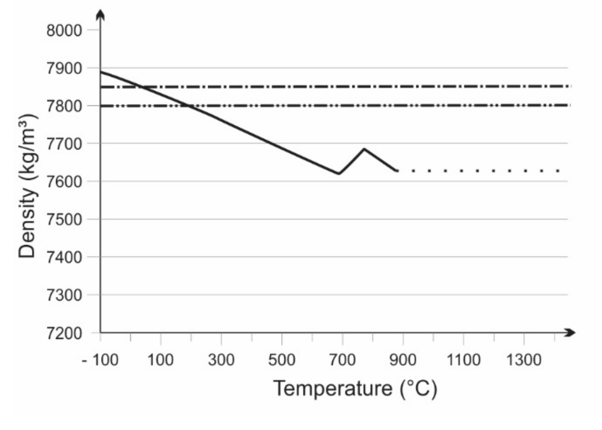

Fig. 1a Density of S 355 J2 structural steel.

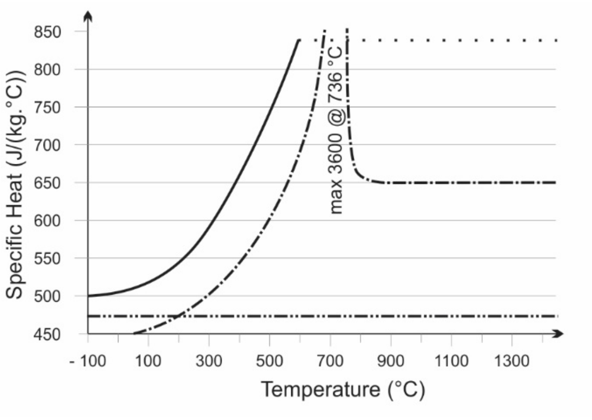

Fig. 1b Specific heat capacity of S 355 J2 steel.

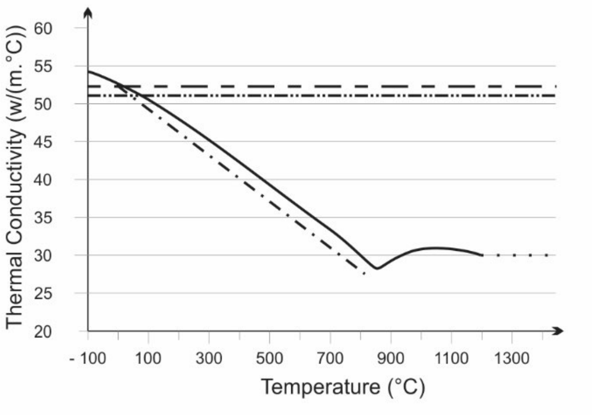

Fig. 1c Thermal conductivity of S 355 J2 steel.

- S 690 QL structural steel, acc. to EN 10025-6

Similar to: 1.8928, TStE 690 V, GB Q690E

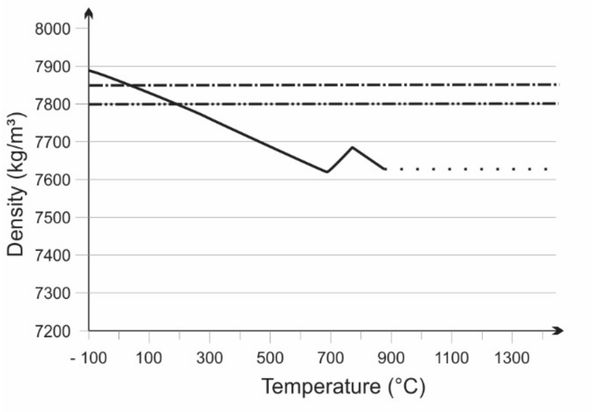

Fig. 2a Density of S 690 QL structural steel.

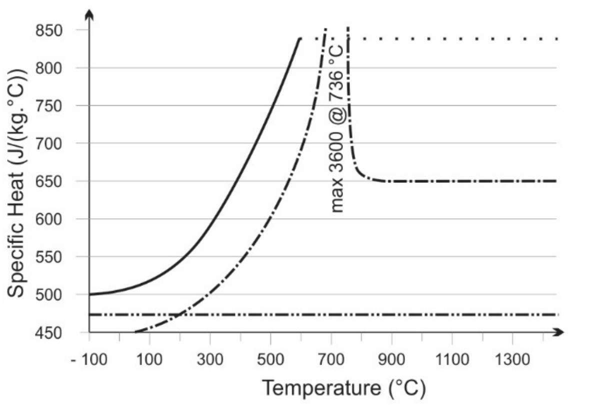

Fig. 2b Specific heat capacity of S 690 QL steel.

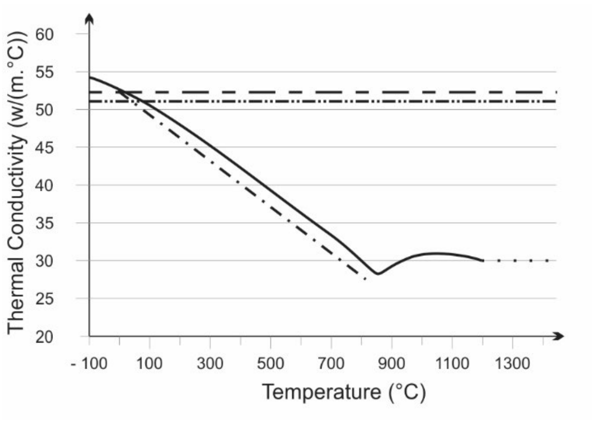

Fig. 2c Thermal conductivity of S 690 QL steel.

- X5CrNi18-10 stainless steel acc. to EN 10088-2

Similar to: 1.4301, ASTM 304

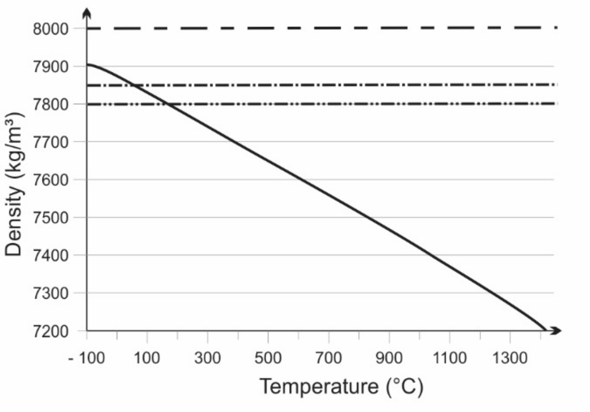

Fig. 3a Density of X5CrNi18-10 stainless steel.

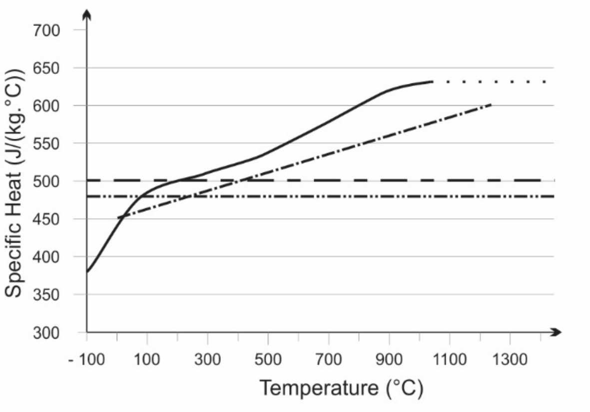

Fig. 3b Specific heat capacity of X5CrNi18-10 steel.

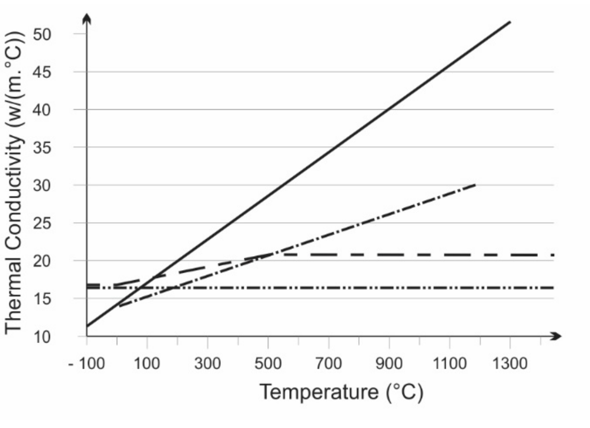

Fig. 3c Thermal conductivity of X5CrNi18-10 steel.

- X2CrNiMoN22-5-3 duplex stainless steel acc. to EN 10088-2

Similar to: 1.4462, ASTM 2205

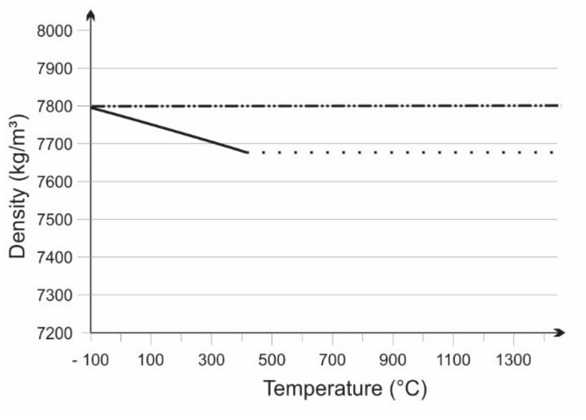

Fig. 4a Density of X2CrNiMoN22-5-3 duplex steel.

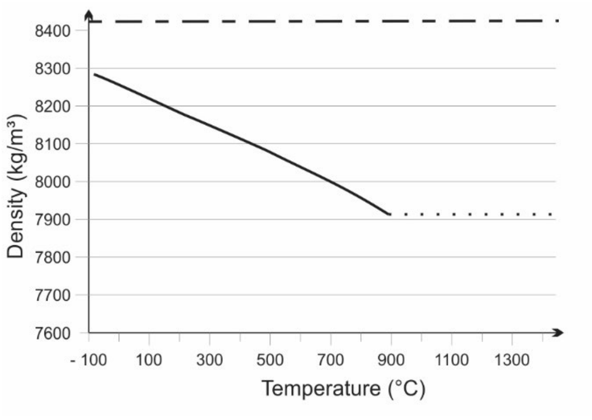

Fig. 5a Density of NiCr22Mo9Nb nickel alloy.

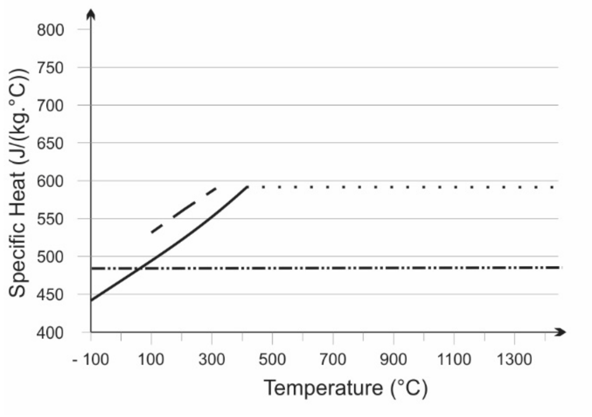

Fig. 4b Specific heat capacity of X2CrNiMoN22-5-3.

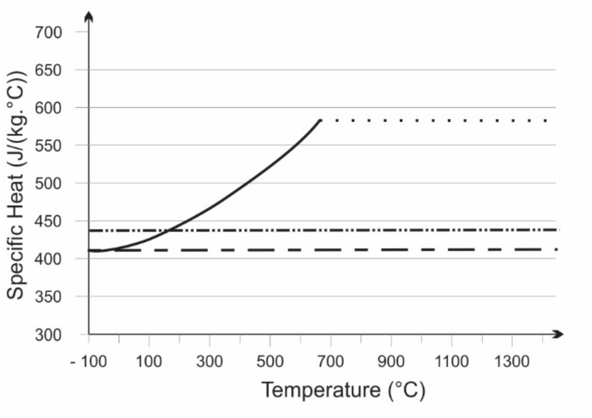

Fig. 5b Specific heat capacity of NiCr22Mo9Nb.

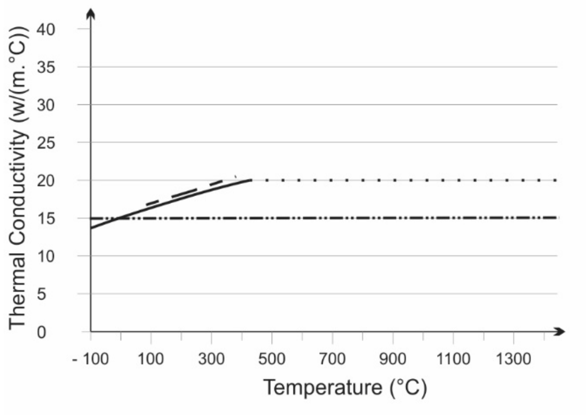

Fig. 4c Thermal conductivity of X2CrNiMoN22-5-3.

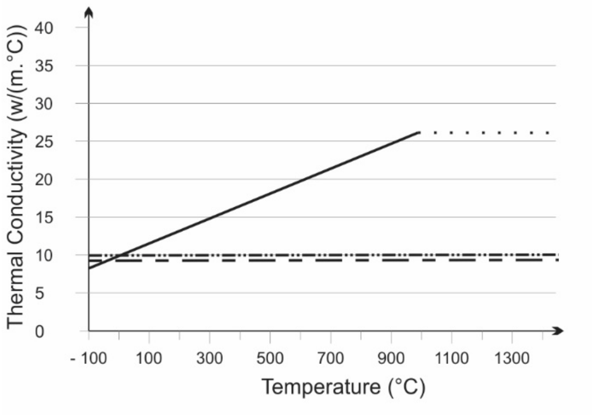

Fig. 5c Thermal conductivity of NiCr22Mo9Nb.

- NiCr22Mo9Nb nickel alloy acc. to EN 10095

Similar to: 2.4856, Inconel 625

- NiCu30Fe acc. to DIN 17443

Similar to: 2.4360, Monel 400

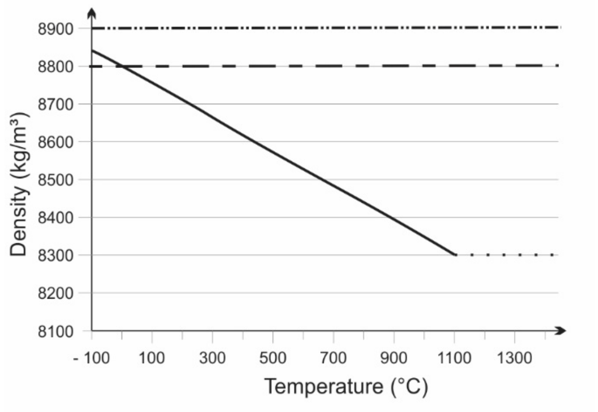

Fig. 6a Density of NiCu30Fe nickel alloy.

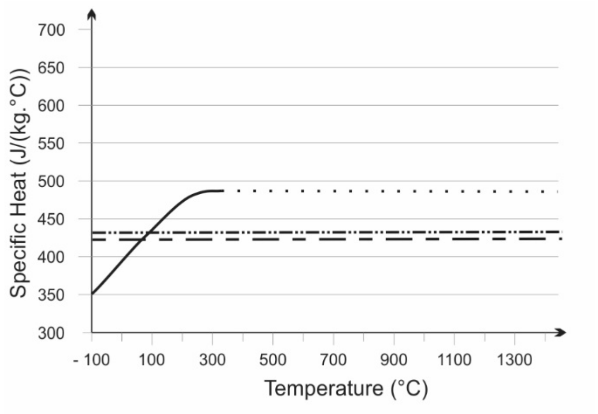

Fig. 6b Specific heat capacity of NiCu30Fe.

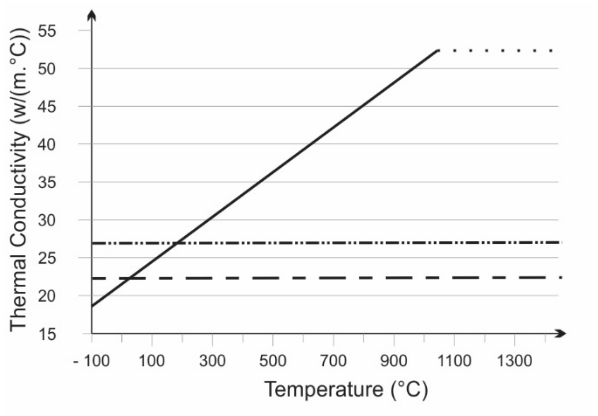

Fig. 6c Thermal conductivity of NiCu30Fe.

- Titan Grade 1, Ti 99.8

Similar to: 3.7025, ASTM B-265

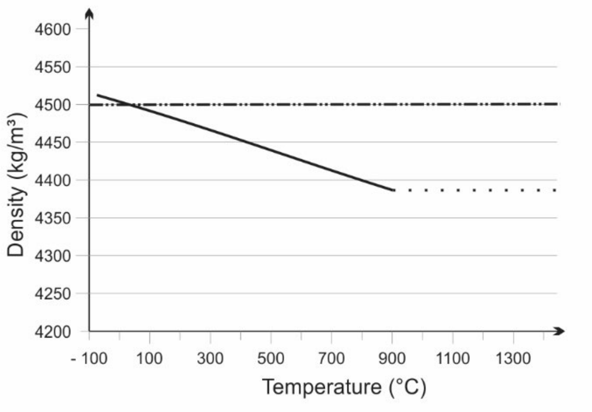

Fig. 7a Density of Ti 99.8 (Titan Grade 1).

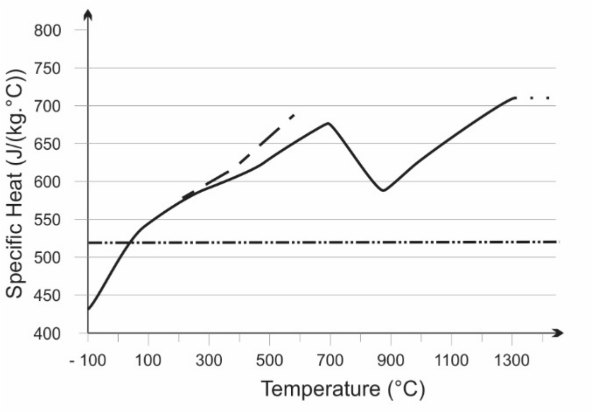

Fig. 7b Specific heat capacity of Ti 99.8.

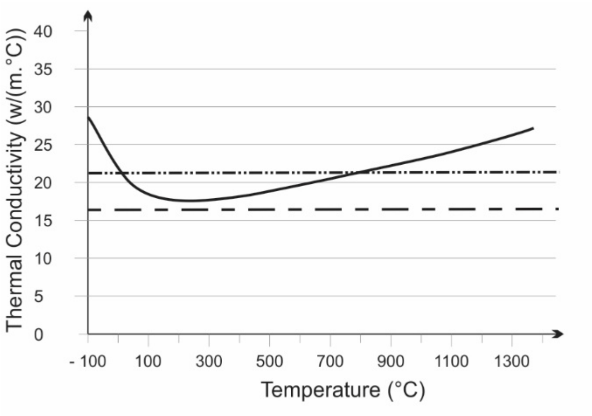

Fig. 7c Thermal conductivity of Ti 99.8.

- Titan Grade 5, TiAl6V4

Similar to: 3.7165

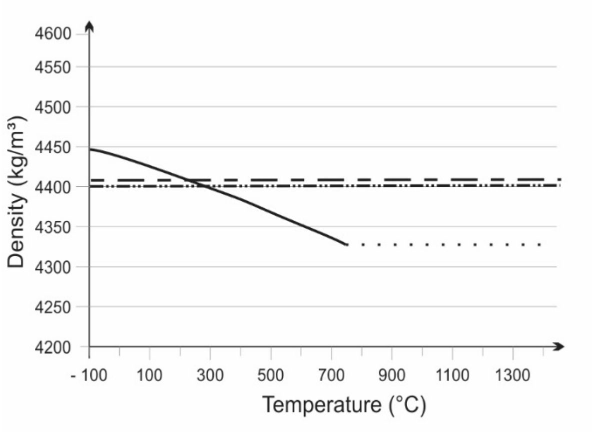

Fig. 8a Density of TiAl6V4, (Titan Grade 5).

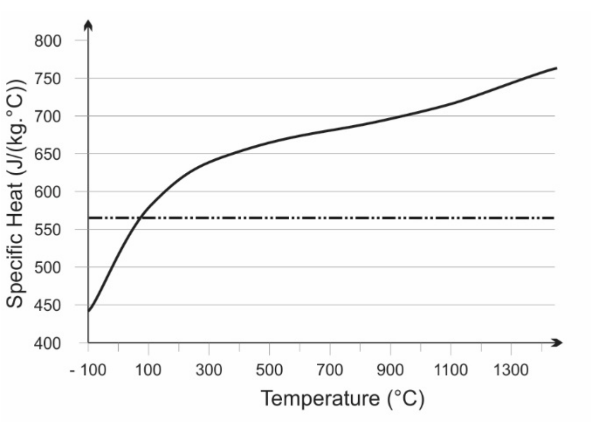

Fig. 8b Specific heat capacity of TiAl6V4.

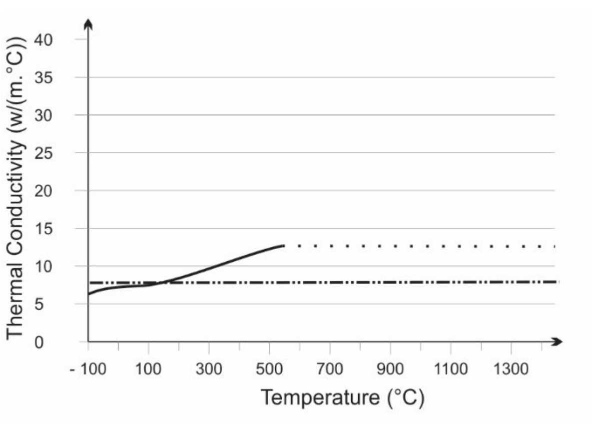

Fig. 8c Thermal conductivity of Ti 99.8.

IV. CONCLUSIONS

For the most common material types there are multiple sources of available data, obtained through experiments, by calculations according to empirical formulas or by estimations based on chemical and structural similarity. The application of the particular source of material properties data in model building should consider the purpose and the application of the simulation results.

Estimation could be appropriate source of data for purpose of investigating trends and general influences.

In cases when high level of reliability or accuracy of the model results is required, input information from verified sources should be used and experimental confirmation should be considered, for the particular material type, grade, origin, manufacturing lot, and in conditions equivalent to the actual application conditions.

It should be noted, that for some types of steels there are significant differences of the material properties data, e.g. in the specific heat capacity of the structural carbon steels. The calculations according to Eurocode 3 [19] show extreme value of 3600 J/(kg °C) at 735 °C, compared to values between 400 J/(kg °C) and 800 J/(kg °C), from [22], [27] and [19]. The reason of the deviation is that in the Eurocode 3 the influence of the phase transformation energy effects were considered in a more focused way.

As visible on Fig 1 (a, b, c) and Fig 2 (a, b, c), he Eurocode do not differentiate the properties of the different grades of structural steels. The assessment of the thermal properties of structural steels described in [35] and [36] showed differences in the material properties, calculated according to Eurocode 3 [19] and the data obtained by experiments, for different grades of structural steels.

In critical applications, the use of the input data, provided by the regulations is compulsory. More than one model results, relevant to building structures, should be obtained and evaluated: according to the standard, according to data sources considered as reliable and according to test data.

ACKNOWLEDGMENTS

The authors are grateful to the financial support of the Bulgarian National Science Fund, Contract No KP-06-H57/10, for carrying out the necessary research.

REFERENCES

[1] International Organization for Standardization Technical Committee 176, Quality management systems — Fundamentals and vocabulary, ISO 9000, 2015.

[2] International Organization for Standardization Technical Committee 44, Quality requirements for fusion welding of metallic materials — Part 2: Comprehensive quality requirements, ISO 3834-2, 2021.

[3] European Committee for Standardization Technical Committee 121, EN 1011-1, Welding. Recommendations for welding of metallic materials. General guidance for arc welding, 2009.

[4] European Committee for Standardization Technical Committee 121, EN 1011-2, Welding. Recommendations for welding of metallic materials. Arc welding of ferritic steels, 2001.

[5] Swedish Steel AB, 299 Welding of Strenx. Advanced High Strength Steels. V1, 2015, p 7.

[6] Stahlinstitut VDEh, Stahl-Eisen-Werkstoffblatt 088 Beiblatt 2: Schweißgeeignete Feinkornbaustähle - Richtlinien für die Verarbeitung, besonders für das Schmelzschweißen; Ermittlung

der Abkühlzeit t8/5 zur Kennzeichnung von Schweißtemperaturzyklen.

[7] International Organization for Standardization Technical Committee 44, Numerical welding simulation — Execution and documentation, ISO/TS 18166, 216.

[8] S. Afkhami, V. Javaheri, M.Amraei, T. Skriko, H.Piili, X.L.Zhao, T.Björk, Thermomechanical simulation of the heat-affected zones in welded ultra-high strength steels: Microstructure and mechanical properties, Materials & Design 213, 2022, https://doi.org/10.1016/j.matdes.2021.110336

[9] P. H. G. Dornelas, F.W.C. Farias, V.H.P.M. Oliveira, D.O. Moraes, P. Z. Júnior and J. P. Filho, FEM-thermodynamic simulation methodology to predict the influence of t 8/5 on the coarse grain heat-affected zone of a Cr-Mo low-alloy steel pipe 60, Journal of Manufacturing Processes, 2020, pp 520–529, https://doi.org/10.1016/j.jmapro.2020.10.082

[10] P. H. G. Dornelas, J. C. P. Filho, V. H. P. M. Oliveira, D. O. Moraes and P. Z. Junior, Studying the influence of the interpass temperature on the heat-affected zone of an API 5L X65 steel welded pipe joint through computational and physical simulations, International Journal of Pressure Vessels and Piping 194, 2021, https://doi.org/10.1016/j.ijpvp.2021.104548

[11] D. Rosenthal, Mathematical theory of heat distribution during welding and cutting, Welding Journal 20, 1941, pp 220–234.

[12] D. Radaj, Heat effects of welding: temperature field, residual stress, distortion, Springer, 1992.

[13] J. Goldak, M. Bibby, J. Moore, R. House, B. Patel, Computer modeling of heat flow in welds, Metall Trans B 17 (3), 1986, pp 587–600, https://doi.org/10.1007/BF02670226

[14] A. Lecoanet and D. G. Ivey and H. Henein, Simulation of the Temperature Profile During Welding with COMSOL Multiphysics® Software Using Rosenthal's Approach, [Online]. Available: https://www.comsol.com/paper/simulation-of-the-temperature-profile-during-welding-with-comsol-multiphysics-so-19689 [Accessed: Mar. 19, 2023].

[15] E. Nart and Y. Celik, A practical approach for simulating submerged arc welding process using FE method, Journal of Constructional Steel Research 84, 2013.

[16] M. Tongov, Heat Source for TIG welding modelling, Environment Technology Resources Proceedings of the International Scientific and Practical Conference 3:348-356, https://doi.org/10.17770/etr2021vol3.6601

[17] Elsevier B.V., Thermal Conductivity Coefficient, [Online].Available: https://www.sciencedirect.com/topics/engineering/thermal-conductivity-coefficient

[18] Y. Xing, W. Wang and H. Al Azzani, Assessment of thermal properties of various types of high-strength steels at elevated temperatures, Fire Safety Journal 122, 2021, https://doi.org/10.1016/j.firesaf.2021.103348

[19] European Committee for Standardization, EN 1993-1-2: Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design, 2005, pp 23-26.

[20] American Society of Civil Engineers, ASCE 1992: Structural fire protection, ASCE committee on fire protection manual 78, 1992.

[21] ESI Group, SYSWELD - User guide 2020.5,[Online] Available: https://myesi.esi-group.com/downloads/software-documentation/sysweld-2020.5-user-guide-visual-weld-16.0-users-guide-online

[22] COMSOL AB, Heat transfer module user's guide, Internal material properties library, 2018. [Online].Available: https://doc.comsol.com/5.4/doc/com.comsol.help.heat/HeatTransferModuleUsersGuide.pdf [Accessed: Mar. 19, 2023].

[23] National Institute of Advanced Industrial Science and Technology AIST Japan, Thermophysical properties database system, [Online].Available: https://tpds.db.aist.go.jp/tpds-web/index.aspx [Accessed Mar. 20, 2023].

[24] National Technical University KhPI, European steel and alloy grades, [Online].Available: http://www.steelnumber.com/en/steel_composition_eu.php, [Accessed Mar. 20, 2023].

[25] National Center for Forensic Science of University of Central Florida, Material Thermal Properties Database, [Online].Available: https://ncfs.ucf.edu/burn_db/Thermal_Properties/material_thermal.html, [Accessed Mar. 20, 2023].

[26] Slovenian Steel GroupSIJ Metal Ravne, Alphabetical Steel Index, [Online].Available: https://steelselector.sij.si/html/steel_index.html, [Accessed Mar. 20, 2023].

[27] Iron Boar Labs Ltd, MakeItFrom.com database, [Online].Available: https://www.makeitfrom.com/, [Accessed Mar. 20, 2023].

[28] World Material, www.theworldmaterial.com, [Online].Available: https://www.theworldmaterial.com/, [Accessed Mar. 20, 2023].

[29] MatWeb, LLC, Material Property Data, [Online].Available: https://www.matweb.com/search/CompositionSearch.aspx [Accessed Mar. 20, 2023].

[30] Steel Grades, Physical Properties of steel grade 1.4301 [Online].Available: 1.4301 Chemical composition, 1.4301 Properties, 1.4301 Datasheet, France AFNOR 1.4301 (steel-grades.com) [Accessed Mar. 20, 2023].