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THERMOPHYSICAL PROPERTIES OF THE SOŁTMANY METEORITE

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Abstract: Bulk density, porosity and thermophysical properties of the Sołtmany meteorite have been determined. The mean bulk density of the meteorite is $3.475 \cdot 10^3$ kg/m^3, mean bulk density of the crust is $4.3 \cdot 10^3$ kg/m^3, grain density $3.71 \cdot 10^3$ kg/m^3, and porosity 6.4 ± 0.4%. Mean specific heat capacity determined by DSC in temperature range between 223 and 823 K increases from 595 to 1046 J/(kg·K), and is equal to 728 J/(kg·K) at room temperature. Specific heat capacity of various samples is in the range 705–769 J/(kg·K) at room temperature. Thermal capacity of Sołtmany chondrite is equal to $2.53 \cdot 10^6$ J/(m^3·K), thermal diffusivity $(1.5–1.8) \cdot 10^{-6}$ m^2/s, and thermal conductivity 3.9–4.5 W·m^{-1}·K^{-1} at room temperature. Differential scanning calorimetry revealed two reversible phase transitions in the Sołtmany's troilite: α/β transition at 423 K, and β/γ transition at 596.6 K.

Keywords: chondrite, differential scanning calorimetry (DSC), specific heat capacity, thermal capacity, thermal diffusivity, thermal conductivity

INTRODUCTION

Thermophysical properties are important physical properties of terrestrial and extraterrestrial matter. Unfortunately, little effort has been spent in recent years to determine the thermal properties of meteorites, terrestrial planets, asteroids and moons (Beech et al., 2009; Opeil et al., 2010, 2012; Szurgot, 2003, 2011a,b, 2012a,b,c,d; Szurgot et al., 2008; Szurgot & Wojtatowicz, 2011; Szurgot & Polański, 2011), and only a few important materials have been studied and published in XX-th century (Matsui & Osako, 1979; Osako, 1981; Yomogida & Matsui, 1981, 1983; Gosh & McSween, 1999). Measurements and analysis of various physical properties are necessary for characterisation of new extraterrestrial objects, supplied by meteorite falls, which represent matter unprocessed by terrestrial environment. These data can be used for understanding, modelling and interpreting the origin and evolution of a meteorite's parent body (planetesimals, asteroids, and terrestrial planets) in the Solar System. Our recent data on specific heat capacity, and heat capacity of the terrestrial planets: Mars, Earth, Mercury, and Venus, selected asteroids including Vesta, Ceres, and Eros, and Earth's Moon, as well as other natural satellites (Szurgot, 2012a,b,c,d, 2013) can be used to describe the thermal characteristics of Solar System objects. Modelling thermal evolution of asteroids and planets requires precise experimental data on various thermophysical properties of meteorites (Gosh & McSween, 1999; Chaumard et al., 2012).

Specific heat capacity, heat capacity, thermal capacity, and thermal diffusivity are important quantities used to investigate meteorites, and other Solar System objects. Specific heat capacity, *Cp* (J/(kg·K)), represents the heat energy required to change the temperature of a unit mass of a substance by one unit of temperature at a constant pressure ($Cp = M^{-1} \cdot dQ/dT$).

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Heat capacity, C (J/K), represents the energy required to change the temperature of the whole mass of an object (e.g. asteroid, planet, or comet) by one unit of temperature ($C = dQ/dT = C_p \cdot M$). Thermal capacity, $C_{volumetric}$ (J/(m^3·K)), represents the energy required to change the temperature of the unit volume of a substance ($C_{volumetric} = V^{-1} \cdot dQ/dT = C_p \cdot \rho_b$, where ρ_b (kg/m^3) is bulk density of substance, e.g. density of extraterrestrial rock).

Three other thermophysical properties play important roles in modelling the thermal evolution of asteroids: thermal conductivity K (W·m^{-1}·K^{-1}), thermal diffusivity D (m^2/s), and thermal inertia Γ (J·m^{-2}·s$^{-1/2}$·K^{-1}). Thermal conductivity represents the ability of a substance to transport of heat, and governs the flow of heat through a material at steady-state. Thermal diffusivity is the property governing transient heat flow, when temperature varies with time. D can be measured directly by measuring the time it takes for a temperature pulse to traverse a specimen of known thickness when a heat source is applied briefly to the one side; or can be determined indirectly using the relation between D and K; $D = K/C_{volumetric} = K/(C_p \cdot \rho_b)$, i.e. by calculating the ratio of thermal conductivity and thermal capacity (Ashby et al., 2007). Thermal inertia quantifies the ability of material to store and retain daytime heat, and is calculated as the square root of product of thermal conductivity and thermal capacity $\Gamma = (K \cdot C_p \cdot \rho_b)^{1/2} = (K \cdot C_{volumetric})^{½}$.

Our early interest in studying thermophysical properties of meteorites began with the measurements and data collection of specific heat capacity, thermal diffusivity, and bulk density of various meteorites (Szurgot, 2003; Szurgot et al., 2008). These activities are still an important part of our work. We continue measuring, collecting and analyzing data, especially those concerning physical properties of new meteorites. In the last few years we have been looking for interrelations between various physical properties of meteorites, various tendencies and dependencies. Establishing relationships between specific heat capacity and bulk density of meteorites, and between thermal capacity and bulk density of meteorites at room temperature was the first finding (Szurgot, 2011). Measurements of diffusivity of twenty meteorites by laser flash method revealed linear relationship between thermal diffusivity and bulk density of meteorites at room temperature (Szurgot & Wojtatowicz, 2011), and analysis of data by Osako (Osako, 1981) has shown that the linear relationship exists not only at RT but also at low temperatures: 100 K, and 200 K (Szurgot & Wojtatowicz, 2011). An analysis of our experimental data (Szurgot, 2011b), and of the literature data (Opeil et al, 2010) revealed a relationship between thermal conductivity and density of meteorites at room temperature, and at low temperatures (Szurgot, 2011b). The above mentioned relationships have been applied for predicting and estimating the thermophysical properties of meteorites (Szurgot & Polański, 2011), terrestrial planets, asteroids, as well as natural satellites (Szurgot, 2012a,b,c,d, 2013). Opeil and co-workers discovered the relationship between thermal conductivity of stony meteorites and their porosity (Opeil et al., 2012), thus enabling one to predict thermal conductivity of a meteorite when its porosity is known. We will apply the relation in this paper.

Differential scanning calorimetry (DSC) is a useful technique for measuring the specific heat capacity of extraterrestrial matter, temperature of phase transformations, and enthalpy changes in terrestrial and meteoritic minerals. Our preliminary DSC measurements indicate that troilite thermometry can be the promising tool for meteoritic investigations, especially for chondrite investigations. We are convinced on significant possibilities of troilite thermometry.

The Sołtmany meteorite was classified as an equilibrated ordinary chondrite L6 class (shock stage S2, weathering grade W0) (Karwowski et al., 2011). Preliminary compositional data are as follows: olivine $Fa_{25.6}$, low-Ca pyroxene $Fs_{21.9}Wo_{1.5}$, high-Ca pyroxene $En_{46.6}Fs_{8.8}Wo_{44.6}$, feldspar $Ab_{85}Or_5An_{10}$, kamacite (Fe 95.87, Ni 5.23, Co 0.74 wt.%); troilite (Fe 50.23, S 49.69 at.%) (Karwowski et al., 2011). The meteorite also contains accessory minerals: chromite, Fe-Cl apatite, and metallic Cu in taenite (Karwowski et al., 2011). The aim of this paper was to determine various thermophysical properties of the Sołtmany chondrite such as specific heat capacity, thermal capacity, thermal conductivity, thermal diffusivity, the bulk density and porosity of the meteorite, and to reveal and analyse phase transitions in Sołtmany troilite. Presented data on the above mentioned physical properties are especially meaningful as the meteorite was sampled just one week after its observed fall (30th April, 2011), so the mineral composition and texture of the meteorite were not influenced by terrestrial processes.

EXPERIMENTAL

The Sołtmany samples were bought by members of The Polish Meteorite Society from Mrs. Alfreda Lewandowska, the meteorite's finder. The meteorite samples were prepared as polished slices with weights ranging from 0.5 g to 3 g, or as small pieces of irregular shape weighing about 20 mg each.

The bulk density ρ_b of the samples was determined by the Archimedean method from the relation:

$$\rho_b = [W_{air} / (W_{air} - W_{propanol})] \cdot \rho_{propanol}, \quad (1)$$

where W_{air} is the weight of the sample in air, $W_{propanol}$ is the weight of the suspended sample on the sling in isopropanol, and $\rho_{propanol}$ is the density of isopropanol. The estimated relative error in the measurement of ρ_b of Sołtmany meteorite interior samples is about 2–3%, and of the crust about 5%.

The grain density ρ_g was determined using the expression:

$$\rho_g = \rho_b/(1 - P), \quad (2)$$

where ρ_b is the bulk density, and P is porosity. The porosity P of the meteorite, a measure of the connected void space within its interior is defined as P (%) = $(1 - \rho_b/\rho_g)\times 100$ (Consolmagno et al., 2008; Beach et al., 2009).

The porosity P of the Sołtmany samples was determined by measuring the mass of the dry meteorite, and mass of the wet meteorite, i.e. the meteorite saturated with isopropanol. The porosity P (%) was determined using the relation:

$$P(\%) = V_p/V_m = (m_p/m_m)\cdot(\rho_b/\rho_{propanol}), \quad (3)$$

where V_p is the volume of propanol present in the meteorite's voids and cracks, V_m is the volume of the meteorite sample, m_p is the mass of the propanol inside the meteorite, m_m is the mass of the dry meteorite, ρ_b is the bulk density of the meteorite, and $\rho_{propanol}$ is the density of isopropanol at room temperature ($\rho_{propanol}$ = 785 kg/m^3). The measurement accuracy using this technique is estimated to be about 7%.

The porosity measurements were conducted at ambient temperature between 20 and 30 °C, usually at 25 °C, at humidity between 50 and 70%. To measure the weights, first the dry meteorite was measured, then the meteorite was saturated with propanol. The sample was dipped in propanol for about 2–5 min. ensuring enough time had elapsed to saturate the spaces. Measurements were conducted on the initially dry meteorite which was subsequently suspended in propanol and measured at intervals. The weight gradually increased with time due to the propanol filling all cracks and pores until the weight stabilized and the specimen was assumed to be saturated. Measuring the weights with high precision is required to determine the porosity. Since drying of the sample by blowing warm air leads to reversible data for m_m in subsequent measurements, we believe that all of the propanol left interior of the meteorite. However, since some enclosed spaces in the meteorite may still contain propanol, the porosity measurements are more estimates than a precise determination. We likely estimate the lower limit of the porosity, and verification of these results seems to be desirable.

The specific heat capacity Cp of the small (c.a. 20 mg) samples and temperature of phase transitions were determined by a differential scanning calorimeter Q200 produced by TA Instruments (USA). The instrument was calibrated for both temperature and heat flow using indium (melting temperature 156.6 °C) and synthetic sapphire standard respectively with well characterized Cp in the broad range of temperatures. In DSC measurements of Cp of the Sołtmany's samples the following expression was used:

$$C_p = Cp_{sp}\cdot(H/Hsp)\cdot(m_{sp}/m_m), \quad (4)$$

where Cp_{sp} is a specific heat capacity of sapphire standard at particular temperature, m_{sp} is the mass of sapphire standard, m_m is the mass of meteorite sample, Hsp is the heat flow (mW) of the sapphire standard, and H is the heat flow of the meteorite specimen. Samples, with approximately the same mass as the sapphire were sealed in aluminum pans and analyzed in the temperature range between –70 and 560 °C at the heating rate of 20 °C/min under nitrogen flow of 50 ml/min. Specific heat capacity of larger samples was determined using double-walled calorimeters. The relative error in the measurement of C_p of Sołtmany meteorite is 3–4% for DSC, and 5–6% for the double-walled calorimeters. Calibration of the double-walled calorimeter were conducted during our earlier measurements of specific heat capacity of the Morasko iron meteorites (Szurgot et al., 2008) during which selected materials with well-known capacities were measured.

Volumetric heat capacity, (thermal capacity, heat capacity per unit volume), $C_{volumetric}$ (J/(m^3·K) was determined using the relation:

$$C_{volumetric} = C_p \cdot \rho_b, \quad (5)$$

where Cp (J/(kg·K)) is the specific heat capacity, and ρ_b (kg/m^3) is the bulk density of meteorite.

The relationship between thermal conductivity K and bulk density ρ_b of meteorites (Szurgot, 2011b), and between thermal conductivity and porosity (Opeil et al., 2012) have been applied for estimation of thermal conductivity (eqs. (6) and (8)), and relationship between thermal diffusivity D and bulk density of meteorites (eq. (9)) (Szurgot & Wojtatowicz, 2011) for determination of thermal diffusivity of the Sołtmany meteorite at room temperature.

According to the linear fit we have:

$$K = A \cdot \rho_b + B, \quad (6)$$

where K is thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$), ρ_b (kg/m^3) is the bulk density of meteorite, and coefficients A and B are constant for a given temperature: $A = (8.81 \pm 0.61) \cdot 10^{-3}$ $W \cdot m^2 \cdot kg^{-1}$, $B = -26.7 \pm 2.8$ $W \cdot m^{-1} \cdot K^{-1}$ at 298 K; $A = 3.92 \cdot 10^{-3}$ $W \cdot m^2 \cdot kg^{-1}$, $B = -8.50$ $W \cdot m^{-1} \cdot K^{-1}$ at 200 K (Szurgot, 2011b). Constants A and B at 200 K were established by Szurgot who used Opeil and co-workers' data (Opeil et al., 2010; Szurgot, 2011b).

According to Opeil and co-workers, the K of a stony meteorite depends on porosity P (Opeil et al., 2012) and can be expressed by the relation:

$$K = 3.6 + 6.8/P, \quad (7)$$

where K is thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) at 200 K, and P is the porosity P(%). Since K at 200 K for ordinary chondrites L class is usually about 4% higher than at 300 K (Opeil et al, 2012), we have K for Sołtmany's meteorites at room temperature:

$$K = 3.46 + 6.53/P. \quad (8)$$

Thermal diffusivity is a linear function of bulk density and may be expressed by the empirical equation:

$$D = E \cdot \rho_b + F, \quad (9)$$

where D is thermal diffusivity (10^{-6} m^2/s), ρ_b (kg/m^3) is the bulk density of meteorites, and coefficients E and F are constants for a given temperature: $E = 2.49 \cdot 10^{-9}$ $m^5 \cdot kg^{-1} \cdot s^{-1}$, $F = -7.11 \cdot 10^{-6}$ m^2/s at 298 K (Szurgot & Wojtatowicz, 2011), $E = 2.11 \cdot 10^{-9}$ $m^5 \cdot kg^{-1} \cdot s^{-1}$, $F = -6.24 \cdot 10^{-6}$ m^2/s at 200 K. Constant E and F at 200 K were established by Szurgot and Wojtatowicz who used experimental data by Osako (Osako, 1981; Szurgot & Wojtatowicz, 2011). Using a well-known relationship (Ashby et al., 2007):

$$K = C_p \cdot \rho_b \cdot D = C_{volumetric} \cdot D, \quad (10)$$

between K, and C_p, D, and ρ_b one can determine D by the relation:

$$D = K/C_{volumetric} \quad (11)$$

Uncertainty in DSC measurements of temperature of α/β solid-state transition in troilite is 0.1–0,2 K, and β/γ transition 1–2 K.

RESULTS AND DISCUSSION

Bulk density and porosity

In Table 1, data on bulk density and porosity of four samples of the Sołtmany meteorite have been compiled. Samples A and B represent material from the meteorite's interior, and samples C and D material from the interior and of the fusion crust. It is seen that the bulk density of samples with crust is about 3% higher than samples A and B which represent the interior of meteorite. Table 1 reveals that the mean bulk density of Sołtmany is equal to $3.475 \cdot 10^3$ kg/m^3 and the mean bulk density of the fusion crust equals $(4.31 \pm 0.21) \cdot 10^3$ kg/m^3. The density of the fusion crust was calculated using the ratio of volume of crust to the volume of interior. The calculation assumes that interior samples C and D have the same bulk density as the mean value of A and B samples. The data show that mean bulk density of the crust is about 24% higher than mean bulk density of the interior of meteorite.

Recent data on ordinary chondrites show that L chondrites have porosity in the range 4.4–10.4% (Opeil et al, 2012), but Yomogida and Matsui presented a wider range of 2.5–19.4% (Yomogida & Matsui, 1983). The average porosity of fresh falls is (5.6 ± 4.6)% for L chondrites, and (7.0 ± 4.9)% for H chondrites (Consolmagno et al., 2008). Table 1 shows that porosity of Sołtmany meteorite interior (samples A and B) is in the range 6.1–6.7%, and mean porosity is equal to (6.4 ± 0.4)%. Such values are within the range of L chondrites and H chondrites. On average L chondrites are slightly less porous than H chondrites, and Sołtmany's average porosity is slightly higher than average for L chondrites, and slightly lower than average for H chondrites. Samples C and D containing crust have higher porosity (range 7.4–7.8%, mean 7.6 ± 0.4%) than samples A and B representing the meteorite's interior, indicating that crust porosity is close to the average for H chondrites.

Knowing the mean value of bulk density and mean value of porosity enabled us to determine the grain density of the Sołtmany meteorite. The results show that average bulk density ($3.475 \cdot 10^3$ kg/m^3) and average grain density ($3.71 \cdot 10^3$ kg/m^3) of Sołtmany's interior are in the range of ordinary chondrites (Yomogida & Matsui, 1981, 1983; Consolmagno et al., 2008; Opeil et al., 2012). For L and H meteorite falls, the average bulk density is $3.37 \pm 0.18 \cdot 10^3$ $kg/m^3$and 3.42

Table 1. Bulk density and porosity of Sołtmany meteorite at room temperature (300 K). Values of bulk density and porosity represent the average of 3–5 measurements

Sample	Mass	Bulk Density *Interior*	Bulk Density *Interior & Crust*	Bulk Density *Crust*	Porosity
A	0.667 g	$3.48 \cdot 10^3$ kg/m^3			6.1%
B	2.930 g	$3.47 \cdot 10^3$ kg/m^3			6.7%
C	1.160 g		$3.57 \cdot 10^3$ kg/m^3	$4.16 \cdot 10^3$ kg/m^3	7.4%
D	0.467 g		$3.56 \cdot 10^3$ kg/m^3	$4.46 \cdot 10^3$ kg/m^3	7.8%
Range		$(3.47–3.48) \cdot 10^3$ kg/m^3	$(3.56–3.57 \cdot 10^3$ kg/m$^3)$	$(4.16-4.46) \cdot 10^3$ kg/m^3	(6.1–6.7) %
Mean		$3.475 \cdot 10^3$ kg/m^3	$3.565 \cdot 10^3$ kg/m^3	$4.31 \cdot 10^3$ kg/m^3	(6.4±0.5) %

$\pm\ 0.19 \cdot 10^3$ kg/m^3 respectively (Consolmagno et al., 2008). For L meteorites falls, the average grain density is $3.56 \pm 0.10 \cdot 10^3$ kg/m^3, for H meteorite falls is $3.72 \pm 0.12 \cdot 10^3$ kg/m^3 (Consolmagno et al., 2008). Since grain densities of freshly fallen ordinary chondrites are connected with the iron content, the Sołtmany meteorite fall indicates relatively high iron content.

Both the average bulk density and average grain density of Sołtmany chondrite are high. Sołtmany's average bulk density is higher than L chondrites, and higher than H chondrites, while Sołtmany's grain density is higher than L chondrites, and close to H chondrites. It is expected that for fresh falls, grain density alone can be used to distinguish between L and H types (Consolmagno et al., 2008). Our measurements conducted on Sołtmany samples, one year after the fall, indicate high iron content, but overlapping range of values of porosities. However, bulk and grain densities make it difficult to conclusively determine whether the Sołtmany meteorite is either an L or H-type chondrite. The test data seems to indicate that Sołtmany is closer to H chondrites than L chondrites. Values of average bulk density and average grain density of the Sołtmany L chondrite may be higher than expected values for L chondrites as the result of higher Ni content in metal grains (and in bulk chemical composition). The content of Ni in Sołtmany's bulk composition and specifically in its metal grains is typical for H rather than L chondrites (Karwowski, 2012; Przylibski & Łuszczek, 2012).

It is also noteworthy, that the fusion crust is characterized by higher density and simultaneously higher porosity compared to the interior of the meteorite. The reason of higher porosity is the observed presence of vesicles on the surface connected to the gas bubbles inside of the fusion crust. This texture was formed during ablation of the meteors it flew across the Earth's atmosphere and is the remnant of released volatile sulfur compounds formed as a result of sulfides (i.e. troilite) melting (Karwowski, 2012). On the other hand, the higher density of the fusion crust is a result of its mineral and chemical composition. Melts formed during ablation creating a glassy and crystalline fusion crust composed of heavy metals, like Fe, Ni, (Mg), and Cr (Karwowski, 2012). Sołtmany's fusion crust also reveals the presence of heavy minerals, like spinel and chromite. Smaller amounts of silicates (pyroxenes and olivines) and silicate glass (feldspar), in relation to interior of the meteorite (Karwowski, 2012), is the cause of higher density of its fusion crust.

Thermophysical properties of Sołtmany meteorite

Specific heat capacity

In Table 2, data on room temperature values of specific heat capacity *Cp* of three small samples of Sołtmany meteorite are presented. Values of *Cp* presented here where determined by DSC technique. It is seen that specific heat capacity of various samples is in the range 705–769 J/(kg·K), and the mean specific heat capacity is equal to 728 J/(kg·K) at room temperature. Measurements of *Cp* for larger samples by double-walled calorimeters gave values: sample A: *Cp* = 727 J/(kg·K), sample B: *Cp* = 641 J/(kg·K), sample C:

Table 2. Specific heat capacity *Cp* of Sołtmany meteorite small samples at room temperature (300 K)

Cp/Sample	E	F	G	Range	Mean ± SD
Specific heat capacity J/(kg·K)	705	711	769	705–769	728 ± 35

Cp = 707 J/(kg·K), sample D: Cp = 768 J/(kg·K), and the mean Cp = 711 ± 53 J/(kg·K). The mean value of Cp of the larger samples is somewhat smaller but comparable with the mean C_p of the smaller samples that were measured with better precision by DSC technique.

Szurgot established a relationship between specific heat capacity C_p and bulk density ρ_b of meteorites (Szurgot, 2011a). It can be used for estimation of specific heat capacities of meteorites at room temperatures. Figure 1 presents $C_p(\rho)$ relationship together with the mean value of C_p for Sołtmany meteorite (full square). It is seen that Sołtmany's specific heat capacity matches well the presented dependence.

$C_p(\rho)$ may be approximated by the relation (Szurgot, 2011a):

$$C_p = a + b/\rho_b, \tag{12}$$

where a, and b are constants (a = 306 J/(kg·K), and $b = 1.31 \cdot 10^6$ J/(K·m^3)).

Substituting $\rho_b = 3.475 \cdot 10^3$ kg/m^3 into eq. (12) gives C_p = 683 J/(kg·K) for the Sołtmany meteorite, which is close to the experimental values determined by DSC (728 J/(kg·K)), and double-wall calorimeter measurements (712 J/(kg·K)). The results show that this calculated value of C_p is about 6% lower than C_p value determined by DSC (full square experimental point in Fig. 1), and about 4% lower than the C_p value determined by double-wall calorimeter measurements.

Table 3 presents values of Cp of three samples: E, F and G at various temperatures, and Figure 2 shows the $C_p(T)$ dependence for these samples. It is seen that the mean specific heat capacity determined by DSC in the temperature range between 223 and 823 K increases from 595 to 1046 J/(kg·K). C_p is equal to 595 J/(kg·K) at 223 K, 728 J/(kg·K) at 300 K, 823 J/(kg·K) at 373 K, 908 J/(kg·K) at 473 K, 946 J/(kg·K) at 573 K, 964 J/(kg·K) at 673 K, 999 J/(kg·K) at 773 K, and 1046 J/(kg·K) at 823 K. Specific heat capacity of various samples is in the range 576–631 J/(kg·K) at 223 K, 705–769 J/(kg·K) at 300 K, and 936–1114 J/(kg·K) at 773 K. This means that relative changes in specific heat capacity differ about 9% at low temperatures and 18% at high temperatures.

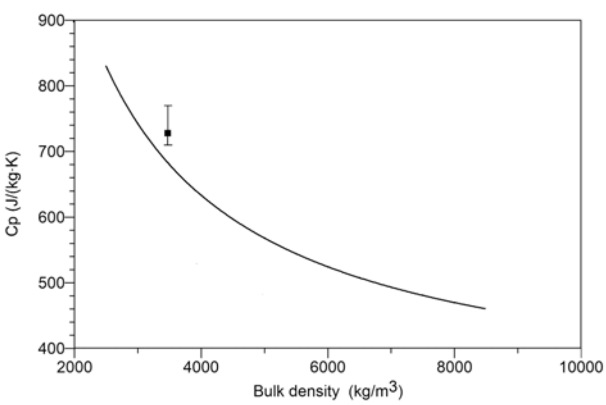

Fig. 1. Dependence of specific heat capacity Cp on bulk density of meteorites (Szurgot, 2011a). The mean value of Cp for Sołtmany meteorite at room temperature is marked by the full square point. The vertical bar indicates scattering of measurements of Cp, and horizontal bars mark upper and lower Cp values

Values of C_p for 100 K, and 200 K presented in Table 3 were determined by extrapolating the experimental data to the low-temperature region. For this calculation, eq. (13) representing the best fit has been used. At 100 K, we have mean C_p = 327 J/(kg·K), and at 200 K a mean Cp = 549 J/(kg·K). Cp at 200 K is more precisely determined than that at 100K since the neighbouring experimental point 223 K is very close to 200 K. In general, the scatter of Cp values reflects variation in the composition of the rock, caused by different contribution of various minerals to these small samples rather than measurements uncertainty.

Recent literature data on the low values tempearture for specific heat capacity of meteorites shows that the average C_p at temperatures of the asteroid belt objects is about half that of materials measured at room temperature (Consolmagno et al., 2013a,b; Beach et al., 2009; Opeil et al., 2012; Yomogida & Matsui, 1983). Since the ratio of mean Cp values at

Table 3. Specific heat capacity C_p[J/(kg·K)] of small samples (E, F, and G) at various temperatures of the Sołtmany meteorite. C_p values in the temperature range 223–823 K were measured by DSC, and in the temperature range 100–200 K were calculated using eq. (13).

T(K)	E	F	G	Range	Mean
100	365*	241*	301*	241–365*	327*
200	536*	521*	579*	521–579*	549*
223	576	577	631	576–631	595
263	647	651	709	647–709	669
283	678	685	742	678–742	702
300	705	711	769	705–769	728
323	740	748	804	740–804	764
373	797	808	864	797–864	823
398	824	831	894	824–894	850
448	881	878	948	881–948	902
473	881	886	956	881–956	908
523	899	900	990	899–990	930
573	916	907	1014	907–1014	946
623	911	903	1033	903–1033	949
673	918	914	1059	914–1059	964
723	922	933	1087	922–1087	981
773	947	936	1114	936–1114	999
823	–	950	1141	950–1141	1046

*Extrapolated values, calculated by the fit expressed by eq. (13).

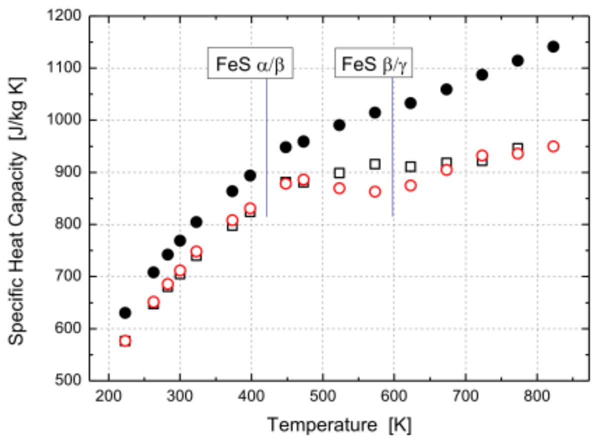

Fig. 2. Specific heat capacity *Cp* of three small samples of the Sołtmany meteorite at various temperatures. Sample E – open squares, sample F – open circles, sample G – full circles. Temperatures of α/β and β/γ solid-state transitions in troilite have been marked

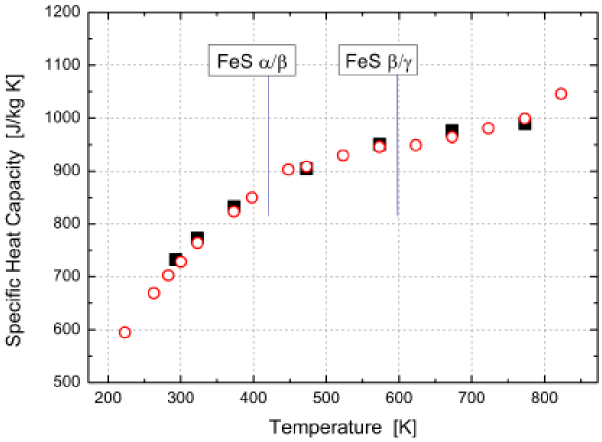

Fig. 3. Mean specific heat capacity of Sołtmany meteorite (open circles), and Gao-Guenie chondrite (full squares)

100K and 300K for the Sołtmany meteorite is equal to 0.45 ($Cp100/Cp300$ = 327 J/(kg·K)/728 J/(kg·K) = 0.45), and the interpolation of *Cp* data for 150 K gives the ratio 0.60, this means that our results for the Sołtmany meteorite confirm this finding.

Figure 3 presents $Cp(T)$ dependence of Sołtmany meteorite (arithmetic mean of three samples E, F and G) and for comparison, $Cp(T)$ dependence of Gao-Guenie chondrite (Beech et al., 2009). The results show that *Cp* of both ordinary chondrites, Sołtmany

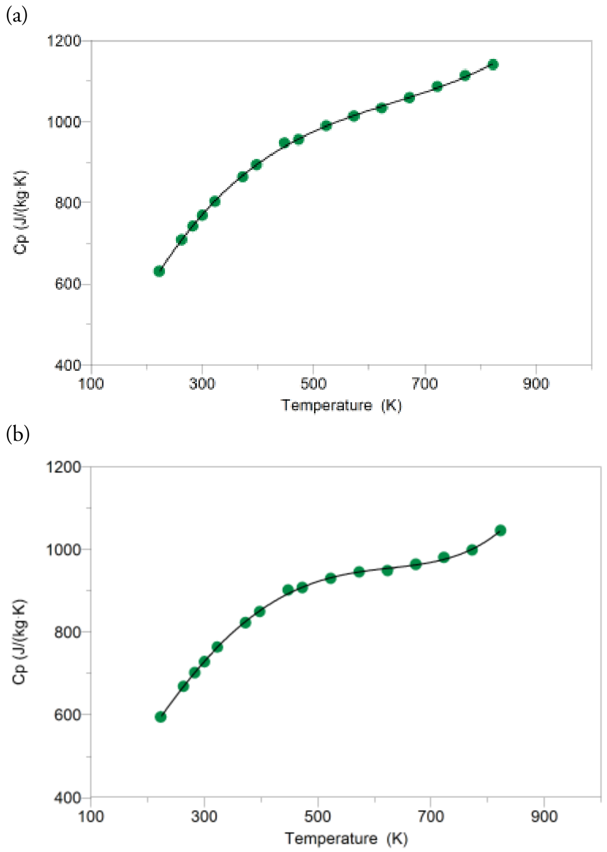

Fig. 4. Specific heat capacity of Sołtmany meteorite as a function of temperature. (a) sample G, (b) mean value of *Cp* of the three samples E, F and G. The fits are given by eq. (13)

representing L group and Gao-Guenie representing H group, are very close to each other indicating that their mineral compositions are also similar. Notice that in Figs. 2, 3, and 4 that α/β, and β/γ solid-state transitions in troilite have no significant effect on the $Cp(T)$ dependence.

The specific heat capacity of Sołtmany meteorite samples measured in this paper can be fit by a quartic function:

$$Cp = A + BT + CT^2 + DT^3 + ET^4 \qquad (13)$$

The fits are shown in Fig. 4 and values of the coefficients A, B, C, D, and E for each sample are listed in Table 4.

Table 4. Values of coefficients *A, B, C, D* and *E* of the quartic fit to the specific heat capacity *Cp* of Sołtmany meteorite samples. The fit is expressed by the equation $Cp = A + BT + CT^2 + DT^3 + ET^4$

Sample	A	B	C	D	E
E	259.4	0.4497	0.007742	$-1.751\cdot10^{-5}$	$1.065\cdot10^{-8}$
F	−131.2	4.183	−0.004639	$-2{,}994\cdot10^{-7}$	$2.075\cdot10^{-9}$
G	−82.7	4.443	−0.006376	$3.532\cdot10^{-6}$	$-1.767\cdot10^{-10}$
Mean	94.32	2.243	0.001651	$-8.802\cdot10^{-6}$	$6.307\cdot10^{-9}$

Phase transitions in Sołtmany's troilite

Troilite, the mineral common in meteorites, undergoes two phase transitions upon heating to temperatures below its melting point (Alton & Gooding, 1993; Alton et al., 1993, 1994; Lauer & Gooding, 1996). α/β transition occurs at 411 ± 3 K, and β/γ transition at 598 ± 3 K (Chase et al., 1985). Our heat flow measurements revealed that the Sołtmany samples contain troilite (FeS), whose two characteristic solid-state phase transformations were detected. The α/β transition, shown in Fig. 5 as a sharp endothermic peak, takes place during first heating scan at 149.93 °C, and is identical for all measured samples (quoted value is an average of four measurements, standard deviation is 0.39 °C). The averaged enthalpy change, ΔH of the α/β transition determined during the first heating scan was of 2.38 J/g, but the specimens displayed large variations in the ΔH values, SD amounts to 0.91 J/g (Tab. 5). Apparently non-uniform distribution of the FeS within the available meteorite fragments accounts for the considerable differences in the ΔH of particular samples (c.a. 20 mg each).

Heating the sample to 560 °C, then cooling it to –70 °C, followed by reheating results in reverse β/α transition at about 141.6°C and again α/β transformation at 148.2 °C (Fig. 5) respectively. During the second heating scan, the α/β transition peak is slightly broader with similar ΔH, approximately 2.2 J/g, which indicates that the original structure of the troilite is essentially restored during cooling.

The β/γ transition occurs at about 323.5 °C (SD = 1.2°C), as depicted in the inset to Fig. 5 for the first heating scan and is listed in Table 5. This β/γ transition is reversible as well.

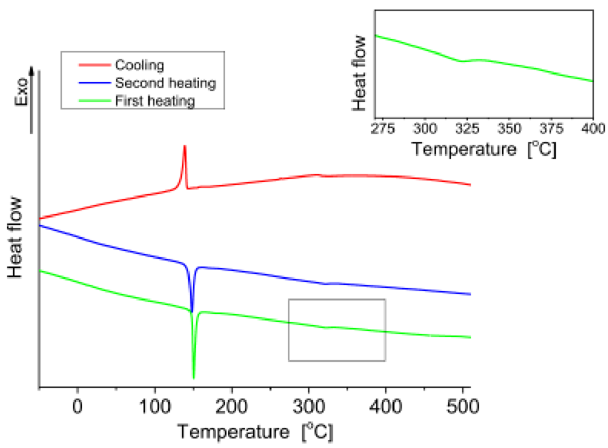

Fig. 5. Heat flow changes during first heating, cooling and second heating scans of Sołtmany meteorite specimens measured by DSC. Inset: enlarged area depicting β/γ transition of troilite. Heat flow is measured in mW, but here are arbitrary units

An analysis of the *Cp* data shows that there is no drastic change in the *Cp* due to α/β transition of troilite at about 423 K (150 °C) (see Figs. 2, 3, where α/β and β/γ transitions are depicted). However, the other FeS transformation of β/γ at 596.5 K (323.5 °C) has little influence on the *Cp* at that temperature.

Data on temperature of solid-state transitions and enthalpy changes ΔH (J/g) for four samples of Sołtmany meteorite are compiled in Table 5. The results show that the mean temperature of α/β transformation is 149.9 ± 0.4 °C, i.e. 423.0 ± 0.4 K, and mean enthalpy change 2.38 ± 0.91 J/g. For temperature of transformation β/γ we obtained mean value 323.5 ± 1.2 °C, i.e. 596.6 ± 1.2 K.

Troilite content in chondrites is about 5 wt% (Hutchison, 2004). Our preliminary data on the mean elemental and mineral contribution established by EDX spectrometry indicate that Sołtmany contains about 4 wt.% of troilite. The mean enthalpy change determined for α/β transformation (2.38 J/g) proves that troilite is present in Sołtmany as a small percentage of the overall meteorite.

We estimated the mean troilite content in our samples using values of temperature of α/β transition, and measured enthalpy change for the transition using both our, and literature data. According to Alton and co-workers data enthalpy change for α/β transition in troilite is equal to 42.5 J/g at transition temperature 423K (Alton et al., 1994), i.e. at the mean transition temperature established for the Sołtmany meteorite. Using the mean value of enthalpy change ΔH = 2.38 J/g and dividing it by 42.5 J/g gives 5.6 wt.% of troilite in the meteorite, on an average. The range of values of troilite content is, however, much broader, between 4 and 8.6 wt.% (see fifth column in Table 5).

Our estimation of troilite content (5.6 ± 2.1 wt.%) seems to be correct since values of enthalpy changes 1.7–3.65 J/g are in agreement with results of Lauer and Gooding (Lauer & Gooding, 1996). Extrapolation of their data indicates that FeS is of the order of 5–10 wt.%. These results support our opinion that Sołtmany has a heterogeneous distribution of FeS.

It is well-known that thermodynamic properties of α/β phase transformation in troilite, as revealed by DSC measurements of terrestrial troilite, depend on, and are important indicators of the thermal history of troilite. The transition temperature and enthalpy change for α/β transformation decrease with increasing maximum temperature of prior heat treatment (Alton et al., 1994). Calorimetric thermometry of

Table 5. Temperature of solid-state α/β, and β/γ transformations, transition enthalpy change Δ*H*, and estimated troilite content in Sołtmany meteorite from thermodynamic data

Sample	*T* (°C) for α/β	Δ*H*(J/g) for α/β	*T* (°C) for β/γ	FeS content (wt.%)
E1	149.9	1.73	322.2	4.1
E	149.4	1.70	322.9	4.0
F	150.1	3.65	323.8	8.6
G	150.3	2.43	325.0	5.7
Mean ± SD	149.9±0.4	2.38±0.91	323.5±1.2	5.6±2.1

meteoritic troilite is a very promising tool for meteoritic investigations. Transition temperature of α/β transformation of Sołtmany's troilite (423 K) is somewhat higher than that established by Alton and coworkers for natural (not previously heated) terrestrial, Del Norte troilite (420–422 K, mean 421 K), and is higher than mean temperature of α/β transformation for previously studied meteorites: EET83213 (L3, unmetamorphosed chondrite) 420.5 K, PAT91501 (L7, highly metamorphosed chondrite) 419 K, and is distinctly higher than that established for Mundrabilla octahedrite: 415.5 K (Alton et al, 1994).

Such a high value of temperature of α/β transformation of Sołtmany's troilite (423 K) indicates low temperature accretion of this chondrite (well below 1000 K), and/or low maximum temperature achieved by heat treatment (e.g. low temperature increase during collision). This is rather unexpected since petrology indicates that Sołtmany belongs to the highly metamorphosed L6 chondrites (Karwowski et al., 2011). Our conclusion is supported by Lauer and Gooding data that L-chondrites record relict temperatures that do not exceeds 458 K (Lauer & Gooding, 1996). Comparison of our data with Lauer and Gooding data indicate that Sołtmany's relict temperature could be even lower than 450 K. The low shock stage (S2) of Sołtmany chondrite (Karwowski et al., 2011) supports this possibility.

The FeS phase transition confirms rather low temperature values during the evolution of the Sołtmany L chondrite parent body and may support the scenario that its parent body was formed as the result of a collision between two partially molten objects (Hutchison, 1996; Sanders, 1996). This type of scenario was proposed by the author (TAP) and team for the Baszkówka L5 chondrite parent body (Przylibski et al., 2003).

We continued DSC measurements of α/β phase transformation in Sołtmany's troilite on several new samples. The effect of the maximum temperature of controlled, laboratory heating and time of heating on the temperature of α/β phase transformation and on enthalpy change in Sołtmany troilite was studied (Szurgot et al., 2013a). It was established that both annealing temperature and annealing time are crucial parameters in the troilite thermometry, and it was confirmed that the α/β phase transition data for the virgin samples indicate a low relict temperature (about 440K) of the Sołtmany meteorite (Szurgot et al., 2013a). It was also established that the troilite present in the fusion crust indicates high relict temperature (about 1000 °C), which is caused by the aerodynamic heating due to atmospheric passage (Szurgot et al., 2013b). Our latest results prove the usefulness of troilite thermometry.

Thermal capacity, thermal conductivity and thermal diffusivity

In Table 6, data on thermophysical properties of the Sołtmany meteorite at room temperature 298–300 K, and data predicted for lower temperature (200K) have been compiled. Below, we will compare literature data on thermophysical properties of chondrites with the properties of the Sołtmany meteorite.

The specific heat capacity of Sołtmany is equal to 728 ± 35 $J \cdot kg^{-1} \cdot K^{-1}$ (mean value) and the *Cp* of chondrites at room temperature is in the range 630–920 $J \cdot kg^{-1} \cdot K^{-1}$(Szurgot, 2003, 2011a). Measurements of specific heat capacity of Gao-Guenie chondrite (H5) gave *Cp* = 732–740 $J \cdot kg^{-1} \cdot K^{-1}$, and of Jilin (H5) gave *Cp* = 726 $J \cdot kg^{-1} \cdot K^{-1}$ (Beech et al., 2009). Both H chondrites have heat capacities comparable with the Sołtmany chondrite.

Yomogida and Matsui calculated *Cp* for H (714 $J \cdot kg^{-1} \cdot K^{-1}$) and for L chondrites (728 $J \cdot kg^{-1} \cdot K^{-1}$ at room temperature (Yomogida & Matsui, 1983). Their results show that H chondrites have slightly greater *Cp* than of L chondrites.

Matsui and Osako in their studies of thermal properties of Yamato meteorites established the following *Cp* values of various chondrites at room temperature: 364 $J \cdot kg^{-1} \cdot K^{-1}$ (Y-7301; H4), 601 $J \cdot kg^{-1} \cdot K^{-1}$

Table 6. Thermophysical properties of the Sołtmany meteorite at room temperature 298–300 K, and at 200K

Property	Sołtmany Mean at 300 K	Sołtmany Mean at 200 K
Specific heat capacity	728 J·kg^{-1}·K^{-1}	549 J· kg^{-1}·K^{-1}
Thermal capacity	2.53·10^6 J/(m^3·K) (eq. (5))	1.91·10^6 J/(m^3·K) (eq. (5))
Thermal conductivity	3.9 W·m^{-1}·K^{-1} (eq. (6))	4.7 W·m^{-1}·K^{-1} (eq. (7))
	4.5 W·m^{-1}·K^{-1} (eq. (8))	5.1 W·m^{-1}·K^{-1} (eq. (6))
Thermal diffusivity	1.5·10^{-6} m^2/s (eq. (9))	1.1·10^{-6} m^2/s (eq. (9))
	1.8·10^{-6} m^2/s (eq. (11))	2.6·10^{-6} m^2/s (eq. (11))
		2.7·10^{-6} m^2/s (eq. (11)

(Y-74647; H4-5), 535 J kg^{-1}·K^{-1} (Y-74371; H5-6), 603 J·kg^{-1}·K^{-1} (Y-74191; L3) (Matsui & Osako, 1979). Their range of *Cp* is wide 364–603 J·kg^{-1}·K^{-1}, but values of *Cp* are significantly lower than values determined by other investigators. Theoretical specific heats calculated by these authors on the basis of chemical composition of meteorites are more reliable (*Cp* = 730 J·kg^{-1}·K^{-1} for Y-7301 H4 chondrite, and *Cp* = 750 J·kg^{-1}·K^{-1} for Y-74191 L3 chondrite). In general, they are about 1.2–2 times higher than corresponding experimental values.

The compilation of our data shows that the *Cp* of the Sołtmany meteorite at room temperature is within the range of values established for L and H chondrites. Our latest DSC data for the mean value of *Cp* of three new samples of the Sołtmany meteorite at 300 K gave the value 671 J·kg^{-1}·K^{-1} (Wach et al., 2013) which is about 8% lower than 728 ± 35 J·kg^{-1}·K^{-1} that was obtained in this paper (Tabs. 2 and 3). The preliminary data for mean *Cp* value of two samples of NWA 4560 ordinary chondrite gave the value 682 ± 15 J·kg^{-1}·K^{-1} at 300 K (Wach et al., 2013). The comparison of *Cp* values for both these meteorites indicates that specific heat capacity of the Sołtmany L6 chondrite is close to the specific heat capacity of NWA 4560 LL3.2 ordinary chondrite.

Thermal capacity of the Sołtmany meteorite at room temperature equals 2.53·10^6 J/(m^3·K), and is close to the mean thermal capacity of stony meteorites (2.5·10^6 J/(m^3·K; Szurgot, 2011a). It is also close to the thermal capacity of solid terrestrial materials (3·10^6 J/(m^3·K; Waples & Waples, 2004). This means that Sołtmany's thermal capacity is comparable with other stony meteorites, and comparable with terrestrial rocks.

Thermal conductivity of Sołtmany at room temperature (300 K) was determined by the authors to be 3.9–4.5 W·m^{-1}·K^{-1}. The latest literature data obtained by direct, precise *K* measurements of chondrites at room temperature revealed the range 0.5–5.2 W·m^{-1}·K^{-1}, for L chondrites *K* = 0.45–3.5 W·m^{-1}·K^{-1}, and for H chondrites the range *K* = 1.4–3.2 W·m^{-1}·K^{-1} (Opeil et al., 2012). *K* values determined by Szurgot for ordinary chondrites at 300 K amount to 1.5–4.5 W·m^{-1}·K^{-1}, for Gold Basin (L4) he obtained *K* = 3.7 W·m^{-1}·K^{-1}, and for El Hammami (H5) somewhat higher value *K* = 4.5 W·m^{-1}·K^{-1} (Szurgot, 2011b). Measurements of *K* by Matsui and Osako gave range of *K* values 0.66–1.13 W·m^{-1}·K^{-1} for H chondrites, and 0.67 W·m^{-1}·K^{-1} for Y-74191 (L3) chondrite (Matsui & Osako, 1979).

In regards to the low temperature *K* values, the porosity – thermal conductivity relation (eq. (7)) in Table 6 gives *K* = 4.7 W·m^{-1}·K^{-1} at 200 K, whereas using the relationship between thermal conductivity and bulk density (eq. (6)) (Szurgot & Wojtatowicz, 2011) gives *K* = 5.1 W·m^{-1}·K^{-1} at the same temperature. These *K* values are close each to other though obtained by two various relationships. They are reliable values, since they are close to the values established by direct *K* measurements of ordinary chondrites (Opeil et al., 2010, 2012), and close to *K* values determined by indirect measurements (Yomogida & Matsui, 1983; Szurgot, 2011b). Using direct measurements, Opeil and coworkers revealed the range of *K* values at 200 K for L chondrites *K* = 0.5–3.2 W·m^{-1}·K^{-1}, and *K* = 0.8–3.5 W·m^{-1}·K^{-1} for H chondrites (Opeil et al., 2012). Based on diffusing data, Yomogida and Matsui for 200K revealed the range of *K* values eq. (10) for L chondrites *K* = 0.5–2.3 W·m^{-1}·K^{-1}, and *K* = 1.1–3.6 W·m^{-1}·K^{-1} for H chondrites at 200 K (Yomogida & Matsui, 1983). An analysis of both low temperature and room temperature values of *K* shows that Sołtmany meteorite thermal conductivity is within the range established for H chondrites, but close to the upper limit of *K* values noted for L chondrites.

Thermal diffusivity of Sołtmany amounts to (1.5–1.8)·10^{-6} m^2/s at room temperature, and *D* of chondrites at room temperature is in the range: (0.5–2)·10^{-6} m^2/s (Szurgot & Wojtatowicz, 2011). Yomogida and Matsui obtained a similar range (0.1–1.2)·10^{-6} m^2/s for chondrites, (0.1–1.1)·10^{-6}

m^2/s for L chondrites, and $(0.2–1.2)\cdot10^{-6}$ m^2/s for H chondrites (Yomogida & Matsui, 1983). Osako established the following values of D at room temperature: $(0.55–0.75)\cdot10^{-6}$ m^2/s for L chondrites (Satsuna, Duwun, and Fukutomi), and $0.75\cdot10^{-6}$ m^2/s for H4 (Kesen) chondrite (Osako, 1981).

Comparison of room temperature values of various thermophysical properties of Sołtmany meteorite with the properties of various chondrites allows one to draw the conclusion that specific heat capacity, thermal capacity, thermal conductivity, and thermal diffusivity of Sołtmany meteorite are within the range of chondrites. Although our analysis concerned mainly room temperature values, the same conclusion, as it is seen for K values, can be drawn from the available low-temperature values of thermophysical properties.

CONCLUSIONS

New data on the fundamental thermal properties of meteorites have been provided in this paper. The Sołtmany meteorite, that fell in Poland on 30th April 2011, has been a very informative source of data. Modern and classical equipment allowed the authors to determine the following properties: specific heat capacity, thermal capacity, thermal diffusivity, thermal conductivity, bulk density and grain density as well as porosity of the interior and crust, temperature of α/β and β/γ reversible transitions in troilite, and enthalpy change during α/β troilite transformation. These data are useful for understanding, modelling and interpreting the origin and evolution of a meteorite's parent body and the ablative heating of meteoroids during their atmospheric passages.

Most of the above mentioned thermophysical properties have been determined for room temperature, but specific heat capacity was measured over a wide temperature range, between 223 and 823 K. C_p low temperature values for 200 K and 100 K were obtained by extrapolation. In general, the results show that the specific heat capacity, thermal capacity, thermal conductivity, thermal diffusivity, bulk density, and porosity of Sołtmany meteorite are within the range of previously studied ordinary chondrites. According to the data, the thermophysical properties of this fresh chondrite are consistent with other L chondrites, though some properties, e.g. K data, may indicate H class chondrites.

DSC measurements are time consuming but very important in meteorite studies. Measurements of temperature dependency of specific heat capacity should be continued on samples of various sizes, especially on larger samples since this paper's results for small samples revealed a scatter in Cp values. This scatter is likely caused by the different compositions of the small specimens, especially differences in iron and troilite content. Optical inspection of these small samples revealed differences in the metal content, and measurements of temperature of α/β troilite transformation, and enthalpy change during this transition confirmed various troilite content in various samples. Detailed measurements of chemical composition of these small samples seem to be desirable. The question of how large the meteorite sample should to be in order to be representative for extraterrestrial rock which properties we determine is an open question in meteorite studies. This question also concerns the Sołtmany measurements. Knowledge of both: modal composition of meteorite and specific heat capacities of their minerals enables one to calculate specific heat capacity of meteorite. Some researches (e.g. Yomogida & Matsui, 1983) prefer calculated Cp values rather than those measured, probably due to scatter in experimental values.

Direct measurements of thermal conductivity and thermal diffusivity of the Sołtmany meteorite should be conducted at various temperatures, including room temperature. The authors are aware that the determination of room and low temperature values are preliminary data based on indirect determination. They are estimations based on recently established dependencies which need confirmation by new, direct measurements. In particular, thermal conductivity data based on relation between porosity and K (eq. (7) (Opeil et al., 2012) are worth confirming since experimental data revealed a wide range of K values even for similar samples (Opeil et al., 2012).

Differential scanning calorimetry revealed two reversible phase transitions in the Sołtmany's troilite: α/β transition at 149.925 K, and β/γ transition at 323.49K. High value of α/β transformation temperature of Sołtmany's troilite indicates low temperature accretion of this chondrite, and/or low relict temperature 440–450 K. Troilite α/β phase transition data confirm rather low temperatures during the evolution of Sołtmany L chondrite parent body, and supports the possibility that its formation is the result of two partially molten objects (Hutchison, 1996; Sanders, 1996). Further research on this phenomenon should be continued for other ordinary chondrities as well as other groups of meteorites. Troilite thermometry data may change our knowledge on the formation and evolution of planetesimals and asteroids in the Solar System.

Results presented here, and ongoing measurements prove the usefulness of troilite thermometry. Temperature of troilite α/β transition and enthalpy change in this transformation supply important information about troilite content. Our latest DSC measurements of troilite α/β transition have shown that FeS present in fusion crust indicates high relict temperature (about 1000°C), which is caused by the aerodynamic heating of meteoroid due to its atmospheric passage (Szurgot et al., 2013b). This means that we not only are able to estimate the fusion crust formation temperature but also estimate relict temperature recorded in various parts of the meteorite, in particularly relict temperature of fusion crust adjacent parts of meteorite, and those coming from the interior of meteorite far from the crust region. All these examples show that troilite thermometry is a very informative and promising method in meteorite studies.

We have presented our preliminary results concerning various thermophysical properties of the Sołtmany meteorite, an ordinary chondrite unaltered by terrestrial processes. The measurements are continued. The agreement between our results and the latest literature data indicate that all the measured, and estimated physical properties of Sołtmany meteorite: bulk density, grain density, porosity, specific heat capacity, thermal capacity, thermal conductivity, and thermal diffusivity are within the range of ordinary L and H chondrites though some indicate L and others indicate H chondrite.

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