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Determining Thermal Properties of A383.1 Aluminum Alloy Depends on Temperature

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Abstract: Thermal diffusivity and thermal conductivity are important parameters for determining products thermal work conditions and production parameters for high quality products. There is two main method for determining these parameters: steady-state and transient measurement methods. Laser Flash Method (LFA) is a nonsteady-state measuring method which is widely used for measuring thermal diffusivity (α) of solid homogeneous and opaque materials. In this study, thermal diffusivity of A383.1 aluminum alloy determined with laser flash method depend on temperature. For this, 25.4 mm diameter and 1 mm thickness experiment specimens prepared from A383.1 aluminum alloy and measured their thermal diffusivity with LFA method at 30 C° to 400 C°. For calculating thermal conductivity (λ) of materials, test specimen's density (ρ) measured with helium pycnometer and heat capacity (Cp) measured with Differential Scanning Calorimeter (DSC) test device. Thermal diffusivity and thermal conductivity results obtained from tests and calculations presented systematically in this paper.

Keywords: Laser flash method, Thermal diffusivity, Thermal conductivity, Aluminum alloys, Differential Scanning calorimeter

Introduction

Thermal diffusivity and thermal conductivity are important parameters for determining products thermal work conditions and production parameters for high quality parts. There is two main method for determining these parameters: steady-state and transient measurement methods. Steady-state methods are applying thermal gradients on test specimens and with this way, they measure thermal conductivity directly and these methods mostly uses for measuring thermal conductivity of thermal insulation materials. But because of the techniques which is used at steady-state methods, tests need relatively bigger test specimens and measurements takes long time. There were three transient test methods using widely: transient hot-wire method, laser flash diffusivity method and transient plane source method. Laser flash method is mostly used because of needed geometrically small specimens and can give results of measurement faster than other methods. But after measuring a materials thermal diffusivity with LFA, for calculating thermal conductivity, density and thickness of the test specimens must be known (Miculescu et al., 2008; Vozár et al., 2003; Altun et al., 2008; Yılmaz, 2004; Lian et al., 2016).

LFA method is firstly put forwarded by Parker and rely on a relatively basic concept. In LFA test, radiant energy resource (laser or flash lamp) shot a pulse to test specimens one surface and energy of the shot absorbed by the specimen. This energy, which absorbed by the specimen, raises temperature at other surface of the specimen. One infrared sensor monitors other surface of the specimen and detects thermal changes on the specimen's surface. Depends on the thickness and required time for temperature rise (thermal curve) to reach a percentage of its maximum value thermal diffusivity is calculated. Cape and Lehman in their works modified LFA method with infinite pulse and effect of time. In LFA method, shape of the laser pulse, non-linear response of infrared

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sensor and bad response of thermal diffusivity of test specimen to temperature may affects test results (Miculescu et al., 2008; Yılmaz, 2004; Lian et al., 2016; ASTM, 2013, Altun & Böke, 2012; Cape & Lehman, 1963; Moskal et al., 2016).

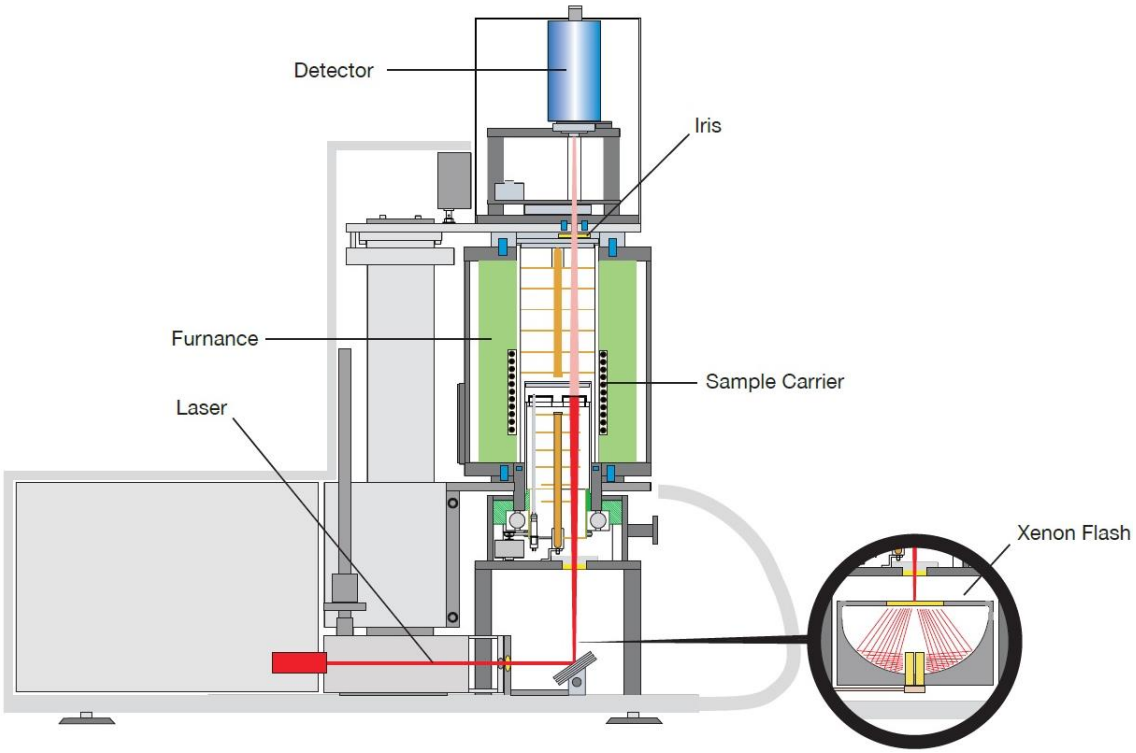

Figure 1. Schematic of the Linseys LFA 1000 laser flash machine (Linseis, 2018)

Because of their advantages like lightweight, high strength and capable of resist high temperatures aluminum alloys widely used in automotive, aerospace and machinery. Knowing thermal properties is important for producing parts with high pressure die casting method and simulations of the method. Unlike other casting methods, because of using metal molds thermal conductivity from casting parts to molds is important for obtain high quality products. At the other for thermal cooling applications like heat sink or heat exchanger plates, also knowing thermal properties is important too (Koru & Serçe, 2018).

Miculescu et al. measured thermal diffusivity of CoCr alloy with LFA method and presented results systematically [1]. Altun et al. made three different study about determining effect of thermal barrier applications on thermal conductivity and measured with LFA method [3, 7, 11]. Yılmaz determined thermal diffusivity of glass ceramic matrix composites based on their thickness with LFA method and presented results [4]. Lian et al. determined thermal conductivity of porous insulation materials with LFA method and present results in their study [5]. An et al. determined thermal conductivity of molten fluoride salt with LFA (An et al., 2015).

In this study, thermal diffusivity of A383.1 aluminum alloy determined with LFA method based on temperature and thermal conductivities calculated. Accordingly, to this prepared test specimens 25.4 mm diameter and 1 mm thickness with A383.1 material and measured their density with gas pycnometer and heat capacity with DSC test device. For preventing reflection of laser pulse, specimen's surfaces coated with graphite spray. Specimens thermal diffusivity measured with LFA test device at 20 C° to 400 C° degrees and thermal conductivity calculated. Results presented systematically in this paper.

Method

LFA Method

In this study, Linseis LFA 1000 used for measuring thermal diffusivity. Linseis LFA 1000 test machine works on principles of Parker's study. Basically, one laser source provides xenon flash pulse. Energy density of the

laser pulse can be varying from 0.05 to 25 Joule/pulse. Laser pulse directed by a mirror to the samples and samples stands in furnaced area. With furnace test temperatures can be selected from -100 C° to 500 C° and test can be performed determined increments at temperature like 5 C° increment from 20 C° to 400 C°. With this way results can be showed in a graphic depend on temperature. At the other side of the test specimen, there is a MCT (Mercury cadmium telluride) detector which monitoring temperature of the specimen's surface. With percentage of its maximum measurement taken by detector and with thickness of the test specimen's thermal diffusivity is calculated. Test device can measure thermal diffusivity from 0,01 up to 2000 mm^2/s. Tests are performed in vacuum condition and max vacuum capacity up to 10^{-5} mbar.

Theory

Pulse method physical model founded on the thermal behavior of an adiabatic slab of material which have initially at constant temperature, whose one side has been subjected to a shot pulse of energy. LFA method assumes:

- Heat flow occur in one dimension,
- Heat losses from specimen's surface are ignored,
- Pulse absorption at the front surface assumed uniform,
- Homogeneity and isotropy of the sab material,
- Infinitesimally short pulse duration.

Mathematical theory of measurement, Parker starts from the equation of the temperature distribution within a thermally insulated solid of uniform thickness L, as given by Carslaw and Jeager (ASTM, 2013),

$$T(x,t) = \frac{1}{L}\int_0^L T(x,0)dx + \frac{2}{L}\sum_{n=1}^{\infty}\exp\left(\frac{-n^2\pi^2\alpha t}{L^2}\right).\cos\frac{n\pi x}{L}\int_0^L T(x,0)\cos\frac{n\pi x}{L}dx \quad (1)$$

where α is the thermal diffusivity of the material. If a pulse of radiant energy Q uniformly absorbed in the small depth g at the front surface x=0, the temperature distribution at that instant can be given by

$$T(x,0) = \frac{Q}{\rho.C.g} \quad (2)$$

For 0<z<g and

$$T(x,0) = 0 \quad (3)$$

for g<x<L. So, Eq. 1 can be written as

$$T(x,0) = \frac{Q}{\rho CL}\left[1 + 2\sum_{n=1}^{\infty}\cos\frac{n\pi x}{L}\frac{\sin\frac{n\pi x}{L}}{\frac{n\pi x}{L}}.\exp\left(\frac{-n^2\pi^2}{L^2}\alpha t\right)\right] \quad (4)$$

where ρ is the density and C is the specific heat capacity of the test specimen. For application only, a few terms will be needed and because of g is a very small number for opaque materials,

$$\sin\frac{n\pi g}{L} \approx \frac{n\pi g}{L} \quad (5)$$

At the rear surface of the specimen, where x=L, the temperature history can be expressed by

$$T(L,t)=\frac{Q}{\rho CL}\left[1+2\sum_{n=1}^{\infty}(-1)^{n}.\exp\left(\frac{-n^{2}\pi^{2}}{L}\alpha t\right)\right] \tag{6}$$

Two dimensionless parameters, V and ω can be defined

$$V(L,t)=\frac{T(L,t)}{T_{M}} \tag{7}$$

$$\omega=\frac{\pi^{2}\alpha t}{L^{2}} \tag{8}$$

T_M represents the maximum temperature at the rear surface of the test specimen. When we combined Eq.6 and Eq.8

$$V=1+2\sum_{n=1}^{\infty}(-1)^{n}.\exp(-n^{2}\omega) \tag{9}$$

When V=0.5, ω=1.38, and therefore

$$\alpha=0.1388\frac{L^{2}}{t_{1/2}} \tag{10}$$

where $t_{1/2}$ is the time required for the back surface to reach half of the maximum temperature rise. With LFA method after determining the thermal diffusivity, with Eq.11 thermal conductivity can be calculated too

$$\lambda=\alpha C_{p}\rho \tag{11}$$

A383.1 Al-Alloy Test Specimen

Chemical composition of A383.1 aluminum alloy determined with spectral analysis and given in the Table 1. Test specimens directly cut from material ingot and shaped 25.4 mm diameter and 1 mm thickness because of the Linseis LFA 1000 specimen holder shapes. You can see the specimen holder at Figure 2.

Table 1. Chemical composition of A383.1 aluminum alloy determined with spectral analysis (% percentage)

Al	Si	Cu	Fe	Zn	Mn	Pb	Mg	Ni	Sn	V	Cr
87,9	8,71	2,32	0,53	0,257	0,183	0,034	0,024	0,019	0,011	0,009	0,008

Figure 2. Specimen holders (a) for solids (b) for liquids

As can be seen in Figure 2 test device can measure both solids and liquids. Differences between specimen holders, for solid, laser pulse directly absorbed by the specimen. But for liquids, specimen holder is like close box and laser pulse absorbed by specimen holder and energy conducted to liquid by it.

Test specimen's density are measured with helium pycnometer. In Figure 3 you can see the test device of helium pycnometer. Heat capacity of the test specimens measured with DSC device. After measurements density and heat capacity of the samples thermal conductivity calculated with Eq. 11.

Results and Discussion

Heat capacity, density and thermal diffusivity of A383.1 al-alloy measured at different temperature. Measurements started at 30 C° and 50 C° increments measured between 50-400 C°. Measurement results can be seen at Table 2.

Table 2. Measured material properties of A383.1 Al-alloy depend on temperature

Temperature, C°	Thermal Diffusivity, α (cm^2/s)	Heat Capacity, Cp (J/gC°)	Density, ρ (kg/m^3)
30	0,329	1,059	2674
50	0,341	1,075	2674
100	0,346	1,093	2674
150	0,349	1,201	2674
200	0,398	1,146	2674
250	0,448	1,059	2674
300	0,452	1,308	2674
350	0,455	1,433	2674
400	0,459	1,517	2674

When we look at the table as can be seen that, when temperature raised, thermal diffusivity raises too. At 30 C° thermal diffusivity of A383.1 Al-alloy is 0,329 cm^2/s. At 400 C° it raised 0,459 cm^2/s. So, change at thermal diffusivity between 30 C° to 400 C° is %40. Increment at thermal diffusivity is linear but at the other hand heat capacities increment is not. Heat capacity increases from 30 C° to 150 C° but after that start decreases. At 300 C° it starts increasing again. Density of the A383.1 Al-alloy measured with gas pycnometer at room temperature. Because density of the material doesn't change at solid state. So, room temperature result of density can be taken until melting temperature.

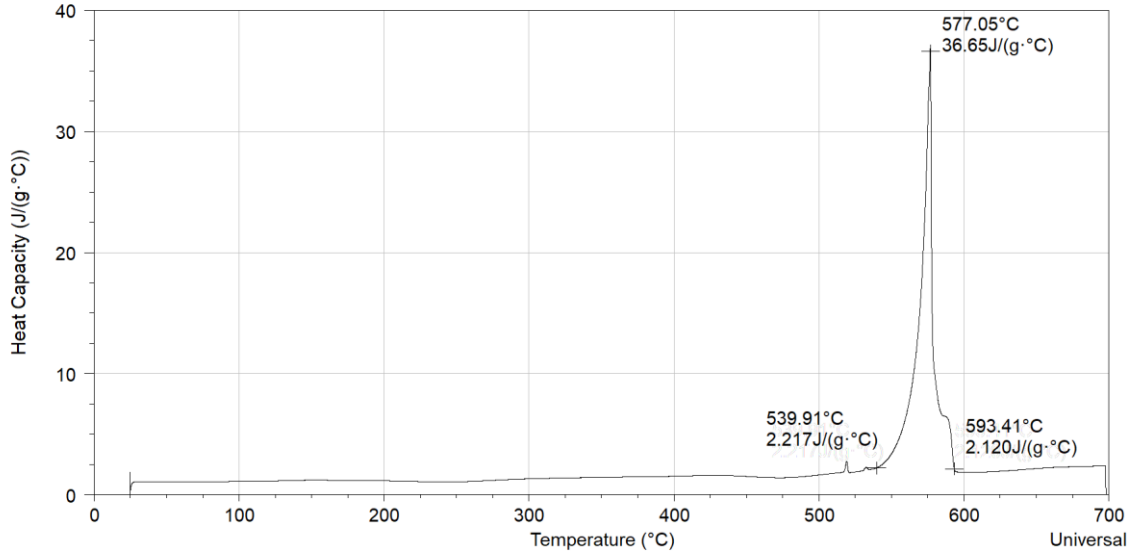

Figure 3. Result of DSC measurents of A383.1 Al- alloy

In Figure 3, measured heat capacity of A383.1 can be seen. In this graphic heat capacity of A383.1 peaks at 577,05 C°. It happens because of phase change of the material. So, melting temperature of A383.1 Al-alloy measured as 577,05 C°

Thermal conductivity of A383.1 Al-alloy calculated with Eq. 11. Result of thermal diffusivity, heat capacity and density used as input. Thermal conductivity results can be seen at Table 3. When temperature increase, thermal conductivity of A383.1 increases too. At 30 C° thermal conductivity of A383.1 is 93,17 W/mK and at 400 C° 186,19 W/mK. So, when temperature get 400 C° from 30 C°, thermal conductivity of A383.1 Al-alloy gets double.

Table 3. Calculated thermal conductivity of A383.1 Al-alloy depend on temperature

Temperature, C°	30	50	100	150	200	250	300	350	400
Thermal Conductivity, λ (W/mK)	93,17	98,02	101,12	112,08	121,96	126,86	158,09	174,35	186,19

Conclusion

In this study, thermal conductivity of A383.1 Al-alloy determined depend on temperature. For this thermal diffusivity of A383.1 material measured with LFA method at 30 C°, 50 C° and 50 C° increment until 400 C°. Measured thermal diffusivity result showed that, when temperature raised, thermal diffusivity raises too. At 30 C° thermal diffusivity of A383.1 Al-alloy is 0,329 cm^2/s. At 400 C° it raised 0,459 cm^2/s. So, change at thermal diffusivity between 30 C° to 400 C° is %40. Heat capacity measured with DSC test device. At the results, heat capacity increases from 30 C° to 150 C° but after that start decreases. At 300 C° it starts increasing again. Heat capacity of the material peaks at 557,05 C° and it showed that melting point of A383.1 Al-alloy is 577,05 C°. Density of the material measured with gas pycnometer and determined as 2674 kg/m^3. With these input data's thermal conductivity of A383.1 Al-alloy calculated. And results showed that, when temperature increases, thermal conductivity of A383.1 increases too. At 30 C° thermal conductivity of A383.1 is 93,17 W/mK and at 400 C° 186,19 W/mK. So, when temperature get 400 C° from 30 C°, thermal conductivity of A383.1 Al-alloy gets double.

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