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Temperature dependent density and thermal expansion of 5088 wrought aluminum alloy by Gamma Ray Attenuation Technique

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Abstract— The density and thermal expansion of wrought aluminum alloy 5088 has been measured from 300K - 850K by measuring attenuation of gamma beam of different energies viz, Cs(661.16 KeV), Am (59.54 KeV) Co (1173 KeV& 1332 KeV). The temperature dependence of linear attenuation coefficient (μ_l) of gamma photons of different energies in the temperature range 300 – 850 K for the alloy has been reported. The gamma ray attenuation studies have been carried out by using a gamma ray densitometer. the variation of density and thermal expansion of the alloy has been represented by linear equations. The coefficients of temperature dependence of density, volume thermal expansion and mass attenuation coefficients have been reported for the alloy.

Index Terms— γ-ray attenuation, linear attenuation coefficient, density, thermal expansion.

1 Introduction

THIS document Density and thermal expansion are the basic parameters in discussing nature and behavior of metals and alloys. Density values are necessary to the process of computer simulation, the calculation of other physical properties and extracting quantitative structural information from diffraction spectra. The knowledge of temperature dependence of their density and thermal expansion is very important for understanding their physical properties like thermal conductivity, specific heats, diffusion coefficients, thermo elastic constants and their applications in various fields.Thermo physical properties can be investigated through a variety of techniques. which have evolved for the determination of density and thermal expansion of solids at high temperature. Some of the techniques are Archimedean method, pycnometry, dilatometry, electromagnetic levitation, Method of maximal pressure in a gas bubble, method of sessile drop, hydrostatic weighing, high temperature electrostatic levitation and gamma ray densitometry. Thermal expansion studies on isotropic solids have been reported by several workers using X-ray diffraction [1-3], dilatometry [4,5], Fabrey-Perot interference method [6] and by other theoretical models [7-13]. The gamma radiation attenuation technique for the determination of thermo physical properties in the condensed state offers several advantages over other methods at high temperatures. This is possible because the gamma ray is not in any kind of physical or thermal contact with the material and hence the thermal losses are also reduced and this condition eliminates sample and probe compatibility problem. Using this technique Drotning [14] measured thermal expansion of isotropic solid materials at high temperatures. He studied thermal expansion of Aluminum and type 303 stainless steel at high temperatures and such studies have been extended by him to study the thermal expansion of metals and glasses in the condensed state [15 16]. A number of other techniques have been used to measure the temperature dependence of density of metals [17-20], alloys [21-28] at high temperatures. Recently the behavior of thermal expansion of carbon fiber reinforced 6061 aluminum alloy has been reported [29] and mechanical properties of alloy 2219 have also been reported [30]. The thermal expansion of ZrW2O8/Polyimide hybrid films was determined [31]. In this communication we report the density and thermal expansion of aluminum alloy 5088 in the temperature range 300 K to 850 K determined from gamma ray attenuation technique, as wrought aluminum alloys have wide range of applications in science and engineering.

2 Experimental

The gamma ray densitometer and a programmable temperature controlled furnace (PTC) was designed and fabricated following the design proposed by Drotning [14]. The furnace can reach up to 1300K.To detect the penetrating gamma radiation a sodium iodide – thallium activated detector was used. The 7.62X10-2m diameter and 7.62X10-2m thick crystal is integrally coupled to a 7.62X10-2m diameter photo multiplier tube (PMT). The PMT has a 14 pin base and can be mounted on two types of PMT preamplifier units. The one used in our study is a coaxial in-line pre-amplifier. The detector has a energy resolution of 8.5% for 137Cs. The alloy studied in the present work was prepared by ingot metallurgy route. The alloy was melted in the air, in the induction furnace and cast iron moulds were used to obtain ingot. The ingot was subsequently homogenized at about 813 K and hot rolled to obtain 12mm - 15mm thick plates.

The chemical composition of 5088 alloy is given in Table 1. The X-ray diffraction (XRD) pattern of the alloy is shown in Fig.1. The XRD pattern confirms that the alloy is in the fcc phase. The alloy sample was machined into a cuboid with all

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the faces finely ground and polished. The dimensions of alloy are 2.275cm x 1.995cm x 1.341cm with a tolerance of±0.001cm. The temperature of the sample was measured using a thermocouple sensor. The thermocouple sensor tip was mounted on the sample holder ensuring a physical contact with the sample for recording precise sample temperature. The sample holder along with the alloy sample and thermocouple was slid through a cork into an air tight quartz tube and was fixed firmly. A diffusion pump was then connected to the sample holder tube for evacuation. For inert atmosphere, argon gas was introduced into the quartz tube through the sample holder tube. Then the quartz tube assembly along with the sample was slid into the programmable temperature controlled (PTC) furnace and fixed at appropriate position ensuring proper alignment(±0.5mm) of sample with collimation 6mm on either sides. The PTC furnace was programmed in such a way that the furnace temperature is increased by 50K in every step starting from 298K, and stabilizes there for 5 minutes. Temperature equilibrium is achieved within 5 minutes and temperature accuracy is ±1% of set point temperature after stabilization. Heating rate between each step of 50K is 5K/min. At each temperature the γ - ray counts of Cs(661.16 KeV), Am (59.54 KeV) Co (1173 KeV& 1332 KeV) with sample (I) and without sample (Io) were detected and recorded using a multichannel analyzer. The recording of γ - ray counts was done for a period of 32 minutes at each programmed temperature. After a time of 32 minutes of isothermal holding, the difference of programmed and sample temperature was 1% of set point. Measurement of γ- ray attenuation counts at every step of temperature was repeated a minimum of nine times before and after the sample was introduced and the average value was considered in all our calculations. The γ - ray counts were recorded while heating and also cooling the sample. The difference in readings was negligible and hence the final readings were recorded while cooling the sample. The cooling rate varied between 10K/min from 1300K-800K, 6K/min from 800K-500K, 4K/min from 500K-400K and 2K/min thereafter up to 298K. This procedure was repeated until the entire temperature range 850K to 300K was covered for all the alloy samples.

3. ANALYSIS OF DATA

For The technique of gamma ray attenuation method is based on the fundamental equation

$$I(T) = I_0(T) \exp[- \mu\, \varrho(T)\, l(T)] \quad (1)$$

where I_0 and I are the intensities of mono energetic gamma ray before and after passing through the sample material.

μ be the mass attenuation coefficient of the sample, ϱ be the density of the sample and l be the thickness of the sample along the beam direction.

It is clear from Eq.(1) that any change in the temperature of the solid is accompanied by change in it's density causing a change in the measured intensity. The density and thermal expansion of the alloys studied in the present work have been determined following the method suggested by Drotning [1].

From equation (1) temperature dependent density is expressed as

$\varrho(T) = (1 / \mu_l) \ln [I_0(T) / I(T)]$ this equation is used to calculate density at different temperatures

α_ϱ is the mean volumetric thermal expansion over a temperature interval $\Delta T = T2 - T1$ is.

$$\alpha_\varrho=(\varrho_2-\varrho_1)/\varrho_1\Delta T \quad (2)$$

α_l is the mean linear thermal expersion over a temperatue interval ΔT is

$$\alpha_l=(l_2-l_1)/l_1\Delta T \quad (3)$$

where $\varrho_1 = \varrho(T_1)$, $\varrho_2 = \varrho(T_2)$, $l_1 = l(T_1)$, $l_2 = l(T_2)$

By multiplying Eqs. (2) & (3), we obtain,

$$\Delta T^2 \alpha_l \alpha_\varrho = 1 / \varrho_1 l_1 (\varrho_2 - \varrho_1) (l_2 - l_1) = 1 / \varrho_1 l_1 (\varrho_2 l_2 - \varrho_2 l_1 - \varrho_1 l_2 + \varrho_1 l_1) = [(\varrho_2 l_2 / \varrho_1 l_1) - 1] - [(\varrho_2 - \varrho_1) / \varrho_1] - [(l_2 - l_1) / l_1] \quad (4)$$

Where z is defined as

$$z=(\varrho_2 l_2/\varrho_1 l_1)-1 \quad (5)$$

Now Eq 4 can be written as using Eqs. (2)and(3), as

$$\Delta T^2\alpha_l\alpha_\varrho=z-(\Delta T)\alpha_l-(\Delta T)\alpha_\varrho \quad (6)$$

The z value can be obtained from measured intensities at different temperatures from Eq. (1)

$I(T_1) = I_0(T_1)\exp[-\mu\, \varrho_1 l_1]$ leads

$$\varrho_1 l_1 = (1 / \mu) \ln [I_0(T_1) / I(T_1)] \quad (7)$$

$I(T_2)=I_0(T_2)\exp[-\mu\, \varrho_2 l_2]$ leads

$$\varrho_2 l_2 = (1 / \mu) \ln [I_0(T_2) / I(T_2)] \quad (8)$$

Dividing Eq.(7) by Eq.(6) leads to

$$z = (\varrho_2 l_2/\varrho_1 l_1) - 1 = \ln \{ [I_0(T_2) / I(T_2)] / \ln [I_0(T_1) / I(T_1)] \} - 1 \quad (9)$$

The relation between volumetric thermal expansion and linear thermal expansion for isotropic materials is

$$\alpha_\varrho=-3\alpha_l(1-2\alpha_l\Delta T) \quad (10)$$

Substitute Eq.(10) in Eq. (6).

$$- 3 \Delta T^2 \alpha_l 2(1 - 2\alpha_l \Delta T) = z - \Delta T \alpha_l + 3 \Delta T \alpha_l (1 - 2 \alpha_l\Delta T)$$

$$6 \Delta T^3 \alpha_l^3 - 3 \Delta T^2 \alpha_l^2 = z - \Delta T \alpha_l + 3 \Delta T\alpha_l - 6 \Delta T^2 \alpha_l^2$$

$$6 \Delta T^3 \alpha_l^3 + 3 \Delta T^2 \alpha_l^2 - 2\Delta T \alpha_l - z = 0$$

Take $\Delta T\alpha_l = \Delta l / l = x$ above equation may be written as

$$6x^3+3x^2-2x-z=0 \quad (11)$$

With this cubic equation x may be determined by substituting the value of z. which gives thermal expansion.

For linear attenuation at different temperatures the following expression is used

$$\mu_l(T) = \mu\, \varrho(T)$$

The intensities of gamma radiation with sample (I) and without sample (I_0) are recorded at every temperature. At room temperature T_1, thickness of the sample l1 is measured and using Eq. (1) μ

is determined. Further measurements of I and I_0 at different temperatures enable the determination of z by Eq. (4) and hence x can be found from the solution of Eq. (6). From the value of x, mean linear thermal expansion (αl) can be determined as a function of temperature. All the measurements are confined to solid phase only and the experimental data obtained in the present work have been fit to a linear equation of the form

$$\varrho(T)=a+bT \quad (12)$$

Since the measurements have been made in the limited temperature range the coefficient of volumetric thermal expansion (CVTE) of all alloys was calculated using the equation

$$\beta=1/\varrho)(d\varrho/dT) \quad (13)$$

where $(d\varrho/dT)$ is the first derivative of density with respect to the absolute temperature which is determined from Eq.(9).

4 RESULTS AND DISCUSSION

The results obtained for the temperature dependence of the linear attenuation coefficient for gamma beam of different energies, density and the coefficient of linear thermal expansion of 5088 are summarized in Table.2. The temperature dependence of the density and the temperature dependence of linear thermal expansion of 5088 alloy have been shown in Fig.2 and 3 respectively.

The density of 5088 alloy decreases from a value of 2650 kgm-3 at 300K to a value of
2363 kgm-3 at 850 K, a decrease of about 10.83%. The temperature dependence of density is a negative linear function of temperature. For 5088 alloy the temperature dependence of density is represented by linear equation

$$\rho(T)=(2804\pm5)+(-0.5136\pm0.0086)T \quad (14)$$

The coefficient of temperature dependence of density is -0.5136kgm-3 K-1 and the coefficient of volume thermal expansion is 52.18 x 10-5K-1. The thermal expansion of 5088 alloy increases linearly with temperature and the results on thermal expansion in the temperature range from 300K to 850K, have been analyzed and is represented by the linear equation

$$\Delta l/l = (0.1083\pm 0.0025)\Delta T+ (-33.77 \pm 1.54) \quad (15)$$

As can be seen from the Table.2 that the percentage of variation of the density over the temperature range from 300K to 850K is 10.83% for the alloy.

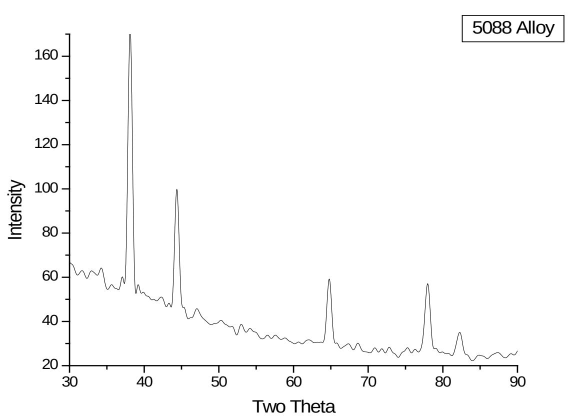

Fig.1. XRD pattern of 5088wrought aluminum alloy

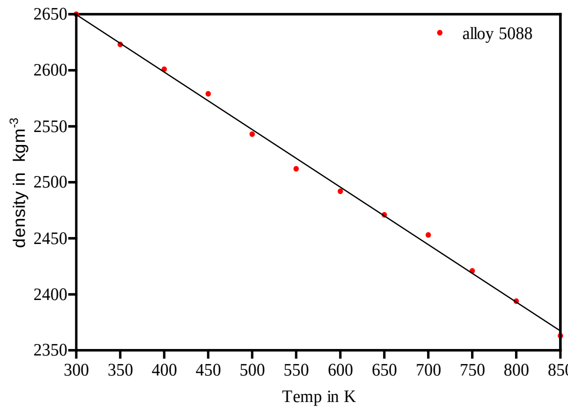

Fig.2.Density of 5088 aluminum alloy at different temperatures

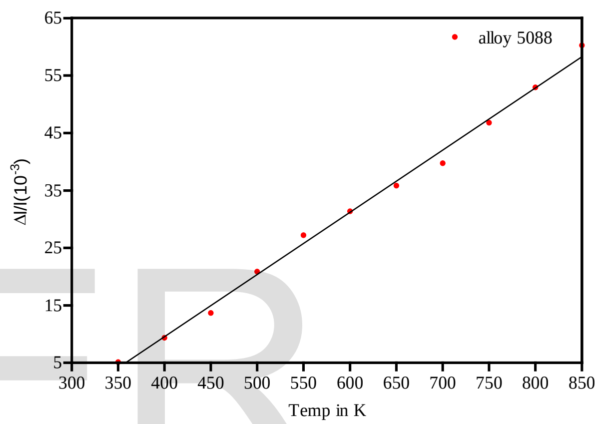

Fig.3.The thermal expansion 5088 aluminum alloy at different temperatures

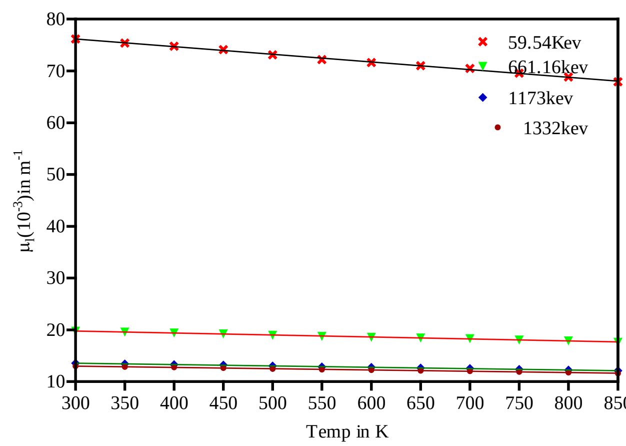

Fig.4.The linear attenuation coefficient of 5088 aluminum alloy at different temperatures and at different energies

The variation of linear attenuation coefficients with temperature and at different energies of gamma photons emitted by Am (59.54 KeV) Cs(661.16 KeV), Co (1173 KeV& 1332 KeV) energy can be seen from Fig.4. They have been analyzed and are represented by following linear equations respectively. It is found that linear attenuation coefficient is negative linear

Table.1. Chemical composition of 5088 wrought aluminum alloy

Alloy	Al	Cu	Mg	Zn	Mn	Fe	Zr	Si	Cr
5088	92.995	0.25	5.5	0.40	0.50	0.35	0.15	0.20	0.15

Table. 2. Linear attenuation coefficient, density and linear thermal expansion of 5088 alloy at different temperatures**.**

T K	**μ_l in (m^{-1})**				**ρ in (kgm^{-3})**	**Δl/l(10^{-3})**
	59.54kev	**661.16kev**	**1173kev**	**1332kev**		
300	76.16	19.79	13.57	13.01	2650	-
350	75.39	19.59	13.43	12.88	2623	5.13
400	74.75	19.43	13.32	12.77	2601	9.38
450	74.12	19.26	13.20	12.66	2579	13.69
500	73.09	18.99	13.02	12.49	2543	20.87
550	72.19	18.76	12.86	12.33	2512	27.21
600	71.62	18.61	12.76	12.24	2492	31.38
650	71.02	18.46	12.65	12.13	2471	35.84
700	70.50	18.32	12.56	12.04	2453	39.73
750	69.58	18.08	12.40	11.89	2421	46.80
800	68.80	17.88	12.26	11.75	2394	52.95
850	67.91	17.65	12.10	11.60	2363	60.25

function of temperature for the alloy.

$$\mu l(T)=(80.58 \pm 0.15)\ (-0.0148 \pm 0.0002)\ T \quad (16)$$
$$\mu l(T)= (20.94 \pm 0.04) + (-0.0038 \pm 0.00006)\ T \quad (17)$$
$$\mu l(T)= (14.35 \pm 0.03) + (-0.0026 \pm 0.00004)\ T \quad (18)$$
$$\mu l(T)= (13.77 \pm 0.02) + (-0.0025 \pm 0.00004)\ T \quad (19)$$

5 SUMMARY

The 5088 aluminum alloys has been prepared by ingot metallurgy route. The gamma ray attenuation measurements have been made using a gamma ray densitometer designed and fabricated in our laboratory based on the basic idea given by W.D Drotning[1]. The results on the variation of linear attenuation coefficient, density and linear thermal expansion with temperature of the alloy have been reported and these variations have been represented by linear equations. The results on this alloy have been reported for the first time using the gamma ray attenuation technique.

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