

Density of liquid Ti-6Al-4V

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Abstract. Ti-6Al-4V is due to its high strength-density ratio a commonly used alloy in aerospace industry applications. But liquid phase data are scarce as preventing contaminations of the reactive high temperature melt during the investigation process poses a challenge. The thermophysical quantity density is of special interest since it is necessary input parameter in modern numerical casting and solidification simulations. Liquid phase density of Ti-6Al-4V as function of temperature was determined employing a fast resistive pulse-heating technique based on the approach to avoid contaminations of the specimen by extremely reducing the experimental duration of the investigation process. Temperature dependent density of liquid Ti-6Al-4V was determined in a temperature range between 2050 K and 2590 K and is presented.

1 Introduction

Titanium Ti-6Al-4V is also known as Grade 5, TA6V or Ti64. This α - β titanium-based alloy is the most commonly of all titanium alloys. Phase stabilizers are aluminum and vanadium. Al reduces density, stabilizes and strengthens α while vanadium provides a greater amount of the more ductile β phase for hot-working. Ti-6Al-4V exhibits strength-toughness combinations between those of steel and aluminum alloys, has the same stiffness than commercially pure titanium but is significantly stronger. [1]. It is widely used in industrial applications such as aeronautic and aerospace due to its good mechanical properties at high temperatures. Within an earlier publication [2] experiments on two different resistive pulse-heating devices (CEA Valduc and TU Graz) have been carried out in order to study thermophysical properties such as electrical resistivity, volume expansion, heat of fusion, heat capacity, normal spectral emissivity, thermal diffusivity, and thermal conductivity of both solid and liquid Ti-6Al-4V. At this time the fast CCD-camera system at TU Graz was not operable, therefore volume expansion was only measured at CEA Valduc. The graph density versus temperature could not be given within publication [2]. As already mentioned in the abstract there is a need of density data of Ti-6Al-4V in the liquid phase. Therefore, within this short note we want to add recently at TU Graz new measured density data for the solid and the liquid phase of Ti-6Al-4V.

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2 Experimental

The specimens - Ti-6Al-4V wire samples of about 0.5 mm diameter and 55 mm length were purchased from Fa. GoodFellow, No: TI015260/1, typical analysis in ppm: Al 6%, V 4%, Fe 300, C 220, H 100, N 100, O 650, rest Ti. The initial diameter of the specimen is measured by a high accuracy laser micrometer KEYENCE LS - 7001 before the experiment. The wire-samples were resistively self-heated as part of an electrical discharge circuit by a current of about 5000 A. Heating rates of about 10^8 K/s reduced the experimental duration to below 50 μ s. Within this time the specimen material was heated from room temperature up to the end of the liquid phase and concurrently monitored by an adapted CCD camera system working with a frame rate of 200.000 images per second.

The recorded images describing the thermal expansion of the specimen were evaluated to calculate the density of the specimen material. Temperature was determined with a pyrometer operating at a wavelength of 1500 nm by measuring the surface radiance emitted from the sample surface. For temperature determination as reference point to calibrate the pyrometer signals a liquidus temperature of $T_{\text{liq}} = 1923$ K was adopted from [2]. An argon atmosphere with 1.5 bar above ambient pressure was maintained for all measurements. More information regarding the pulse-heating system please find in [3].

2.1. Thermal radial expanding

Thermal expanding of the specimen during pulse-heating is monitored by shadowgraph imaging. The cylindrical formed liquid specimen column is backlit by a photoflash and the silhouette is pictured and recorded. To monitor the radial thermal expansion of the specimen an adapted CCD camera setting, capable to record several images during the short experimental duration of less than 50 μ s, is necessary. This requires a fast successive image recording within time-intervals of just a few μ s, which is accomplished by modifying the CCD array controlling. For more information on the operation of the fast CCD array see [4, 5].

Prior each pulse-heating experiment an image sequence at room temperature with the before measured initial diameter is recorded to be able to scale the sequence recorded during heating. Since this setting performs a fast monitoring of a segment of the specimen wire, only the radial expansion of the wire is determined. Experimental series in the past [5] indicate that in the setup at TU Graz no longitudinal expansion of the vertically clamped wire occurs, provided that the heating rate used for the experiment is high enough.

Thus density as function of temperature $D(T)$ can be calculated from density at room temperature only by considering thermal radial expansion of the wire sample.

3 Results and Discussion

3.1. Density as a function of temperature

The material's pronounced mechanical strength eased the handling regarding specimen preparation and assembling of the specimen in the pulse-heating setting and led to a straightforward operating when performing the pulse-heating experiments. The stability of the vertical aligned liquid metal column could be facilitated without difficulties. Image series were recorded with relatively long exposure times (633 ns) leading to images of pronounced contrast. The recorded image series were depicted as intensity profiles and evaluated according the procedure described in [4]. Thermal radial expansion was obtained

by relating the image sequence recorded during the pulse-heating to an image sequence recorded prior starting the heating process. Density was calculated and depicted as function of temperature, presented in Figure 1.

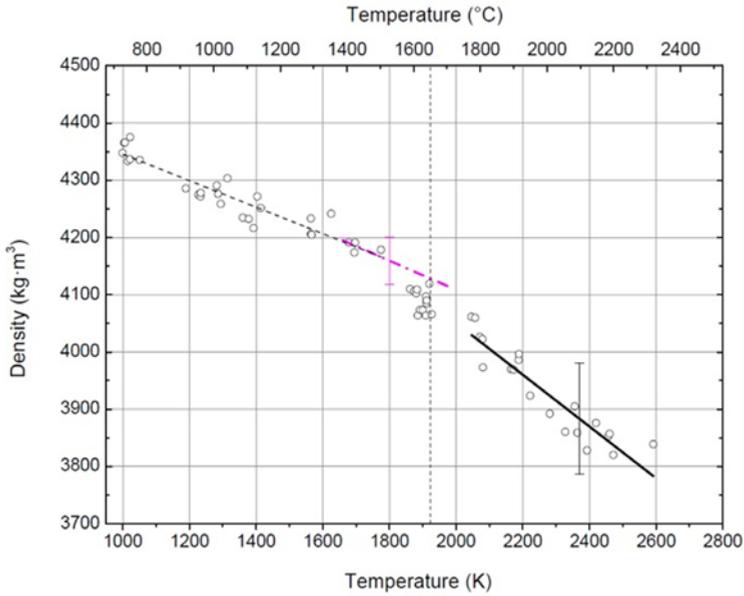


Fig. 1. Density of Ti-6Al-4V as function of temperature. Open circles with dedicated line in black: Results for density with linear least square fit obtained by pulse-heating. Pink dash-dotted line literature data for comparison [6]. Vertical dashed line: liquidus temperature of $T_{liq} = 1923$ K.

3.2 Least squares fit for the liquid phase

The linear least square fit for density D versus temperature T was obtained to be:

$$(D) = 4955 - 0.452 \cdot T \quad (2046 \text{ K} < T < 2592 \text{ K}) \quad (1)$$

For comparison literature data of Li et al. [6] are plotted as dash-dotted line in the liquid phase. There is a good agreement of the pulse-heating results with the data of Li. We could not find any additional density data of liquid Ti-6Al-4V for comparison.

3.3 Numerical density values in the liquid phase

Density was calculated from the ratio of the determined specimen diameters:

$$D(T) = D_{RT} \left(\frac{d(T)}{d_{RT}} \right)^{-2} \quad (2)$$

With d_{RT} ; $d(T)$... diameter of the specimen at room temperature; diameter as function of temperature and $\frac{d}{d_{RT}}$ the relative radial expansion of the wire; D_{RT} ; $D(T)$... density at room temperature; density as function of temperature (for data evaluation a density at room temperature of $4420 \text{ kg}\cdot\text{m}^{-3}$ was adopted [2]).

Table 1. Tabulated density results of liquid Ti-6Al-4V determined with the pulse-heating setting

Temperature (K)	$\left(\frac{d(T)}{d_{RT}}\right)^2$	Temperature (K)	D (kg·m ⁻³)
2046	1,088	2046	4030
2057	1,089	2050	4028
2072	1,098	2100	4006
2079	1,099	2150	3983
2081	1,113	2200	3961
2165	1,113	2250	3938
2173	1,114	2300	3915
2188	1,109	2350	3893
2189	1,106	2400	3870
2222	1,127	2450	3848
2282	1,136	2500	3825
2328	1,145	2550	2802
2393	1,155	2592	3783
2356	1,132		
2364	1,145		
2420	1,141		
2457	1,147		
2461	1,146		
2472	1,157		
2592	1,152		

4 Uncertainties

The uncertainty of density is dominated by the uncertainty of the diameter determination and results to an expanded uncertainty of 3%. Within Figure 1 an uncertainty bar is indicated for the liquid phase. According to GUM [7], this uncertainty is an expanded relative uncertainty with a coverage factor of $k = 2$. Literature data of Li et al. [6] were reported with an uncertainty of 1%.

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