PERGAMON

Available online at www.sciencedirect.com
ScienceDirect

Acta Astronautica 64 (2009) 256–263

ACTA ASTRONAUTICA
www.elsevier.com/locate/actaastro

Analysis of the data obtained from liquid metal diffusion experiments conducted on the MIR space station

M. Shirkhanzadeh*

Department of Mechanical and Materials Engineering, Queen's University, Nicol Hall, 60 Union Street, Kingston, Ontario, Canada K7L 3N6

Received 28 February 2008; received in revised form 26 May 2008; accepted 17 June 2008
Available online 8 August 2008

Abstract

Recent liquid metal diffusion experiments onboard the MIR space station have led to the proposal that suppression of g-jitter may change the temperature dependence of the diffusion coefficient from a square law to a linear dependence. It has also been claimed that the diffusion coefficients obtained under isolation mode are significantly lower than their non-isolated counterparts. A thorough reanalysis of the original data leads to three principal findings: (i) a linear temperature-dependence does not emerge when all available diffusion data obtained on MIR in the isolation mode are considered in the analysis. This finding suggests that the $D \propto T$ relation that was shown previously for a number of dilute alloy systems may simply arise because very limited numbers of data were considered for analysis for each system; (ii) the measured diffusion coefficients obtained with g-jitter suppressed are not reproduced in two replicated experiments; and (iii) the diffusion coefficient values are not consistently below the corresponding non-isolated microgravity data. These facts suggest there is an uncontrolled source of experiment variation that is much stronger than the effect of g-jitter on the experiments. On the basis of these new findings, it is proposed that the results from the liquid metal diffusion experiments conducted on MIR do not support the conclusions drawn.

Keywords: Diffusion in metals; Microgravity; Microgravity vibration isolation mount (MIM); Thermotransport; MIR space station; g-Jitter

1. Introduction

Recent liquid metal diffusion experiments onboard the MIR space station have led to the proposal that suppression of g-jitter may change the temperature dependence of the diffusion coefficient from a square law to a linear dependence [1–6]. It has also been suggested that the diffusion coefficients measured in the isolated mode are significantly lower than Frohberg's results [7] and those obtained in the non-isolated mode on MIR [1–4] and on the space shuttle flights (Space Shuttles Endeavour Mission STS-47 and the Space Shuttle Columbia Mission STS-52) [8,9]. The microgravity experiments on the MIR space station were conducted using the Canadian Microgravity Vibration Isolation Mount (MIM) developed by the Canadian Space Agency (CSA). The MIM was intended to provide the opportunity for: (a) exposing the diffusion couples to the g-jitter, (b) isolating the diffusion couples from g-jitter and (c) subjecting them to a forced vibration superimposed on the isolating state. Unfortunately, it appears that the diffusion data obtained with MIM operating in various modes are unreliable because of serious errors in measuring the processing time and temperatures, and do not support the main general conclusions drawn. What makes the diffusion coefficients

* Tel.: +1 613 5332748.
E-mail address: shirkhan@queensu.ca.

0094-5765/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2008.06.025

reported even more doubtful is the magnitude of the errors that occurred during the post-flight analysis of the solute concentration profiles. As pointed out by Garandet et al. [10], benchmark experiments should be thoroughly analyzed in terms of the sources of errors in order to allow an unambiguous conclusion to be reached. This is particularly true in the case of microgravity experiments performed on the MIR space station since it seems unlikely that other researchers will find the opportunity to independently replicate these experiments in the near future. At the time of writing, the results of the microgravity experiments conducted on MIR have been reported in numerous journal papers and conference proceedings by Smith [2,5], Smith et al. [1,6], Herring et al. [3], and Tryggvason et al. [4]. The conclusions drawn based on these experiments have called all other liquid diffusion experiments [11–14] into question but the sources of errors in the MIR experiments have not been adequately characterized. Because of the enormous interest in the subject, it is important that any uncharacterized sources of experimental variation or reasonable alternative explanations for the patterns in the experimental data are brought to light. That is what we have endeavoured to present in this analysis.

The analysis of the original microgravity data obtained on the MIR space station is now presented. One finds that within a set of data obtained under isolation mode, a $D \propto T$ relationship does not emerge when all available diffusion data obtained with g-jitter suppressed are considered in the analysis. Moreover, the measured diffusion coefficients obtained under isolation mode are not reproduced in two replicated experiments and are not consistently below the corresponding non-isolated microgravity data.

2. Sources of data

Data for the analysis was acquired from various sources. These included published journal papers [1–4], conference papers [5,6], thesis [15], and relevant reports including a report entitled "Results of liquid metal diffusion Experiments—Final Report" [16] that has been cited previously in a number of published journal papers by Smith et al. [17,18]. This report is cited here to draw attention to serious problems that were encountered during the space experiments on the MIR space station. This is deemed to be important because the conclusions reached in the published papers by Smith et al. appear to be questionable when one actually considers the scale of the problems reported in [16]. Critical, in many cases, was the availability of the tables in the cited thesis and reports that contained the original data where it was possible to extract the precise, numerical data underlying the published figures. The numerical values of the diffusion coefficients in particular were considered to be important for the analysis of the temperature dependence of the diffusion coefficients for each dilute alloy system. These data are referred to in the discussion section as "original plotting data".

3. Results and discussions

3.1. Variation of the diffusion coefficients with temperature in microgravity with g-jitter suppressed

The original proposal that suppression of g-jitter in microgravity may change the temperature dependence of the diffusion coefficient from a square law to a linear dependence was based on the experiments conducted on MIR for a number of dilute binary alloys including Pb–(Au, Ag, Sb), Sb–(Ga, In), Bi–(Ag, Au, Sb), Al–(Fe, Ni, Si), and In–Sb [1–4]. One reason for the lack of confidence in the proposed $D \propto T$ relationship is the relative paucity of the diffusion data that were considered for each system and the fact that in all cases the data appear to fit the linear relationship very well despite the serious problems that were encountered during experiments. Table 1 shows the number of data points that were used to establish the linear dependence for each binary alloy system. For example, for the lead–1 wt% silver diffusion couples, only five data points were considered to demonstrate the $D \propto T$ relationship [1–4]. In Fig. 1, the original plotting data points for the lead–silver system (open circles) are presented. It is seen that the linearity that can be claimed on the basis of these data points appears to be remarkable. The question that was asked was whether the reported $D \propto T$ relation could be explained as arising from the fact that only few data points were considered for the analysis. It was tempting to find out if an alternative relationship could be established when all available diffusion data for the lead–silver system obtained under isolation mode were included in the analysis. It was possible to identify at least two additional data points for the lead–silver system ($D = 2.46 \times 10^{-9}\,m^2/s$ at 400 °C and $D = 3.89 \times 10^{-9}\,m^2/s$ at 600 °C) (black circles) that were obtained under microgravity in the MIR space station with g-jitter suppressed and that were reported earlier by Smith in [5,16]. But in order to begin the analysis, the original plotting data were given the benefit of the doubt, and it was reluctantly assumed that all measured diffusion data reported in the past were valid and sufficiently accurate. It is seen in Fig. 1 that the two additional data points clearly do not fit the expected linear trend but they cannot be discarded since