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Article *in* The Review of scientific instruments · June 2008

DOI: 10.1063/1.2930813 · Source: IEEE Xplore

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(Received 14 December 2007; accepted 28 April 2008; published online 28 May 2008)

GaInSn, a eutectic alloy, has been successfully used in the Magneto-Thermofluid Research Laboratory at the University of California-Los Angeles and at the Princeton Plasma Physics Laboratory for the past six years. This paper describes the handling and safety of GaInSn based on the experience gained in these institutions, augmented by observations from other researchers in the liquid metal experimental community. GaInSn is an alloy with benign properties and shows considerable potential in liquid metal experimental research and cooling applications. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2930813]

I. INTRODUCTION

GaInSn is a low-temperature, liquid metal alloy (67% Ga, 20.5% In, and 12.5% Sn by volume, though compositions vary). Some GaInSn physical parameters are compared to those of other liquid metals in Table I. Unlike many liquid metals, GaInSn is chemically compatible with a wide variety of metals, plastics, rubbers, and glasses at low temperatures. GaInSn also has more attractive cooling and handling properties than those of Hg, Pb, and Pb alloys. GaInSn and its variant alloys have potential uses in electrical engineering,[1,2] computer engineering,[3,4] energy research engineering,[5–7] medicine,[8,9] and other applications.[10,11]

Researchers at the University of California-Los Angeles (UCLA) and Princeton Plasma Physics Laboratory (PPPL) have been conducting various magnetohydrodynamic (MHD) experiments with relevance to basic physics and fusion reactor cooling since 2002. They have collected data to benchmark computational models of liquid metal free surface, closed channel, and rotating shear flows. The experimental and modeling work are described elsewhere.[5,6] Some of the experiences with GaInSn alloy handling are described here.

One of the main drawbacks to Ga and its alloys is price, which can vary widely with world market demand, and is a major constraint in the design of the experiments. The Magneto-Thermofluid Research (MTOR) flow loop volume is ~15 l, flowing at a maximum of 0.5 l/s at pressures below 0.3 MPa, with a working temperature of 15–100 °C. The MTOR flow loop components were constructed of stainless steel and copper to allow for high-temperature (100 °C) loop operations, although plastic tubing may be used for low-temperature operation. Standard flange and pipe thread connections were used. The free surface test sections were constructed of acrylic and lexan to allow flow visualization. The flow loop pump is an air-cooled, electromagnetic induction pump; however, pump waste heat does increase the GaInSn temperature and a water-cooled heat exchanger is often used. An electromagnetic flowmeter is also used in the MTOR loop. GaInSn has higher density than that of Na, NaK, or Li and consequently has smaller Hartmann and Stewart numbers. It generally has better MHD parameters than those of mercury or PbBi alloys. The loop has operated for over six years with no serious leaks and no reports of pipe erosion.

The Magnetorotational Instability Experiment (MRI) at PPPL is a magnetized Taylor–Couette experiment designed to observe instability responsible for the accretion rate in astrophysical disks.[12] The experiment is filled with about 32 l of GaInSn by pneumatic transfer using argon gas. Materials used in plumbing for conveying the liquid metal to both the experimental vessel include polyvinyl chloride (PVC) pipe, and nylon, and Tygon PVC tubing. Threaded fittings are sealed with room-temperature vulcanizing sealant.

II. GaInSn HANDLING IN THE LABORATORY

System precleaning is necessary to remove residues and construction debris before charging a system because these impurities can lead to orifice plugging, galling of bearings, metal embrittlement, and plugging of instrument lines.[13] The MTOR pipework was thoroughly cleaned initially with wire brushes and washed with alcohol and acetone to remove any leftover grease or debris before initial charging with GaInSn.

When GaInSn is exposed to air, it slowly oxidizes to form Ga_2O_3 contamination. At MTOR, the flow loop is normally run under an argon cover gas. However, the flow loop is routinely opened to air for short periods of time when making modifications or repairs. PPPL researchers first purge their loop and experimental vessels with high purity argon gas (99.999%) and then circulate the gas through a purifying filter with a strong oxidizer to additionally reduce oxygen levels and further slow down oxidation of the GaInSn.

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TABLE I. Comparison of physical properties of GaInSn with those of other liquid metals (Refs. 2, 5, 15, 21, and 22).

Composition	$Ga^{67}In^{20.5}Sn^{12.5}$	Ga	$Ga^{75.5}In^{24.5}$	$Ga^{61}In^{25}Sn^{13}Zn^{1}$	Li	Hg	Na
Melting Point (°C)	10.5	29.8	15.5	7.6	180.5	−38.8	97.8
Boiling Point (°C)	>1300	2204	2000	>900	1342	357	883
Density (kg/m^3)	6360	6080	6280	6500	534	1353	927
Conductivity ($\Omega^{-1}\,m^{-1}$)	3.1×10^6	3.7×10^6	3.4×10^6	2.8×10^6	2.8×10^6	1.0×10^6	1.0×10^7
Viscosity (m^2/s)	2.98×10^{-7}[a]	3.24×10^{-7}	2.7×10^{-7}	7.11×10^{-8}	6.4×10^{-7}	13.5×10^{-7}	7.4×10^{-7}
Surface tension (N/m)	0.533[b]	0.7	0.624	0.5	0.35	0.5	0.2
Sound speed (m/s)	2730	2860	2740	~2700	4500	1450	2550
Water compatibility	Insoluble	Insoluble	Insoluble	Insoluble	Reactive	Soluble	Reactive

[a]UCLA measurements using a glass viscometer tube are typically closer to $4.0\times10^{-7}\ m^2/s$.
[b]PPPL measurements indicate that oxides can significantly reduce surface tension.

The GaInSn alloy itself can be cleaned periodically to remove oxide buildup. An ethanol and hydrochloric acid solution is mixed consisting of two parts acid and one part ethanol. Just enough of this solution is used to cover the bottom of a plastic cleaning tank. The GaInSn is transferred with pressurized argon from its storage vessel, through plastic tubing, and into the plastic cleaning tank. During this transfer, the GaInSn passes through a stainless steel wire mesh that has been prewetted to help allow the GaInSn to pass through it more easily. The wire mesh is used to filter any large debris in the liquid including any larger precipitate clumps. The finest mesh used at MTOR is typically a 100×100 mesh with 0.0055 $in.^2$ openings. The GaInSn remains in the cleaning tank in contact with the acid solution until clean (it can be stirred occasionally), and then it is drawn back into the storage tank by vacuum. The clean GaInSn can be heated to above 100 °C to drive out any small bubbles of cleaning solution. Heating the GaInSn to ~40 °C while in contact with the acid solution significantly accelerates the cleaning process. Appropriate ventilation is necessary to safely exhaust the acid vapors and hydrogen reaction bubbles. The alloy may be depleted in Ga after many cleanings, and so a periodic chemical analysis is performed to determine if Ga needs to be replenished.

Most liquid metals do not easily "wet" new surfaces.[14,15] A primary reason is surface oxides on the metal. Selecting metals with low surface roughness, thorough prior cleaning, and raising the system to elevated temperatures can speed up the wetting process. Ga and GaInSn easily wet glass surfaces at room temperature but in practice do not readily wet metal surfaces.[16] However, since GaInSn is liquid at room temperature, various acidic based cleaning fluxes can be used in contact with liquid Ga and the metal to clean and wet the metal surface. The HCl-ethanol solution is sometimes used for this purpose as well as commercial fluxes such as those available from the Indium Corporation of America. Slightly heating the metal surface often helps accelerate the process. GaInSn was found to more readily wet the stainless steel cylinders used in the apparatus for the MRI experiment at PPPL after they were scrubbed with diluted phosphoric acid (5% concentration), rinsed with water followed by an alcohol rinse, and then dried with a heat gun. Preheating the equipment to be wetted at above 300 °C for 1 h or longer will also promote fast wetting.[13] Rubbing the GaInSn into metal surfaces has also been an effective treatment for improving wetting at room temperature.

Once a surface has been successfully wetted, it typically will wet easily in subsequent operations. For the MTOR inclined channel, the GaInSn initially formed rivulets instead of wetting the entire surface of the back wall made of acrylic. A smooth, nonoxidized metallic coating was used for some tests so that the alloy would adequately wet the flow plane. Thin nickel coatings have also been used as a barrier between Ga alloys and incompatible metals.[11] Other metals, such as tungsten, niobium, and molybdenum, have also had success as thin coatings.

GaInSn is not chemically reactive like liquid Ga and is compatible with most metals and plastics, which makes handling easier. Notable exceptions of incompatible metals include aluminum, which is readily attacked at room temperature, and copper, which is attacked over long times at elevated (>100 °C) temperatures.[17] The Ga alloy used in dental material is cast in polytetrafluoroethylene (PTFE) molds and displays a tendency to cling to stainless steel tools, so plastic coated tools have been used with moderate success when manipulating the alloy. Some dentists have stated that the Ga alloy will cling to the PTFE tools as well as metal tools.[8] Ga alloys have been used successfully with PVC tubing whose recommended upper service temperature is about 50 °C.

Smither[10] suggested that a Ga spill could be cleaned up by pouring cold water of less than 29 °C on the metal pool. The cold water will freeze the Ga and allow easy mechanical retrieval with spatulas or other tools, leaving no residue. Smither's approach can also be used for GaInSn, which freezes at 10 °C. Pipettes or squeeze bottles can be used to retrieve liquid Ga droplets. Soap and water or a multipurpose household spray cleanser (e.g., Fantastik, Ajax, Formula 409) will remove residual smears of GaInSn and its oxides. Ethanol can also be used to clean surfaces.

Rubber gloves are recommended during cleanup, though there is little evidence of skin absorption. Insulating the hands provides safety from stray electrical currents and also keeps the frozen metal from melting. Gloves will also keep skin oils from the GaInSn, easing purification and reclamation of the spilled mass. In general, there is no safety concern with elemental vapor, but there is a small concern that oxide could be released from the spill. Ga_2O_3 melts at over 1000 °C, so it will not evaporate from the spill, but small quantities of fine particulate could be mobilized and inhaled during cleanup. Oxides also can be tracked throughout the laboratory if not cleaned thoroughly.

III. GaInSn SAFETY IN THE LABORATORY

There are several safety issues to consider with any flow loop: personnel exposure to toxic or reactive chemicals, high pressure or temperature, and electrical hazards. Toxic substances are perhaps the highest safety concern in most laboratories. Fortunately, GaInSn is a chemically benign metal alloy.[8] Its components all have very low vapor pressures at elevated temperatures,[18] on the order of 10^{-9}atm at 538 °C and virtually zero at room temperature. Therefore, GaInSn spills do not evolve respirable metal vapors.

The HSC computer code was used to predict possible room-temperature GaInSn reactions with ambient air.[19] The results predicted that some oxides would form. The reaction rate at 20 °C is not expected to produce significant quantities of Ga_2O_3, and very little In_2O_3 or SnO_2 will be produced. Only trace amounts of GaN would be produced. The HSC code did not predict any reactions with polyethylene or PVC; this lack of reaction has also been seen in practice. Burton and Burton,[1,2] as well as MTOR experience, indicate, that Ga alloy reacts with copper, leaving the copper surface pitted. Narh *et al.*[20] tested a variety of materials for chemical reactivity with Ga, including polyethylene, polypropylene, polymethyl methacrylate, and polystyrene. All had negative results after several days of exposure with temperatures held at the plastic softening points.

Generally, leaks at pressures of greater than 4.4 MPa are needed to pose personnel safety issues of skin injection or incision. Expelling small failed parts as missiles at injury thresholds of 40 J or more kinetic energy from a flow loop usually requires ~0.8 MPa or higher pressure. Safety precautions for the eyes should always be taken when working near any pressurized vessel or rotating equipment to protect the eyes from pressure energy, pressure-driven or other kinetic missiles, and foreign material intrusion.[19]

Since GaInSn is an electrical conductor, spills may provide a conductive path to energized equipment or any electrical grounds. As with other liquid metals, providing catch pans or trays is a prudent measure to capture a spill for maximum retrieval of the liquid.[13] Catch pans or trays will keep the alloy from electrical contact and from copper wiring.

To date, there have been no operational issues or safety concerns with either the MTOR at UCLA or the MRI experiment at PPPL. Other flow loops operating with GaInSn or Ga have also been reported in the literature. Many have operated for thousands of hours and have not reported any system leaks or long-term technical outages.[19] Perhaps the high surface tension of Ga and its eutectics impedes leakage flow from small cracks that would easily flow water or alkali metals. Generally, liquid metal heat transfer loops operate at high temperatures but modest pressures and flow rates because metal coolants conduct heat well. For modest temperature and flow rate GaInSn flow loops, corrosion, erosion, and other degradations appear to have had minimal impact on system operation.

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