Journal of Informatics and Mathematical Sciences
Vol. 10, No. 3, pp. 505–513, 2018
ISSN 0975-5748 (online); 0974-875X (print)
Published by RGN Publications
http://www.rgnpublications.com

DOI: 10.26713/jims.v10i3.1206

Research Article

Tungsten Inert Gas Welding of Al-Mg Alloys With and Without Scandium Addition

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Abstract. In this study, a comparative evaluation of Tungsten Inert Gas (TIG) welding on two different alloys, one with the addition of rare earth metal Scandium and the other alloy without the addition of scandium was undertaken. The Innovative Recycled Cast Al-Mg-Sc alloy has been prepared using Vacuum Induction Melting Casting Furnace, which is available in India and the TIG welding process was applied over it. Microstructural examination revealed that both welds contain shrinkage voids and porosity in the weld zone. Brittle dendrites formed in the wrought alloy without scandium reduces the yield stress to a very low level. Very fine grains formed in the cast Al-Mg-Sc alloy TIG welded joint and the nature of non-dendritic grains formed are responsible for the enhancement of yield stress. The weld tensile properties of cast scandium added aluminum-magnesium alloy plates were found out to be better than the wrought alloy plate. These results clearly show that Cast Al-Mg-Sc alloy compared to Wrought AA5083-H321 alloy is good for industrial applications.

Keywords. Tungsten inert gas welding; AA5083-H321 alloy; Scandium; Tensile properties

MSC. 76N15

Received: November 1, 2017 **Accepted:** December 29, 2017

This article was submitted to "National Conference on Fluid Mechanics (NCFM 2017)" organized by SSN College of Engineering (Anna University), Chennai, India during October 27-28, 2017.

1. Introduction

The 5xxx series aluminum alloys are widely used in marine industry, where lightweight, corrosion resistance, and high fatigue strength are the desired properties. In 5000 series aluminum alloys, the chief alloying element is magnesium [1], one of the most effective and widely used additives for aluminum. Application of these alloys are also found in heavy industries used for cranes, marine fabrications, tank trailers, truck trailers and beds, rail road gondolas, concrete mixtures, pressure and cryogenic vessels.

Presently, TIG welding process is one of the most well established processes which can not only weld all metals of industrial use but also produces the best quality welds amongst the arc welding processes [2].

Extensive research has been conducted on Al-Mg alloys containing scandium [3]. The addition of scandium in Al-Mg alloy system is intended to take advantage of the unique precipitation hardening characteristics of scandium in aluminum. Sc combines with Al to form a stable Ll_2 phase Al_3Sc, precipitates coherently in a spherical configuration. Despite the relatively low solubility of Sc and, hence, limited volume fraction of the Al_3Sc phase, it produces a significant strength increment [4]. In fact, Al_3Sc is the most potent strengthener, on an equal atomic fraction basis, known in Al-base systems. The Al_3Sc precipitate is also extremely effective in stabilizing substructure, thus allowing the use of strain-hardening and stabilization treatments to push the strength of Al-Mg-Sc alloys to the levels achieved by traditional precipitation-hardening systems. By adding scandium to the alloy system Al-Mg, Al-Mg-Li, and Al-Cu-Li, increases in strength amounting to 20-50 MPa per 0.1 wt.-% Sc can be achieved [5]. This strength-augmenting effect of scandium in the aluminum alloys was pointed out for the first time in 1971 in a U.S. patent [6].

The Wrought Al-Mg-Sc Alloy with chemical composition Al-4.5Mg-0.26Sc was TIG and Friction Stir welded and tested for its relative performances [7]. Similar studies were contacted using Al-5.8Mg-0.3Sc alloy plates and their characteristics were analyzed [8, 9]. The Fatigue performance of Friction Stir Welded Al-6.0Mg-0.35Mn-0.2Sc-0.08Zr (in wt pct) has been studied recently [10]. No TIG welding work was done in Cast Al-Mg-Sc alloy till today.

In this work, a study of the mechanical properties of TIG bead-on-plate welds of 5mm thickness was carried out on both AA5083-H321 and Cast Al-Mg-Sc containing around 0.30% of Scandium alloys. Tensile tests, Micro hardness tests and Chemical compositional measurements of both weld joints were performed in order to determine the influence of welding process on the microstructure and the mechanical properties.

2. Experimental Procedures

Bead-on-plate welds on the Wrought AA5083-H321 and Cast Al-Mg-Sc alloy 5 mm thick plates were made autogenously using alternating current Tungsten Inert Gas Welding machine with a standard 2% Thoriated tungsten electrode. The electrode tip configuration was a blunt point with a 90° included angle. The diameter of the electrode is 2 mm. The argon shielding gas flow rate was 40 l/min. The welding speed was kept at 150 mm/min. Miller Syncrowave 350 power source has been used to make the welds.

The starting materials used in the preparation of the experimental cast Al-Mg-Sc alloy were AA 5083-H321 alloy and Al-2wt% Sc master alloy. Appropriate amounts of the staring materials were melted in a vacuum induction melted furnace to 780°C to produce an Al-Mg-Sc alloy with a nominal composition similar to AA 5083 with 0.29 wt% Sc addition.

After welding, samples were cut across the weld for metallographic analysis and tensile tests using EDM machining process. The configuration and size of the transverse tensile specimens were prepared as per ASTM-E8 standard. Prior to the tensile tests the Vickers hardness profiles across the weld were measured under the load of 1 Kgf for 15s along the centerlines of the cross-section of the tensile specimens using an automatic micro-hardness tester [11].

The cross-sections of the metallographic specimens were polished with alumina suspension, etched with Keller's reagent (150 ml water, 3 ml nitric acid, 6 ml hydrochloric acid and 6 ml hydrofluoric acid) at 0° C for about 10 seconds, and observed by optical microscopy. Microstructural characterization of the weld was performed using conventional metallographic techniques and Scanning Electron Microscope [11].

The chemical compositional analysis was done using a Vacuum Emission Optical Spark Spectrometer (model: Spectro Lab: 750V, Germany) on the base metal and the bead of the welds. The compositional analysis was done on the weld beads to assess the quantity of losses due to evaporation in the alloying elements. The chemical compositions were found out as an average of readings taken at two locations [11].

3. Results and Discussions

3.1 Optical Microstructure of the Base Metal AA5083-H321

The optical micrograph of the base metal is shown in Figure 1. This wrought alloy contains precipitates like Al_3Mg_2 and dispersiods like Al_6(Fe,Mn). The microstructure of the base metal of the cast Al-Mg-Sc alloy is shown in Figure 2. This cast alloy contains precipitates like Al_3Mg_2 and dispersiods like Al_6(Fe,Mn), Mg_2Si and Al_3Sc. The strengthening precipitates are shown in Figure 3 and Figure 4.

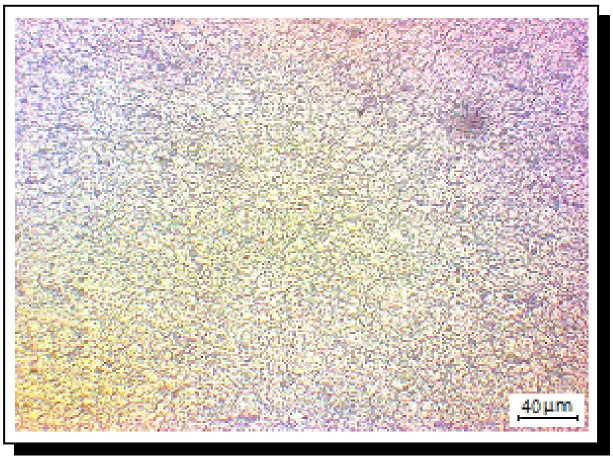

Figure 1. AA5083-H321 Base Metal

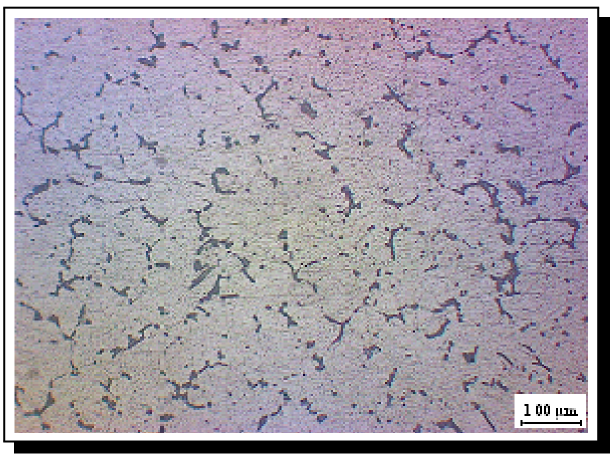

Figure 2. Cast Al-Mg-Sc Base Metal

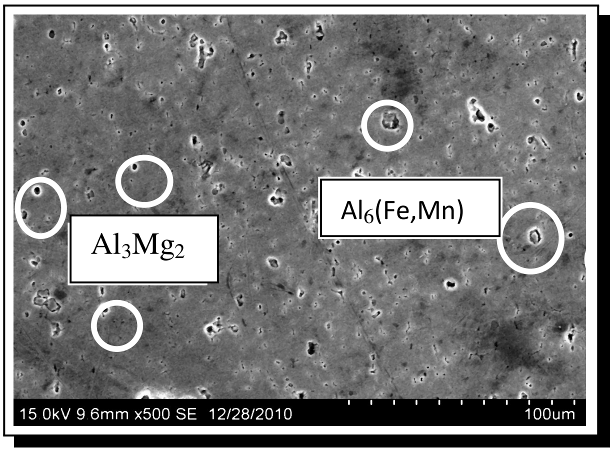

Figure 3. AA5083-H321 SEM Microstructure [11]

Figure 4. Cast Al-Mg-Sc TEM Microstructure [12]

3.2 Optical microstructure of TIG welded Wrought AA5083-H321 alloy

The weld microstructure of the TIG welded joint at the top is shown in Figure 5. The TIG weld microstructure is containing fine grains compared to the base metal microstructure of AA5083-H321 aluminum alloy shown in Figure 1. The spherical shaped pores of diameter 80 micrometer have been formed at the top of the weld bead and shown in Figure 5. Similar formation of micropores were observed and reported in the literature during MIG, TIG and LB welding processes [13–15]. The Microstructure of TIG weld at the middle is shown in Figure 6.

Figure 5. AA5083 TIG weld (Top)

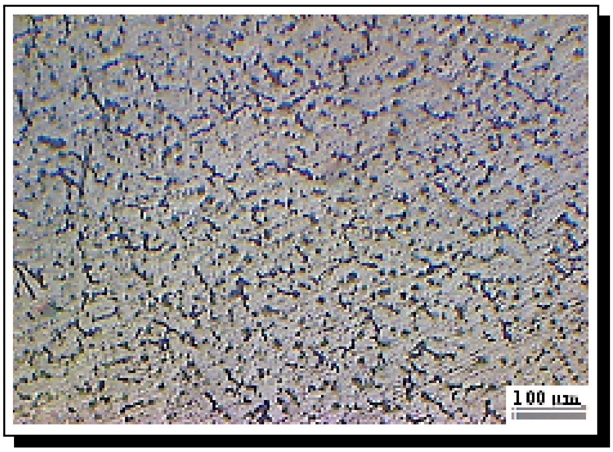

Figure 6. AA5083 TIG weld (Middle)

3.3 Optical Microstructure of TIG Welding of Cast Al-Mg-Sc Alloy

The spherical shaped pores of size less than 50 μm have been formed at the weld bead and shown in Figure 7. The weld microstructure of the TIG welded joint is shown in Figure 8. The TIG weld microstructure is containing fine grains compared to the base metal microstructure of cast Al-Mg-Sc aluminum alloy shown in Figure 2.

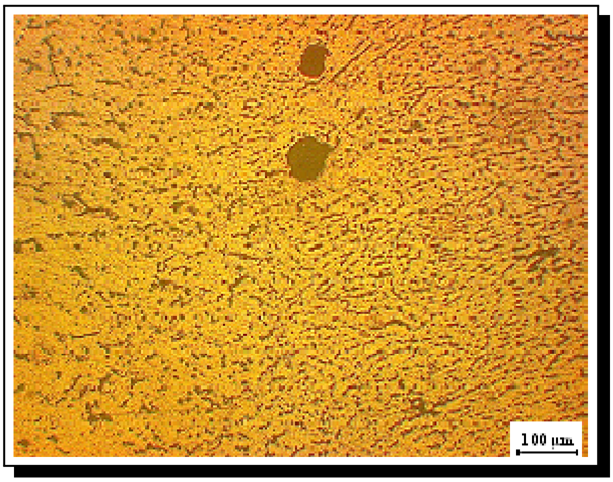

Figure 7. Porosity at the HAZ of the TIG welds

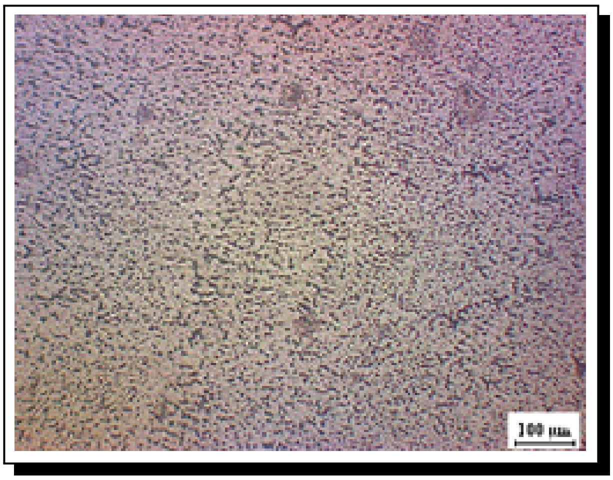

Figure 8. Weld microstructure of TIG weld

3.4 SEM Microstructure of TIG Welding of AA5083-H321 and Cast Al-Mg-Sc Alloys

The SEM image of TIG welded joints of wrought AA5083-H321 aluminum alloy weld is shown in Figure 7. The dendrites formed during the fusion welding process are clearly visible here. Dendrites are having brittle nature and naturally reduce the tensile properties of TIG welded joints. The SEM micrograph of TIG welding process of cast Al-Mg-Sc alloy is shown in Figure 10, which contains coarse precipitates in it. The nano-sized Al_3Sc particles in the SEM micrographs are responsible for better tensile properties.

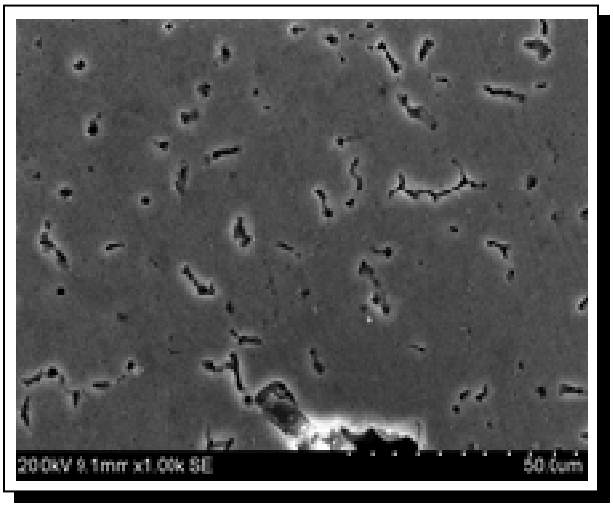

Figure 9. AA5083-H321 TIG weld

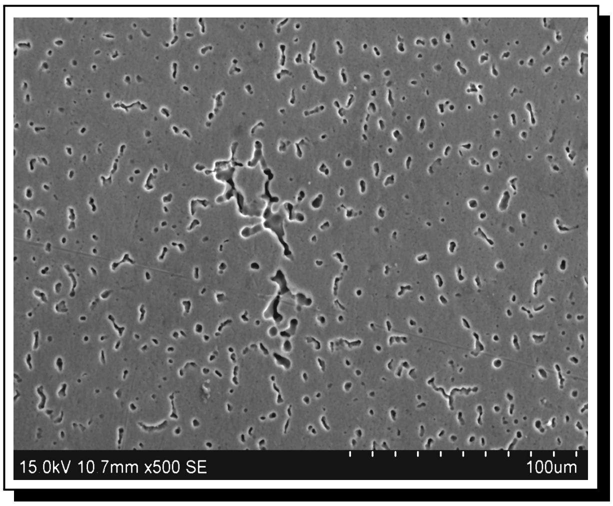

Figure 10. Cast Al-Mg-Sc TIG weld

3.5 Tensile Properties

The tensile properties of the TIG welded samples of both wrought and cast alloys are shown in Table 1. The 0.293 wt-% scandium added cast Al-Mg-Sc alloy exhibits better weld yield stress than the wrought alloy. There is an increase of 67 MPa was observed in the weld yield stress of TIG welded cast Al-Mg-Sc alloy, which in nearly 38% greater than the weld yield stress of TIG welded AA5083-H321 alloy. This enhancement of yield strength is mainly due to the presence of

Al_3Sc dispersiods in the microstructure of the cast alloy. There is no variation in the UTS of TIG welded cast Al-Mg-Sc, when compared to the UTS of TIG welded AA5083-H321 alloy. The ductility properties of the TIG welded samples of both wrought and cast alloys are shown in Table 1. The percentage elongation of cast Al-Mg-Sc TIG welded samples is around 22% lesser than that of the wrought AA5083-H321 TIG welded samples.

The observed lower tensile ductility values in the Al-Mg-Sc alloy compared to the Sc-free alloy are thought to be due to the presence of the coherent Al_3Sc particles in the scandium containing alloy. Such a reduction in ductility is a well known phenomenon in alloys hardened by coherent precipitates [16–18]. The lower tensile ductility in the Sc-containing alloys seems to be due to the high volume fraction of Fe- and Si-containing inclusions at high-angle grain boundaries in this alloy. These inclusions are known for their detrimental influence on ductility by early crack nucleation in rolled Al-alloys tested in the short-transverse direction [3, 19].

Table 1. Tensile properties of TIG welded joints of AA5083-H321 and Al-Mg-Sc alloys

Type of weld	Yield stress, MPa	Tensile strength, MPa	% Elongation
AA5083-H321 TIG Weld	177	266	14.4
Wrought Base Metal AA5083-H321	262	291	26.4
Al-Mg-Sc TIG Weld	244	258	11.3
Cast Base Metal Al-Mg-Sc	217	228	6.8

3.6 Hardness

The hardness values across the transverse cross-sections of the welds were plotted in the form of a graph in Figure 11.

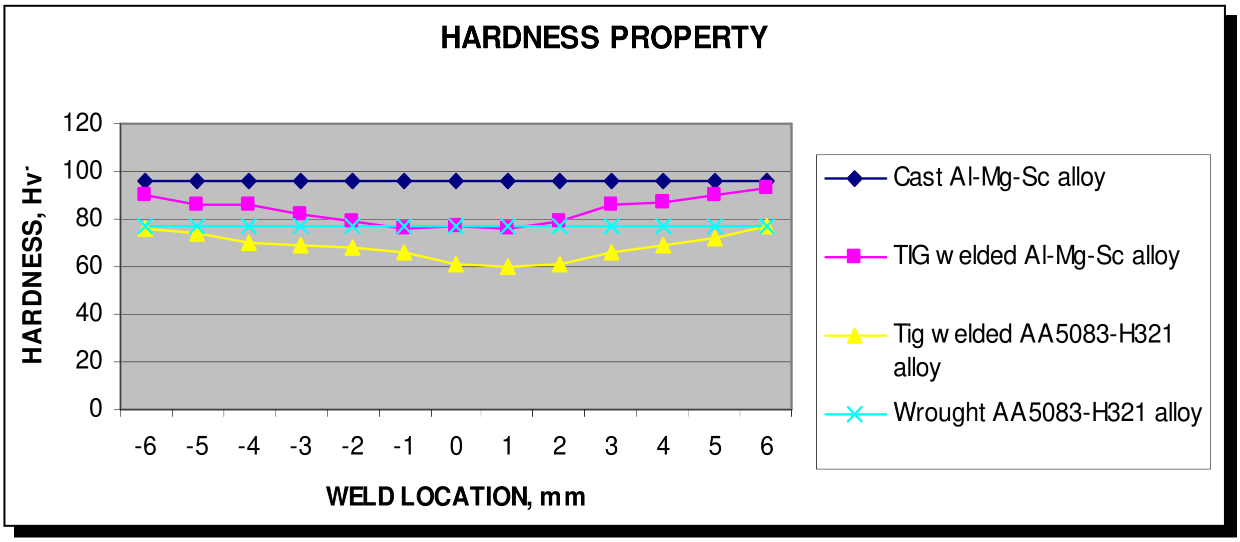

Figure 11. Variation of Hardness of TIG welded samples and their Base metals

The hardness chart clearly indicates that there is always a drop in hardness values in the weld zone compared to the base metal. The maximum drop in hardness during TIG welding of wrought alloys is around 22%, where as for cast Al-Mg-Sc TIG welds is around 18%. The hardness is reduced in TIG welded joint of AA5083-H321 weld zone due to higher heat input. In case of TIG welding, very high arc temperature increases the peak temperature of the molten weld pool causing a slow cooling rate. This slow cooling rate, in turn, causes relatively wider dendritic spacing in the fusion zone [20–22].

3.7 Changes in Chemical Composition

The Magnesium, Manganese and Zinc present in the base metal were subjected to evaporation during fusion welding processes of aluminum alloys [23]. The chemical compositions are shown in Table 2. In our study, we have got a loss of 39.5% magnesium, 16% of manganese and 20% zinc in the fusion zone of the TIG welded samples wrought AA5083-H321 aluminum alloy plates. The loss percentage observed in the TIG welded samples of Cast Al-Mg-Sc alloy plate were of 35% magnesium. On comparing the loss percentages of volatile elements from both the materials, we can conclude that the loss percentage of magnesium is slightly more in the case of AA5083-H321 alloy.

Table 2. Chemical Composition of Base metal and welded samples

	Mg	Mn	Fe	Si	Zn	Cu	Cr	Ti	Sc
Base Metal- AA5083-H321	4.214	0.787	0.407	0.16	0.12	0.025	0.01	0.01	—
TIG welded joint	2.57	0.657	0.33	0.20	0.098	0.048	0.009	0.01	—
Base Metal-Cast Al-Mg-Sc	3.954	0.647	0.356	0.133	0.00	0.016	0.023	0.023	0.30
TIG welded joint	2.567	0.656	0.032	0.208	0.066	0.032	0.008	0.009	0.263

3.8 Discussions

The material is gradually softened from the strain hardened state to the fusion boundary where the strain hardening is severely destroyed by the TIG welding heat input. The lower hardness values of the fusion zone are simply the result of unstrained cast microstructure and also of Mg loss. Since wrought AA 5083-H321 aluminum alloy is non-heat treatable, it is not surprising to find this hardness behavior. The reduced hardness in the HAZ and the fusion area, and the considerable porosity in the fusion zone, explain the degraded mechanical properties of the TIG welds. The 16% loss of manganese in the TIG welded joint of AA5083-H321 aluminum alloy also reduces the strength properties of the alloy as well as its welded joints.

Even though, both TIG welds subjected to more or less same amount of magnesium loss, the weld yield stress of cast Al-Mg-Sc alloy is better than the wrought alloy AA5083-H321 because of the presence of the dispersiod Al_3Sc in the cast alloy.

The TIG weld contains pores in the HAZ, whose presence will introduce stress concentration in the cross-section, which will reduce the strength of the joint. Being a fusion welding process, in TIG welding process, the microstructure of the weld contains coarse grains compared to the base metal of the cast Al-Mg-Sc alloy. Formation of the dendrites in the weld also affects the tensile properties of the TIG welded joint. However, the slow cooling rate in TIG welded joint of the cast Al-Mg-Sc aluminum alloy causes nucleation and growth of Al_3Sc dispersiods in large numbers. Hence, higher resistance to indentation and better hardness and better tensile properties compared to the TIG welded joints of wrought AA5083-H321 aluminum alloy. Hence, presence of the dispersiod Al_3Sc overcomes all the drawbacks of TIG welding process and produces better tensile properties in TIG welded joints of cast Al-Mg-Sc alloy plates compared to the cast base metal properties.

4. Conclusions

Microstructural examination revealed that both welds contain shrinkage voids and porosity in the weld zone. Brittle dendrites formed in the wrought alloy without scandium reduces the tensile properties to a very low level. Very fine grains formed in the cast Al-Mg-Sc alloy TIG welded joint and the presence of Al_3Sc are responsible for the enhancement of yield stress.

Cast Al-Mg-Sc alloys are having better yield property compared to the wrought AA5083-H321 aluminum alloy. There is an enhancement of 32% in yield stress values and 8.5% decrease in ultimate tensile strength. Similarly, the percentage elongation of cast welded samples is 15% inferior than their wrought TIG welded alloys.

The drop in hardness in the TIG weld is less for the cast Al-Mg-Sc alloy than the TIG welded wrought AA5083-H321 aluminum alloy.

On comparing the loss percentages of volatile elements from both the materials, we can conclude that the loss percentage of magnesium is almost same during both processes. The loss of manganese is more in the TIG welded wrought alloy AA5083-H321 by 16%.

Competing Interests

The author declares that he has no competing interests.

Authors' Contributions

The author wrote, read and approved the final manuscript.

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