

# The impact of fuel and oxidiser change on aluminium melting

Pooyan Kheirkhah, Valmiro Sa, Marie Kistler and Anand Makwana\* discuss a study on the impact of change in furnace gas composition on the melt quality of three alloys.

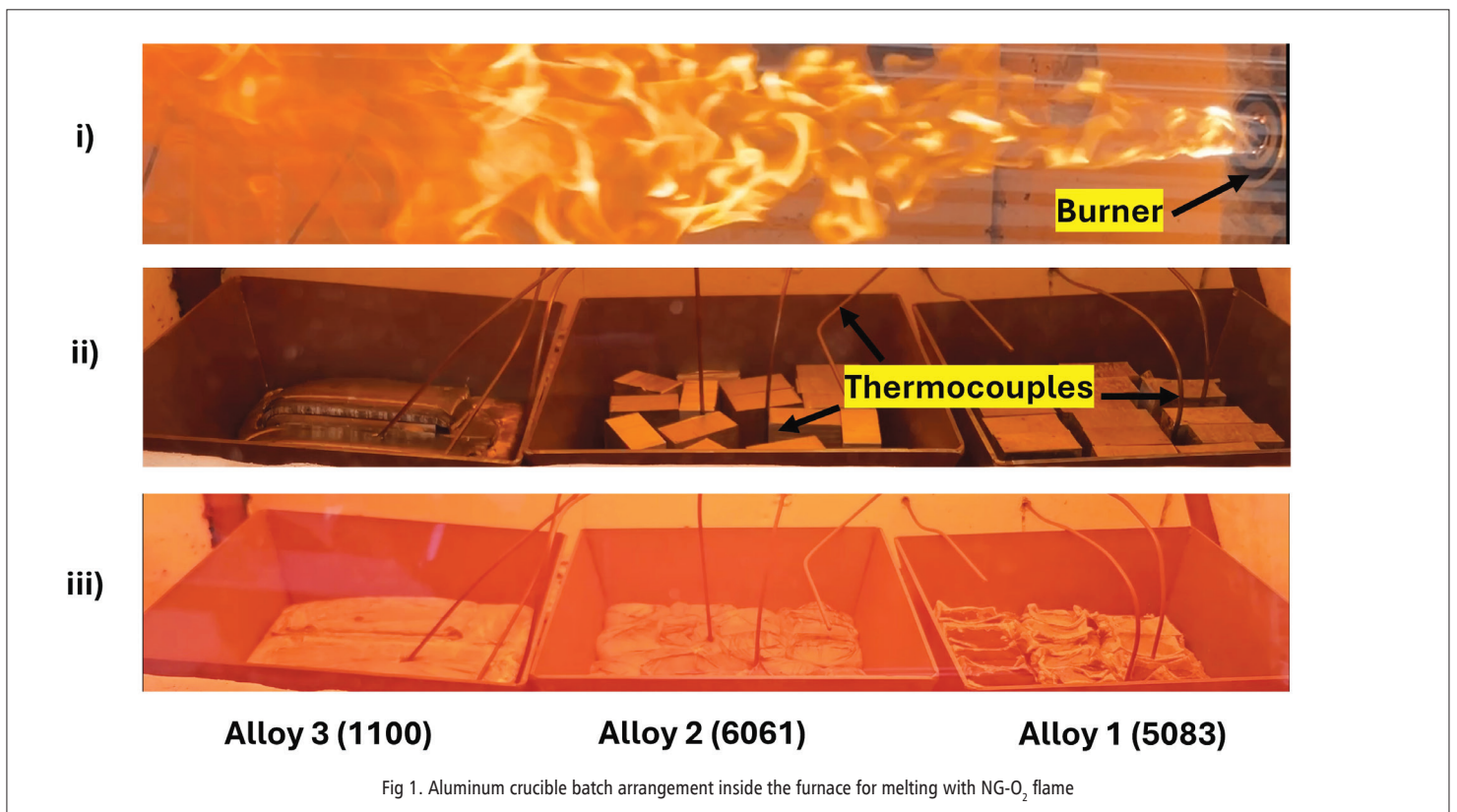


Fig 1. Aluminum crucible batch arrangement inside the furnace for melting with NG-O<sub>2</sub> flame

Aluminum production from melting recycled scrap (secondary route) requires only 5% of the energy needed to produce aluminum from bauxite ore (primary route).

The energy required for the melting process in secondary production is provided by combustion. Using oxy-fuel combustion technologies could enhance the thermal efficiency of the melting process, reduce the operating costs and operational carbon footprint<sup>[1]</sup>.

The use of hydrogen (H<sub>2</sub>) as a fuel is being considered to assist producers to further

lower their operational carbon footprint. Hydrogen combustion generates higher amounts of water vapor (H<sub>2</sub>O) and no CO<sub>2</sub> compared to natural gas combustion.

In the current study, the impact of furnace gas composition (concentration of CO<sub>2</sub> and H<sub>2</sub>O) when switching from natural gas (NG) to hydrogen burned with oxygen (O<sub>2</sub>) on the melt quality and oxidation of three different aluminum alloys (0% Mg, 1% Mg and 4.5% Mg) is investigated.

Secondly, the impact of melt hold temperature on oxide formation in these

aluminum alloys is presented. Finally, this paper shares data on how the switch from a NG-air to a NG-O<sub>2</sub> flame impacts total melt oxidation.

## Test setup

The experiments were conducted at Air Products and Chemicals' Research Laboratory in a box furnace. Three aluminum alloys with different magnesium (Mg) content Al-1100 (0% Mg), Al-6061 (1% Mg), and Al-5083 (4.5% Mg) were used to study the effect of furnace atmosphere

\*Air Products and Chemicals, Allentown, Pennsylvania, United States, [www.airproducts.com/applications/melting-non-ferrous](http://www.airproducts.com/applications/melting-non-ferrous)

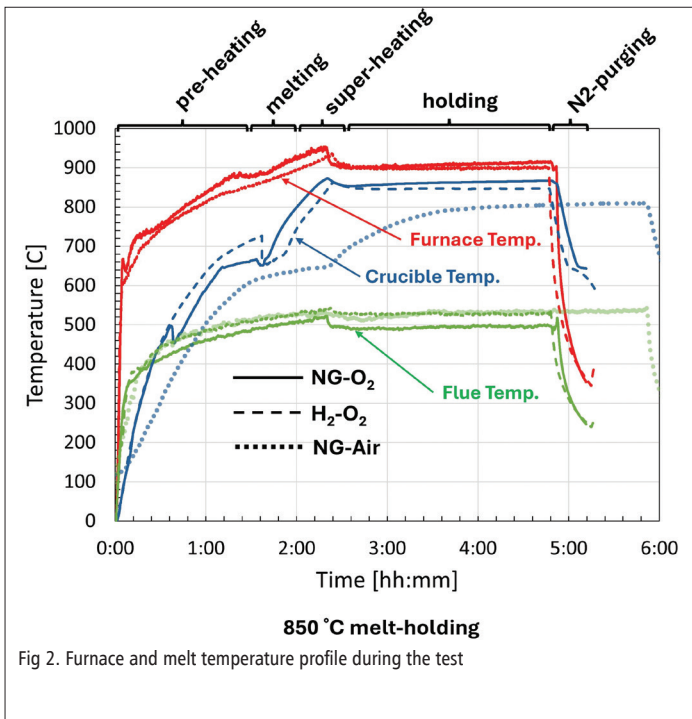


Fig 2. Furnace and melt temperature profile during the test

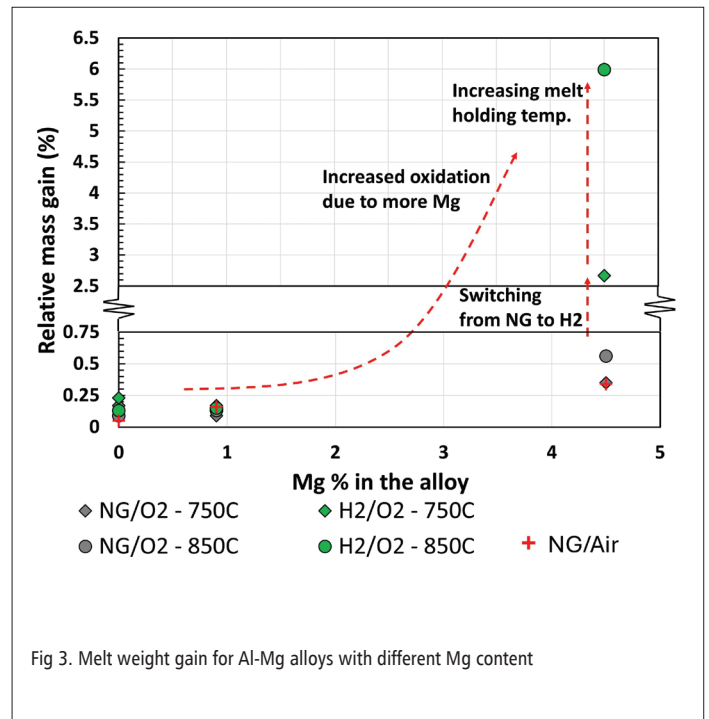


Fig 3. Melt weight gain for Al-Mg alloys with different Mg content

and melt hold temperature ( $T_{hold}$ ) on the oxidation behavior of the alloys. More experimental details can be found in Refs. [2, 3]. The arrangement of the furnace inside is shown in **Figure 1**. The temperature above the crucible was within  $\pm 20^\circ\text{C}$ , ensuring a minimal impact of crucible location within the furnace.

**Experimental conditions**

The test conditions are summarised in **Table 1**. The main difference between the NG- $\text{O}_2$  and  $\text{H}_2$ - $\text{O}_2$  melting tests is the changes in furnace composition ( $\text{CO}_2$  and  $\text{H}_2\text{O}$ ). A test was also performed with a NG-air (unheated air) flame at  $T_{hold} = 800^\circ\text{C}$  to compare the change in oxidation due to a change in oxidizer.

The furnace, flue gas, and crucible temperatures during the  $850^\circ\text{C}$  melting tests are shown in **Fig 2**, illustrating the different test phases.

The burner firing power was controlled to heat the charge material to its melting point and the melts were then superheated to the desired  $T_{hold}$ .

The real-time temperature/furnace composition data was used to control the burner firing power to have similar temperature-time history and oxygen ( $\text{O}_2$ ) concentration (4% wet basis) between the different tests.

The total duration of the NG-air test was longer due to the lower heat transfer efficiency of the NG-air flame.

The weight of the charged material was measured before and after each test to calculate the net weight gain due to oxidation during the melting process.

Test ID	Fuel/Oxidizer		Burner power	$T_{hold}$	Furnace gas composition – wet [% vol.]		
		Melt (kW <sub>t</sub> )	Hold (kW <sub>t</sub> )	°C	O <sub>2</sub>	H <sub>2</sub> O	CO <sub>2</sub>
1	NG- $\text{O}_2$	48	38.1	850	4.0%	64%	32%
2	$\text{H}_2$ - $\text{O}_2$		38.1	850	4.0%	96%	-
3	NG- $\text{O}_2$		35.2	750	3.7%	64.2%	32.1%
4	$\text{H}_2$ - $\text{O}_2$		35.2	750	3.5%	96.5%	-
5	NG-Air		42.5	800	4.0%	16%	8%

Table 1. Furnace conditions during the melting tests

Table 2. XRD composition of the oxides (weight %) in  $750^\circ\text{C}$  melted samples

Compounds (wt.%)	NG- $\text{O}_2$ melt	$\text{H}_2$ - $\text{O}_2$ melt
	5083 (Al-4.5Mg)	
MgO	78.7%	80.0%
$\text{MgAl}_2\text{O}_4$	11.8%	18.6%
$\text{Fe}_2\text{O}_3$	4.6%	0.7%
AlN	4.9%	0.7%

Samples were collected from the solidified melt for chemical analysis and microscopy (XRD and SEM-EDS), as detailed in Refs. [2, 3].

**Results/Discussion**

**Mass gain due to melt oxidation**

The net weight gain of each aluminum sample due to oxidation during the melting process is shown in **Fig 3**. The results show the melt oxidation was higher for the Al-4.5Mg alloy compared to the Al-1.0Mg and Al-0Mg alloys.

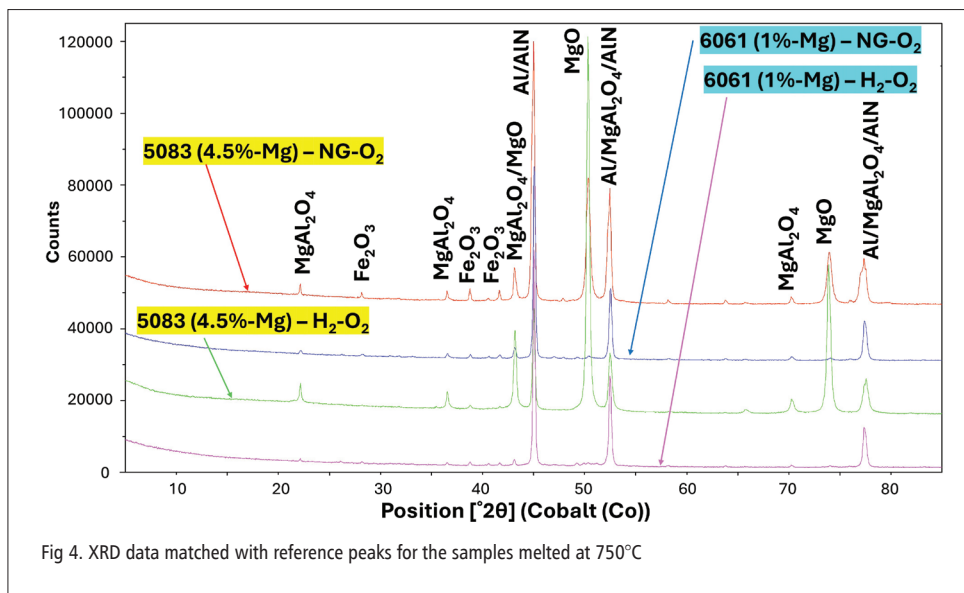
*Effect of fuel type:* It is noteworthy that a fuel switch from natural gas to hydrogen does not increase the melt oxidation noticeably for alloys with less than 1 wt.% Mg. In contrast, the Al-4.5Mg alloy

oxidizes roughly four times more at  $T_{hold} = 850^\circ\text{C}$  when melted with the  $\text{H}_2$ - $\text{O}_2$  flame as compared to the NG- $\text{O}_2$  flame. Increased oxidation of high-Mg aluminum alloys with hydrogen flames has been reported [4].

*Effect of oxidizer type:* Melt oxidation using a NG-air flame for all three Al-Mg alloys show a similar melt oxidation to the NG- $\text{O}_2$ -melted case.

*Effect of melt hold temperature:* **Fig 3** shows the hold temperature has a greater impact on oxidation of the Al-4.5Mg alloy as compared to < 1% Mg alloys.

For Al-4.5Mg alloy, decreasing  $T_{hold}$  from  $850^\circ\text{C}$  to  $750^\circ\text{C}$  has lowered the amount of oxidation by about 40% and 55% for the NG- $\text{O}_2$  and  $\text{H}_2$ - $\text{O}_2$  tests, respectively.



This indicates that the furnace temperature can have a greater impact on melt oxidation when using hydrogen fuel.

#### Characterisation of the oxide layer XRD Results

The XRD data from the Al-1.0Mg and Al-4.5Mg samples melted with NG-O<sub>2</sub> and H<sub>2</sub>-O<sub>2</sub> flames at T<sub>hold</sub> = 750°C is presented in Fig 4.

For both flames, there is a strong presence of the MgO and MgAl<sub>2</sub>O<sub>4</sub> peaks in the Al-4.5Mg, while the oxides detected on the surface of the Al-1.0Mg alloy are mostly comprised of MgAl<sub>2</sub>O<sub>4</sub>.

This difference in oxide formation is believed to be due to the local depletion of Mg (due to MgO formation) below the critical Mg composition (4% weight at

750°C) favouring MgAl<sub>2</sub>O<sub>4</sub> formation in the Al-1.0Mg alloy and completion of the breakaway oxidation.

In contrast, due to higher concentration of Mg in Al-4.5Mg alloy, MgAl<sub>2</sub>O<sub>4</sub> formation was still underway at the end of the experiment as confirmed by detection of MgO.

The weight percentage of the compounds in the oxide layer of the Al-4.5Mg alloy are estimated from the XRD data and is presented in Table 2.

Results show a similar % ratio of MgO and MgAl<sub>2</sub>O<sub>4</sub> between the NG-O<sub>2</sub> and H<sub>2</sub>-O<sub>2</sub> melt. In addition to the Mg-oxides, other compounds of Fe, Mn, Al, Si were detected in the samples.

While a representative sample was collected for analysis, this result may

not represent the presence of all the compounds produced from trace elements in the material.

#### SEM/EDS Results

The phase maps for Al-1.0Mg and Al-4.5Mg alloys melted at 750°C are shown in Fig 5.

Fig 5 shows a higher oxidation layer thickness for the high-Mg alloy in Fig 5 (b) and (d) as compared to the low-Mg alloy shown in Fig 5 (a) and (c), consistent with higher metal oxidation in the high-Mg alloy as shown in Fig 3.

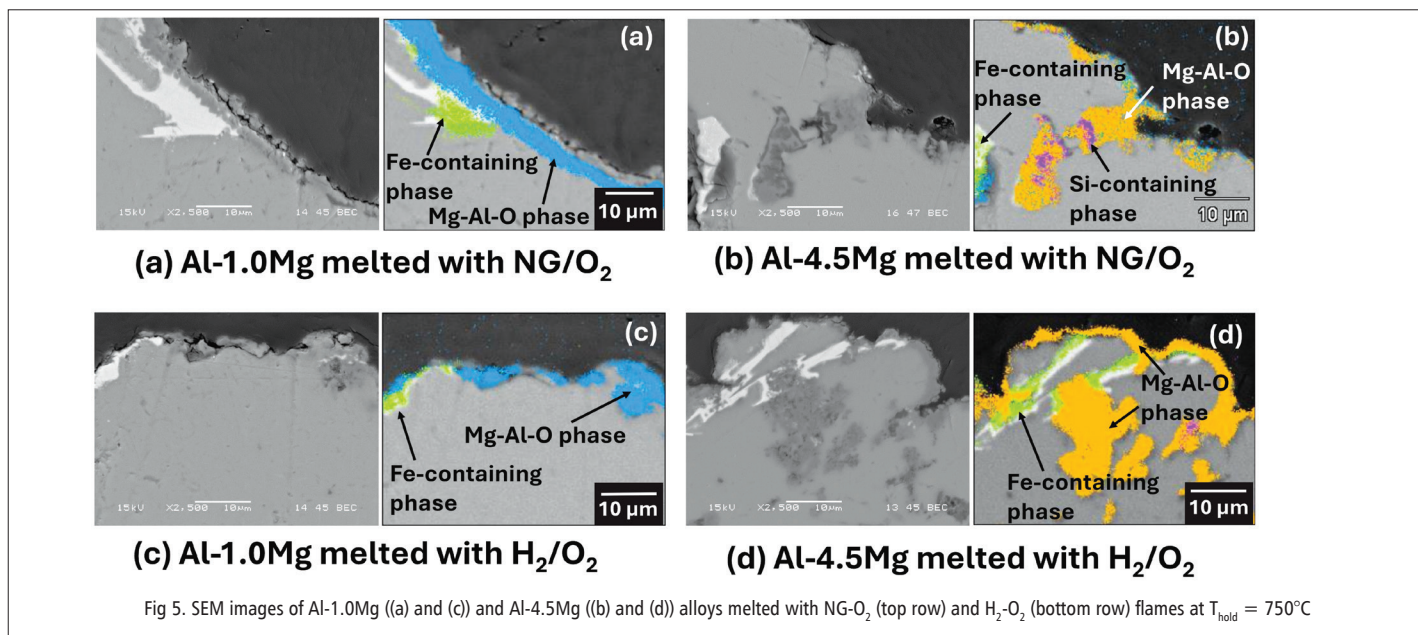
*Impact of fuel change:* Comparison of the Al-1.0Mg oxide layer in the NG-O<sub>2</sub> melt (Fig 5 (a)) and the H<sub>2</sub>-O<sub>2</sub> (Fig 5 (c)) melt indicates a similar layer that is relatively coherent and formed within 5µm of the exposed surface. This phase is composed of an Al-Mg-O-rich phase, likely MgAl<sub>2</sub>O<sub>4</sub>, as detected in XRD.

The Al-4.5Mg alloy is oxidized in a less coherent fashion resulting in oxidized lumps 20-30µm below the surface in Fig 5 (b) and (d). The H<sub>2</sub>-O<sub>2</sub> melt of the Al-4.5Mg alloy shows a larger oxide thickness compared to the NG-O<sub>2</sub> melt, consistent with oxidation results in Figure 3.

The oxidized regions in the Al-4.5Mg alloy (orange colour) are potentially the coexistence of MgO and MgAl<sub>2</sub>O<sub>4</sub>, as detected in the XRD results.

Other detected compounds correspond to Mg-Al-Si-O (purple) and Al-Fe (green) phases.

*Impact of melt hold temperature:* The SEM-EDS analysis of the Al-4.5Mg samples under 850°C melt-hold condition (not shown here) revealed an oxide layer thickness of ~10-15µm versus ~5µm for



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the 750°C hold temperature.

As expected, metal oxidation increases with an increase in the melt hold temperature.

We would expect that increased oxidation in the 850°C melting test is due to increased formation of  $MgAl_2O_4$ , as the breakaway oxidation had progressed further than in the 750°C melt.

The complete conversion of the magnesium in the Al-4.5Mg alloy to  $MgO$  and  $MgAl_2O_4$  will result in a 2.7% and 10.7% mass increase, respectively.

Comparison of the observed weight gains (0.5 to 6%) for the Al-4.5Mg alloy in **Fig 3** to these maximum calculated amounts indicate that some unoxidized Mg is likely present in the melt, and the oxides contain a mixture of both  $MgO$  and  $MgAl_2O_4$ . For the  $H_2$  melt, the shift toward  $MgAl_2O_4$  formation is especially significant for the 850°C melting test where the melt mass gain (6%) is closer to the 10.7% theoretical mass increase corresponding to 100% conversion of Mg to  $MgAl_2O_4$ .

### Conclusions

Three aluminum alloys with different magnesium amounts, 0 wt. %, 1 wt. % and 4.5 wt. %, were melted using NG-air, NG- $O_2$  and  $H_2$ - $O_2$  flames to study how changes in furnace composition and melt hold temperatures affect melt quality and oxide formation.

For the tests with natural gas fuel, an oxidizer change from air to oxygen showed no significant impact on the total melt

oxidation.

Industrial-scale field demonstrations using an oxy-fuel burner have shown improvement in melt loss on the order of 0.5-1.0 %.

A fuel change from natural gas to hydrogen did not affect the amount of oxidation in alloys with 1% Mg or less but significantly increased the oxidation for the 4.5% Mg alloy.

For both fuels at  $T_{hold} = 750^\circ C$ , the oxide detected on the Al-1.0Mg was predominantly  $MgAl_2O_4$  with virtually no  $MgO$  and for the Al-4.5Mg alloy, the sample showed the presence of a mixture of  $MgO$  and  $MgAl_2O_4$  oxides, indicating the breakaway oxidation has partially progressed.

These experiments showcase that the impact of hydrogen combustion on low-Mg% aluminum alloys is minimal and improve confidence that large-scale field trials on these alloys can be the next step toward full commercial use.

The high-Mg% aluminum alloy tests show that the oxidation rate increased when switching to hydrogen.

In operations that produce these alloys, additional technologies to better control furnace or melt hold temperature can be implemented to minimise the oxidation.

The results show that reducing the  $T_{hold}$  from 850°C to 750°C decreased the melt oxidation for the hydrogen fuel by a greater % as compared to natural gas fuel, even though the total oxidation is higher for hydrogen fuel vs natural gas. ■

### References

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