WELDABILITY STUDY ON ATOMET 4601+TIC ALLOY STEELS

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Abstract: The present research work aims to study the effect of 2%TiC addition on weldability characteristics of ATOMET 4601 pre-alloyed Powder Metallurgy (P/M) alloy steel under Tungsten Inert Gas (TIG) welding. Rectangular compacts of ATOMET 4601 and ATOMET 4601+2%TiC were prepared with a suitable die-punch setup by applying suitable uniaxial load. Ceramic coating was applied over the surface of green compacts to prevent oxidation during sintering. The dried and coated green compacts were sintered in a muffle electric furnace of 3.5 kW at a temperature 1100 ±10 °C for 30 min. The sintered compacts were subjected to hot upsetting to gain maximum density. TIG welding is done on the sinter-forged alloy steel strips with suitable filler materials. Mechanical tests and microstructural examinations were carried out on welded and un-welded alloy steels for weldability studies and analysis. Increasing the density of alloy steel is found to enhance the mechanical strength of alloy steels by reducing pore size and number of pores in the material. Addition of 2%TiC to the ATOMET 4601 enhances the welding strength of the alloy steel. As the welded materials have better strength than the parent material, it may be concluded that ATOMET 4601+2%TiC has better weldability characteristics under TIG welding.

Keywords: ATOMET 4601+2%TiC; Mechanical Properties; Microstructure; SEM; TIG Welding; XRD.

1. Introduction

Powder metallurgy (P/M) enroutes the advantage of manufacturing near net shaped materials under economical basis. As a result of advanced technology, structural parts manufactured by P/M route have been extensively used as automobile components due to their good balance between impact strength, tensile strength, and corrosion resistance. Such P/M components found as a replacement of wrought alloys in several applications due to its high performance at an economical cost [1, 2]. Welding of sinter-forged P/M alloys possesses a challenging task due to their inherent porosity in the material. Several welding techniques are available for joining sinter-forged materials, but evolving a cost-effective methodology is a vital challenge. Welding is the most effective and economical joining technique adopted for fastening a number of small parts with higher productivity and enhanced properties. In the present research work, TiC an hard alloying element is admixed with pre-alloyed ATOMET 4601 subjected to TIG welding to find the mechanical and metallurgical changes on addition of 2%TiC on both parent and welded metal are contrastively analyzed with optical images, SEM fractographs and XRD of tensile fractured base metal and welded metal. Gas Tungsten Arc Welding (GTAW/TIG), LASER beam welding (LBW) and Friction Resistance Welding (FRW) evolved as a most prominent welding technique for sintered steels [3]. GTAW process results better in controlling the welding parameters (heat input, travel speed and type of filler metal) during the welding [4]. It has found that mechanical properties of dissimilar welded joints of AISI 4140 and AISI 304 made by electron beam welding (EBW) are superior compared to other welding processes such as TIG and FRW due to macro segregation and enrichment of chromium, nickel, iron and carbon at high temperature [5]. The most effective way of increasing the penetration of TIG welding is to use inorganic compounds named activated flux by a process called activated TIG welding. The activated TIG welding of stainless steels can gain a depth of 8 mm in a single-pass weld without the need for edge preparation [6-7]. The additions of TiO2, CdCl2 and AlF3 increased the weld penetrations drastically, and good weld appearances of welded joints were achieved [8-11]. It has been found AA 6061 aluminium alloy showed an enhanced tensile property under FSW compared to GTAW and GMAW due to very fine equi-axed microstructure in the weld zone [12]. The study of
welding behaviour of sintered and forged Fe–0.3%C–3%Mo low alloy steel resulted that density of base metal has negligible influence on hardness of the weld zone and microstructural integrity and mechanical strength of welded/parent P/M alloy steels is increased upon enhancing the density of alloy steels and the welded joint is found to have better tensile strength compared to the base material due to the formation acicular ferrite at the fusion zone [13]. The weldability of 12%Cr ferritic stainless steel with EN 1.4003 and UNS S4 1003 steel with an addition of 0.01%C to enhance the weldability under hybrid plasma plus TIG welding process using two different 309 and 316 austenitic stainless steel consumables. They have experimentally found that the joint made by 316 filler has better toughness than that of 309 filler rod [14]. The study of effect of pulsed TIG welding on mechanical properties of Al-Mg-Si alloy has showed that the weld specimen exhibits lower impact and tensile strengths compared to the un-welded metal due to the formation of inter-dendritic network microstructure at the weld zone when using 4043 alloy as a filler material [15]. TIG welding is found to be a feasible welding process for sinter-forged Atomet 4601 pre-alloyed steel [16]. The welding strength behaviour on adding 2%TiC to Atomet 4601 pre-alloyed steel under TIG welding process is addressed in the present research work.

2. Experimental Details

ATOMET 4601 designed for high performance, high strength powder metallurgy and powder forging applications procured from Rio Tinto - QUEBEC METAL POWDERS, Canada is used as a base pre-alloyed metal powder for specimen preparation. 2%TiC (Titanium Carbide) is added to the pre-alloyed ATOMET 4601 to compare with pre-alloyed steels as shown below in Table 1.

<table>
<thead>
<tr>
<th>Chemical Compositions</th>
<th>% of weight</th>
<th>Powder compositions &amp; Filler material</th>
<th>Powder compositions &amp; Filler Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ATOMET 4601 Pre-alloyed powder</td>
<td>ER 80S-G Elemental Powder ER 80S-B2</td>
</tr>
<tr>
<td>Fe</td>
<td>97.536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.004</td>
<td>0.11</td>
<td>0.012</td>
</tr>
<tr>
<td>Ni</td>
<td>1.60</td>
<td>0.90</td>
<td>0.20</td>
</tr>
<tr>
<td>Mn</td>
<td>0.20</td>
<td>1.50</td>
<td>0.70</td>
</tr>
<tr>
<td>Mo</td>
<td>0.55</td>
<td>0.15</td>
<td>0.65</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
<td>0.005</td>
<td>0.025</td>
</tr>
<tr>
<td>O</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>0.45</td>
<td>0.20</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>0.025</td>
<td>0.012</td>
</tr>
<tr>
<td>Cr</td>
<td>-</td>
<td>0.40</td>
<td>1.50</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>X-factor</td>
<td>-</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

The elemental powder TiC was mixed with ATOMET 4601 in an indigenously fabricated ball mill using ceramic balls for 10 hrs. The homogenous pre-alloyed and blended powders were then compacted in to a rectangular shape of 76x15x5 mm using Universal Testing Machine (UTM) of capacity 1000 kN with a suitable die-punch setup by applying uni-axial force of 430 kN to obtain 85 % theoretical density. Further to avoid oxidation prior to sintering, ceramic coating was done on the green compacts and made to dry for 24 hrs. Later dried samples were subjected to sintering using 3.5 kW capacity electrical furnace at a temperature of 1100 ± 10 °C for 30 min. The sintered specimens were subjected to hot forging to gain improved densities (96 %) of the P/M alloy steel and the density was measured as per the Archimedes’ principle. Then, the scales deposited over the surface of the sintered specimens were cleaned and machined off to get uniform dimensions before subjected to TIG welding. Preheating was done before welding across faying surface. The rectangular strips of ATOMET 4601 were welded using standard ER80S-G filler material of Ø2.5 mm. The welding parameters were set at 9 V, 73-77 A, DC of negative polarity, welding speed at 60–65 mm/min and the inert gas flow rate set at 11 lpm for TIG welding process. Similarly ATOMET 4601+2%TiC were welded using the standard ER 80S-B2 of Ø2.4 mm filler material and the welding parameters were set at 9 V, 83-88 A, DC of negative polarity, welding speed at 60–65 mm/min and the inert gas flow rate set at 14 lpm without any joint preparation for TIG welding process. The welded and un-welded materials of alloy steels were subjected to various mechanical tests such as impact, tensile and hardness in order to study the weldability characteristics of the alloy steels. The micro hardness of welded region of both the alloy steels was measured using SHIMADZU Micro Vickers hardness tester (Japan). The surface morphology of the welded and un-welded alloy steels were observed using Kyowa MELUX2 microscope fitted with CCD camera interfaced with a computer and image analyser. SEM fractographs of the tensile fractured specimens of the both alloy steels were observed using JEOL Field Emission Scanning Electron Microscope (TSM-6701F, Japan). XRD of tensile fractured ATOMET 4601 and ATOMET 4601+2%TiC were taken in order to find the micro phase changes in the alloy steel samples. The surface morphology of the fractured tensile specimens of the alloy steels have also been corroborated with the weldability characteristics of the alloy steels.
3. Results and discussion

A. Impact Properties of Parent and Welded Alloy Steels

Fig. 1 shows the impact strength of parent and welded ATOMET 4601 and ATOMET 4601+ 2%TiC alloy steels. Impact specimens were prepared according to the standard ISO 148 of sub-size 10x2.5x55 mm and Charpy impact test was conducted for the alloy steels. TiC is found to be a hard alloying element, enhances the strength of ATOMET 4601+2%TiC of both parent and welded metal compared to that of ATOMET 4601 parent and welded metal. It is observed from the figure that though the TiC contains hard phases, absorbs more energy than that of base material. Moreover, the micro phase changes at the welded region of TiC added alloy steel absorbs still more energy compared to the parent material. It is understood from the figure that the addition of TiC to the ATOMET 4601 significantly improves the impact strength of both the welded and un-welded alloy steels.

B. Tensile Properties of Parent and Welded Alloy Steels

Figs. 2 and 3 show the fractured welded tensile specimens of alloy steels. Tensile specimens were prepared according to the ASTM E8 standard and tensile test was conducted using digital Tensometer for ATOMET 4601 and ATOMET 4601+ 2%TiC alloy steels. Addition of TiC has played a vital role in improving the strength of base metal ATOMET 4601.

Table 2. Tensile Properties of Atomet 4601

<table>
<thead>
<tr>
<th></th>
<th>TENSILE TEST RESULTS</th>
<th>ATOMET 4601</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent</td>
<td>Welded Metal</td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>% elongation in length</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>% reduction in area</td>
<td>20</td>
<td>22.40</td>
</tr>
</tbody>
</table>

Table 3. Tensile Properties of Atomet 4601+2%TiC

<table>
<thead>
<tr>
<th></th>
<th>TENSILE TEST RESULTS</th>
<th>ATOMET 4601+2%TiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent</td>
<td>Welded Metal</td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>77</td>
<td>100</td>
</tr>
<tr>
<td>% elongation in length</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>% reduction in area</td>
<td>22.22</td>
<td>25.55</td>
</tr>
</tbody>
</table>

Table 2 and 3 show the tensile strength of parent and welded ATOMET 4601 and ATOMET 4601+ 2%TiC alloy steels. It is observed from the tables that the welded alloy steels have higher ultimate tensile strength (UTS) compared to that of parent alloy steels in both the cases. Moreover, addition of TiC to the ATOMET 4601 invariably enhances the UTS. On the other hand from
Fig. 4, there is no significant variation in the tensile yield properties such as %elongation in length and %reduction in area between the alloy steels. As the welded alloy steels in both cases have better tensile strengths compared to that of parent alloy steels, it can be concluded that ATOMET 4601 and ATOMET 4601+2%TiC have good weldability properties in TIG welding.

![Figure 4](image)

**Figure 4.** Bar chart of tensile yield properties of ATOMET 4601 & ATOMET 4601+2%TiC

C. Hardness Profile of Parent and Welded Alloy Steels

![Figure 5](image)

**Figure 5.** Plots of hardness values at various zones of weldment of welded ATOMET 4601 & ATOMET 4601+2%TiC

Fig. 5 shows the hardness values at various zones of welded regions of ATOMET 4601 and ATOMET 4601+2%TiC. Vickers hardness tester was used to find the hardness at the various zones of weldment by applying 5 N axial load for 10 s. The melting of parent and filler materials at the faying surface and subsequent cooling invariably increases the hardness at the fusion/weld zone (WZ) comparing with heat affected zone (HAZ) and base metal region. Addition of filler material at the weld zone forms the new alloy phases, which could also enhance the hardness at the weldment. Heat affected zone is subjected to recrystallization temperature and further cooling after welding makes the zone harder than the base metal. The total width of WZ and HAZ are extended upto 6000 µm each on either side the joint. The highest hardness of 200 HV is found in the case of TiC added alloy steel due to the presence of carbides in the material. The maximum hardness observed for the ATOMET 4601 welded alloy steel is 165 HV. Both the alloy steels are exhibiting the same declining trend of hardness profile starting from the centre of welded joint.

D. Microstructure

Optical images of base metal as well as welded alloy steels are shown in Figs. 6 (a)-(d). The surface morphology of ATOMET 4601 is depicted in Fig. 6(a). The prealloyed ATOMET 4601 powder contains various chemical elements, which are invariably enhances the strength of pre-alloyed steel powders in usage. The chemical constituents such as chromium, manganese, silicon and phosphor present in the alloy steel react with one another and forms new micro phases, which could further strengthen the material. The major element iron reacts with little amount of carbon and forms the ferric carbide, which is one of the hard phases found in the material. Though the microstructure contains ferrites in majority, other micro phases are also seen in the image, which are the combinations of carbides, oxides and other hard phases. Fig. 6(b) shows the microstructure of ATOMET 4601+2%TiC alloy steel. It is observed from the microstructure that the titanium carbide is embedded in the ferrite matrix of the alloy steel. The carbide phase plays a vital role in enhancing the mechanical strength of the alloy steel.

![Microstructure Image](image)

(a) PARENT ATOMET 4601
Fig. 6(c) shows the optical image of weldment of ATOMET 4601 prealloyed steel. The three zones are clearly visible in the image. The fusion boundary is clearly distinguishing the other regions. The voids present in the alloy steel are eliminated to the maximum extent at the weld zone. More number of pores is visible in the parent material zone. The heat affected zone is also visible with lesser number of pores. It is observed from the image that the new phases formed at the fusion zone are totally dissolved into the ferrite grains. The newly formed micro phases are evident at the parent metal zone.

Fig. 6(d) illustrates the optical surface morphology of welded region of ATOMET 4601+2%TiC alloy steel. Though it seems like ATOMET 4601 weldment, the embedded carbide titanium carbide phases in the ferrite matrix is observed in the parent metal zone. Bigger size crater is also seen in the image, may be due to lack of filling of filler material during welding. Similar to ATOMET 4601, the new micro phases are completely dissolved into the ferrite grains at the time of melting of material during welding.

**E. SEM Fractographs**

Scanning Electron Microscope (SEM) images were taken at the tensile fractured region for both the parent and welded metal of ATOMET 4601 and ATOMET 4601+2%TiC. The Fractured surface morphology of the tensile specimens of the un-welded and welded ATOMET 4601 is shown in Figs.7. (a) & (b). It is clearly evident from the image that the inter-granular fracture/failure has occurred in the case of parent metal. On the other hand, the dimple fracture has occurred for the welded specimen due to grain refinement during the welding process. The grain refinement of microstructure enhances the tensile and impact strengths of welded alloy steel.
Figure 7. SEM of tensile fractured specimens of parent & welded alloy steels

Figs. 7(c & d) show the SEM images of the fractured tensile specimens of parent and welded ATOMET 4601+2%TiC alloy steels respectively. The SEM image Fig.7. (c) shows the combination of both ductile and brittle fracture. At some places the carbide pull is accomplished along with the fracture. The SEM image of tensile fractured ATOMET 4601+2%TiC welded alloy steel specimen is shown in Fig.7. (d). Serration like an image is observed in the figure. It may be due to the formation of carbides and other hard phases of the concerned alloying element present in the material. There is a deep hole appeared in the image, due to lack of filling or entrapped gas pockets during welding. The tensile fracture has occurred nearer to the weldment in the case of both the alloy steels.

F. XRD

The welded specimen upon fracture in tensile are exposed to the X-ray diffraction analysis to identify the chemical compositions present in the fractured region. Fig. 8 (a) shows the XRD of ATOMET 4601 welded alloy steel taken at the fractured region. Fe3C found in the XRD, showed as iron and carbon combined together as a phase effect. Chromium, manganese and silicon react with oxygen and present as chromium oxide (Cr8O21), manganese oxide (MnO2) and silicon oxide (SiO2) respectively. Nickel and Phosphorous reacts with each other and forms a new phase nickel phosphate (Ni8P3). The non-reacted sulphur is also found in the material.
Fig. 8 (b) illustrates the XRD image of ATOMET 4601+2%TiC tensile fractured specimen. Apart from other new phases, titanium carbides and oxides are mainly observed in the material. These two new phases play significant role in promoting the strength of alloy steel. Nickel-molybdenum oxide (NiMoO4) is observed in the material, which is one of the hard phases in the material. Silicon is observed without reacting with any other chemical element. The main constituent iron reacts with sulphur and observed as iron sulphide (FeS). The presence of chromium in the filler material reacts with other alloying elements and found as Cr(PO3)3. The formation of new phases during welding is found to enhance the mechanical properties of both the alloy steels.

Conclusions
1. The highest hardness is observed at the fusion zone in ATOMET 4601 and ATOMET 4601+2%TiC alloy steels.
2. The formation of new phases found in the fusion zone improves the mechanical properties of the alloy steels.
3. The carbide formation in the case of TiC added alloy steel is found to enhance both impact and tensile strengths of alloy steels.
4. The tensile and impact strengths of welded alloy steels are found to have higher values than that of parent material.
5. The combination of ductile cum brittle mode of tensile fracture has been identified from the SEM images of both the alloy steels.
6. The ferritic structure is observed as a basic microstructure for the alloy steels.
7. As the welded alloy steels have greater mechanical strength, it may be concluded that the alloy steels such as ATOMET 4601 and ATOMET 4601+2%TiC have better weldability characteristics under TIG welding.

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References


