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A systematic review of effect of different welding process on mechanical properties of grade 5 titanium alloy

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ABSTRACT

Welding is widely used in the final stage of the casting production and in fabricating the components for joining. The simplicity of titanium welding and its special effects on mechanical properties is therefore extremely important conditions in the case of engineering workings. The idea of this review is, to sum up the welding capability and its effects on mechanical properties of grade 5 titanium alloy tubes. It has been identified that the titanium welding is used in different fields throughout the world. The GTAW process is the best method to weld the titanium alloys.

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1. Introduction

Welding process uses the high temperature to melt the metal and then allowing them to cool for joining the metals and thermoplastics as one [1]. Welding method is effective, light in weight, high corrosion resistance, inexpensive for making the joints permanently and is employed in the manufacturing of automobile parts, aircraft frames, machine parts and other structural works [2]. Nowadays the welding process is developing faster and its elementary studies on the welding mechanism give the relation between microstructure, mechanical properties and the variation in parameters [3].

Welding is used broadly because it is appropriate for ranging the thickness and element shapes and sizes. The eminent welding techniques are: Shielded metal arc welding (SMAW): It is also known as the “stick welding”, is a manual arc welding process which uses the electrode covered with flux to lay the weld. Gas tungsten arc welding (GTAW): It is also known as TIG (Tungsten inert gas) welding, which uses the non-consumable tungsten electrode to produce the weld. Gas tungsten constricted arc welding (GTCAW): It is the new variant of welding method used to produce the accurate joint efficiency. Gas metal arc welding (GMAW) or Metal inert gas welding (MIG). It is the welding process in which the electric arc forms between the consumable MIG wire electrode and the work piece metal, which heats the metal work piece, causing them to melt and join. Flux cored arc welding (FCAW): It is an automatic or semi-automatic process. Now and then the protective gas is outwardly supplied; it is relied on the flux to produce the guard from the atmosphere. Submerged arc welding (SAW): It is an ordinary arc welding process enclosed with an electric arc under a bed of granulated flux. Electro slag welding (ESW): It is an extremely industrious, single-pass welding process for wide materials in an upright or close to upright position [4].

At distinctive welding temperatures, Ti-6Al-4V (one of the most commonly used alloys of titanium) is considered by its relatively high strength, low thermal conductivity, and superior reactivity to oxygen [5]. The titanium alloys can be bonded with various types of steels to attain the multi-functional applications as they hold up the elevated strength and stability at reasonably high temperatures [6]. Ti-6Al-4V is an alpha-beta alloy, during welding, the complexities in the microstructure are set up and they attempt to increase the hardness and strength when melted [7]. The joining of thermoplastic complex structures is rapidly growing as its usage is replacing the metallic and thermoset complex counterparts to endure the static and fatigue loads useful to aerospace vehicles [8].

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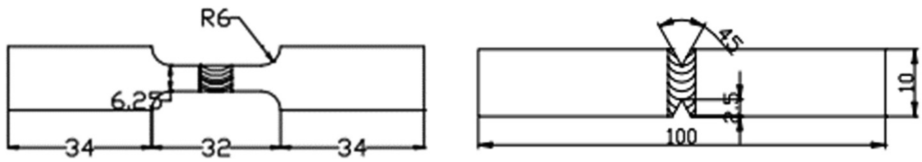

Fig. 1. Flat tensile specimen: (a) un-notched (b) notched [81].

2. Mechanical response

As the heat is produced during the welding process, it has the well-known effects on mechanical properties of components namely tensile property, hardness, fatigue crack growth resistance, fracture toughness [9]. In reaction to the direct result of process parameters on tensile strength, it is found that the tensile strength is directly proportional to welding speed(s) and gas flow rate (G) and inversely proportional to the wire feed rate (F) and welding voltage (V) [10]. In the GTAW and GTCAW welding methods, it is observed that, when test temperature increases, the tensile strength of the joints decreases and the increase in test temperature increases the elongation of the material [11]. In the longitudinal and transverse directions, the micro and macro hardness dimensions were constant and it is observed that the alloy to be harder in transverse than in the longitudinal direction [12]. The microstructure analysis found that the performance of superplastic on Ti-6Al-4V alloy was governed by the phase transformation and grain boundary sliding (GBS) [13]. During the tensile test, the fracture tends to occur in the material at its weakest zone and the obtained results indicate that the mechanical properties are related to the circumstances of the parent material for giving out the welded structures without any defects [14]. The consequence of fatigue cracks growth resistance on the titanium alloy automatically condensed by the welding process and found that as compared to other processes the laser welds have the advanced fatigue crack growth resistance [15] and the standard specimens for tensile test have been shown in Fig.1.

3. Porosity variation and its cracking on welding titanium alloys

Cavities in the weld metal are typically referred to as the pores or porosity. From the base of the weld pool, the weld metal porosity of a titanium alloy is known to be created [16]. Through the titanium welding process, the pores set up are rounded and it is allied with the evolution of gas. On the loading conditions, the pore cracking mechanism has possessions on crack initiation and propagation [17]. Due to the imperfection from the grease, dirt, oil on the exterior of the weld piece, the arrangement of the weld porosity occurs [18].In the region of weld metal, the weld bead geometry has the superior authority on the fatigue act of the joint in the microstructure [19]. Due to the inappropriate circumstances in the laser welding, the huge amounts of porosity are introduced into the section of the fusion zone and it is shown that the porosity is nearby the tapered fusion zone of the imperfect penetration welds [20]. At the pores, the pore cracking begins primary to the development of leak paths and those cracks with profound lying huge pores are expected to build up into leaks [21]. At the stage of low heat input, the weld pool dimension becomes small leading to the superior speed of solidification; as a result, it leads to porosity arrangement because the bubbles which could not run away prior to the solidification method were captured [22]. To close the development of porosity, it is characterized in three stages: bubble development, growth and escape [23] (Fig. 2).

4. Effect on welding current and voltage

Using the Hall-Effect current sensor, the welding current can be calculated and it is found that the current is surrounded at the contact tip of the welding pistol and fixture from which the arc voltage can also be calculated [24]. On comparing the variables with material responses (temperature, resistance, reflection, velocity) the process inputs (current, voltage) can be adjusted [25]. The arc length, weld metal properties can be guarded by the arc voltage, as the arc voltage increases the arc length also increases which grades in wider bead thickness [26]. In the plasma arc welding (PAW) process, surrounded by the certain range raising the welding current gives the stronger heat and force act from the plasma arc surface, in turn, the measurement grows as the current increases, increase in measurement concludes in increase of plasma voltage [27]. Using the different processes, the experiment was conducted on the arc and metal efficiency and establishes that inside a given process for the choice of current investigated the arc efficiency has not diverse notably [28]. In gas metal arc welding, for the measurement of droplet size, it is found that as the current raises its value the droplet size decreases and it starts to move away from the calculated standards as the current raises [29]. The variations in the current for the steady range of voltage power source introduced by the contact tube-to-work distance (CTWD) may cover the variations as of the weakening contact tube [30]. In the GTAW method, irrespective of the variations in the base current and pulse-on-time, two regions occur which initially increase the tensile properties and then decrease because of the grain size refinement [31].

5. Microstructural variation

In the laser beam welding, from the weld pool to the base material the combined section undergoes variations in thermal rise; due to this spatial and sequential division of temperature, it produces the non-uniform microstructure [32]. As the microstructure has elevated spatial gradients in the heat-affected zone, it grades the difference in the mechanical variations among the base material and fusion zone [33]. An increase in the carbon content in the weld metals, rising division of lesser temperature commodities together with martensite was experimented [34]. When the dendrites are united in a manner and if the cracks are united to the interior of the fusion weld method, then the well-united dendrite microstructure caused by the addition of filling the tapered gap welding method is accepted to consequence in elevated fatigue crack growth [35]. Microstructures of the old fusion zone at the different temperatures were comparable and establish the existence of decayed martensitic configuration and they are likely to situate at the lath margins [36]. The heat-affected zone ($\alpha + \beta$) has the microstructure gradient which is very rigid to compact with, the huge changes in properties among the base metal and heat affected zone in HAZ (β) phase [37]. The layer width has a small influence on microstructure and has the main role on the unique materials, as in SLM it is found that the ambient gas is produced and the gas varied with the powder has no time to run from the molten pool [38]. In the SLM process, the microstructure model varies in

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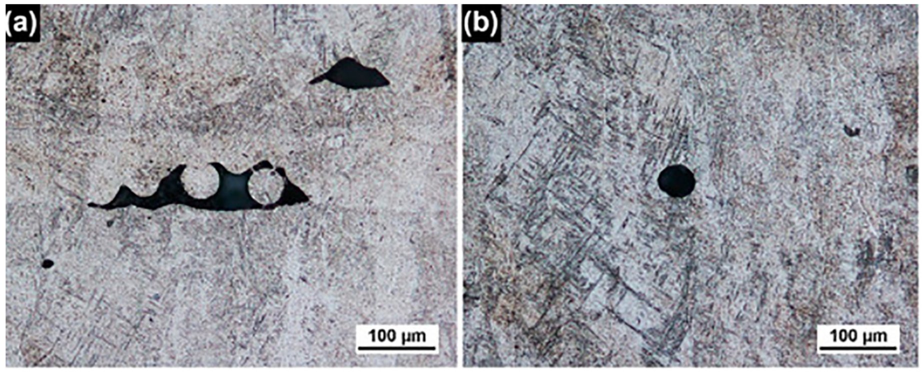

Fig. 2. Porosity in electron beam melting of Ti-6Al-4V: (A) Lack of fusion pore and (B) gas pore [82].

three different views: top, front and side view; on the outlook of elevated temperature gradients, the nearby phase is the extremely fine acicular martensite [39]. The enhanced mechanical properties were endorsed to microstructure enhancement, lessening in the β grain surface area and an increase in the β grain compactness and enlarge in the volume fraction of α primary phase [40]. The contrast was made on the mechanical properties of bi-lamellar structures and the original structures and found that the yield stress at room temperature or above is improved as well as the resistance to fatigue crack nucleation is improved [41]. The fine grain size is initiated in the friction weld joints due to the dynamic recrystallization obsessed by the widespread plastic deformation related with the frictional and forging stages and the wide-ranging grain refinement is observed [42]. On the observation, it was found that when the sample is cooled at temperatures varying from the solution treatment to the subsequent isothermal ageing process, the continuous layer of α phase is formed behind the β phase boundaries [43]. To bring back the microstructure to the uniform stage under the rapid cooling condition the liquid nitrogen is sprayed along the top surface which resulted in the process of high rate of heat loss to reduce the temperature gradient [44] (Fig. 3).

6. Effect of residual stress on welding titanium alloys

The transverse residual stresses are tensile in the weld with the exterior areas subjected to compressive residual stresses for balancing the stresses and found that the maximum tensile residual stress (200 MPa) is approximately 25% of the yield strength of the base substance and it is found to be at the centre-line of weld [45]. In the case of friction stir welding, when the material is subjected to a sufficient amount of air- cooling of about 760 degrees Celsius for 45 min in the argon atmosphere, this enables the drop of residual stress. On welding the substance, the elevated tensile

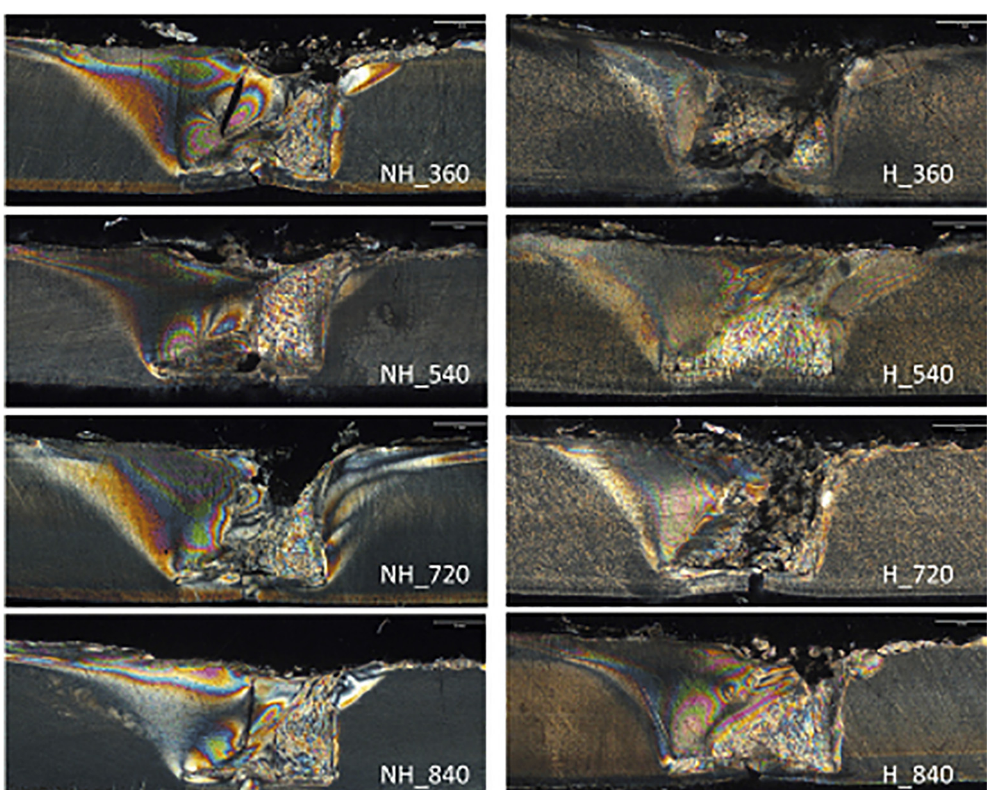

Fig. 3. Weld cross-sectional micrographs under cross-polarised light for samples welded with assisted heating (H) or without heating (NH) [83].

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residual stresses promote the fracture in the weldment; the compressive residual stresses, in the base shield repeatedly united with the deformation, and may decrease the buckling strength [46]. A material with great tensile residual stresses has a small variation in fatigue strength, but a suitable compressive residual stress can significantly develop it [47]. On the character of the morphology of TI alloys, the friction welds tend to consequence in several issues on structural integrity. One of them is when the thermal conductivity of the titanium is lesser; the friction welds are naturally allied with the large residual stress [48]. The special effects on the deep cryogenic treatment (DCT) on the residual stress of electron beam welding of Ti-6Al-4V joints found that, by the side of the direction of welding the transverse and longitudinal residual stress standards reduced respectively [49]. On concluding, according to the linear friction welds the residual stresses are generated through two processes. First is due to the plastic deformation experienced by the material at high temperatures. Second is due to the thermally induced strain from the disparity in thermal extension and reduction of the substance throughout heating and cooling [50]. The residual stresses can increase the harm by creep, fatigue, environmental degradation. On welding, compressive yielding occurs just about the molten material due to the heating and expansion of weld material. In opposite, on the cooling and shrinkage of metal, the tensile residual stress in the longitudinal direction of the weld is induced [51]. In laser gas nitriding, Subsequent to the nitriding process, the specimen decreases its residual stress value due to the preheating of the specimen at high temperature throughout the application of the stress relief behavior [52]. The exact standards for the crack under the combined load in majority of the cases can be given by choosing the crack under the tensile residual stress and at the external load cases should be different [53]. The laser welded joints found to have the better super plasticity on low strain rates. By increasing the temperature and decreasing the strain rate, it is observed that the peak stress of the material at the weld zone decreased but the peak stress was higher than that of the parent material [54].

7. Effect of heat treatment

The heat treatment method was passed out at a temperature of 955 °C for 30 min in an argon environment kept at the Lindbergh atmospheric furnace where the post-heat treatment method encompasses the characteristics like hardening and softening of the material [55]. The weld zone geometrical difference and flash morphology confirms that the friction time had a considerable effect and the weld zone width drop was experimental with an increase in concavity [56]. The microstructures and mechanical properties of mass Ti-6Al-4V parts obtained by SLM and SEBM were compared and found that the SLM parts formed the better yield and ultimate tensile strengths than the SEBM parts, but found that the ductility of SEBM parts were better [57]. For welding the metals, the fusion welding is the most generally considered method in the industry because it possesses the toughness and tensile strength properties of high-quality [58]. At 900∘C, the heat treatment system resulted in greater hardness and weld ability and at the quick growth rate of heat treatment the ductility and strength of the material improved, by lessening the β mass of the grain [59]. At each position it is found that, by rising the welding speed, the temperature found to be decreased and the high and low temperature variations at these localities close and far from the melting pool are acceptable [60]. Post-weld heat treatment is used in titanium weld structures to reduce the residual stresses produced throughout the fabrication, to steady state the weld zone microstructure and to recover the ductility or absolute the base material heat treatment [61].

8. Experimental analysis of various gases

The filler material is used in the gas-shielded welding is generally carried out with the gas in the ternary and quaternary mixture comprising argon, helium and oxygen which makes it to improve the welding ability [62]. The consequence of shielding gas mixtures variation on the grain size dimensions and morphology in the fusion zone found that the grain size depends upon the shielding gas composition [63]. The titanium alloy was nitride by heating at a particular temperature for a suitable time in the atmospheric nitrogen, the coating was formed where the Al, V and oxygen were dissolved and the nitriding process increased the micro hardness [64]. The denser deposits can be generated by dropping the hydrogen and oxygen content of the recycled powder and it can also be generated by utilizing the air as the process gas [65]. The additional energy can be obtained in the energy source with the better penetrating ability when the helium content of the shielding gas is greater but the improved content of helium can decrease the weld width, augment the root width and make the base of weld cross-section smoother [66]. If the shielding gas flow rate is increased, the electron density of the plasma decreases obviously i.e. increasing the shielding gas flow rate can decline the plasma eruption [67]. The shielding gas is supplied to the work piece fixture from both sides equally for shielding the trailing sides of the bead of the weld and the gas is also supplied from the top surface of the material along the nozzle axis and from the another nozzle which is inclined to an angle with a flow rate at the laser column [68]. The gases released by the flux cored arc welding (FCAW) are very dangerous. The release of these gases during the welding process depends upon the constituents of the wire inside the core but not upon the shielding gas that were used [69]. The avoidable utilization of the shielding gas and the flow at variance changes frequently, the deformity can be formed in the weld structures on improper cooling when the discrepancy occur between the shielding gas flow and the changing welding conditions [70].

9. Fatigue life prediction on titanium alloys

The welding residual stresses have the substantial effect on the fatigue life of the weld, by nucleating the crack or extending the crack grain size the fatigue life is controlled [71]. Due to the plastic strain at the notches the fatigue cracks can occur and the life of the spot weld specimens mainly depend upon the type of the specimen, the practical load amplitudes, the diameter and the thicknesses specified for the weld geometry [72]. On welding the coiled tubes, it was found that the fatigue lives were stronger for the high strengthened tubing to the low strengthened tubing with the high internal pressures possessed in it [73]. With the variation in the endurance limit, the fatigue life to the crack initiation considers the factors like the grain size and stress concentrations in its calculation which require tensile tests to determine the elastic properties [74]. By evaluating the proportions at which the energy is unrestricted and the threshold stress intensity concentration factors accompanying with the voids can enumerate the bending fatigue results of the weld material [75]. During the process if the fatigue damage occurs, it results in the formation of the gap between the two stages and the connection between the fatigue size and the corresponding fatigue life is significant for fatigue design and its estimation [76]. The fatigue cyclic life can be long-lasting as the crack starts multiplying which in turn the stress strain characteristics will have powerful influence on the induced geometry which can extensively hinder the rate at which the crack starts multiplying [77]. In case of low cycle fatigue, at the preliminary stage the fatigue life of a irregular specimen is equal to the entire fatigue life of the regular specimen subjected to the stress

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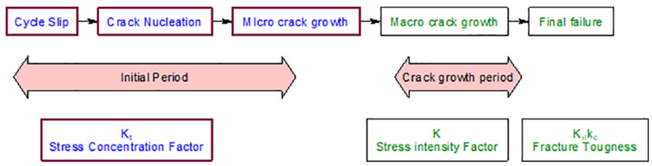

Fig. 4. Fatigue life phase and factors [84].

and strain range factors [78]. In the spot weld structures, it is observed that with the increase of the loads the fatigue life of a material decreases, however, with the increase of the spot weld diameter the fatigue life increases [79]. In the fatigue analysis, the fatigue crack initiation was found to be at the interior surface, the dissimilarities in the fatigue resistance of TI tubes were found between the high temperature environment and the air environment [80] and the schematic representation is given in Fig. 4.

10. Conclusion

In this paper, the mechanical properties and parametric variations of the titanium alloy (Ti-6Al-4V) using diverse welding methods are discussed in detail and reviewed the results of welding capability. Due to the nature of physical and mechanical properties, the titanium has further benefits like high melting temperature, light weight compared to the steel but it requires higher durability. This type of welding technology is used in various kinds of fields in our life. On welding the titanium alloys (Ti-6Al-4V), the problem that arises is that the welding portion should not change its state at high temperatures i.e. the oxide layer must be separated before welding the titanium. For welding metals, the welders with high skills and with wide applications known are needed to carry out this process. It is found that, among all the welding techniques the gas tungsten arc welding (GTAW) is the generally used technique for joining the titanium alloys except for the parts of the thick sections which does not require the high skills at welders. In welding the unnecessary occurrence can be controlled by applying the high frequency micro-oscillations at the tip of the welding point in case of the MIG process. Hence to conclude that, due to the various developments found around us, we can try to utilize this in a better manner and can enhance the further more developments in upcoming generations.

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