A Review on Welding and Fatigue Behaviour of Titanium and Its Alloys

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Abstract: Titanium is metal element which comprises about 0.44% of earth’s crust. The abundance and reliable properties of this element made it essential in field of engineering works. Welding is a fabrication process which fuse the materials together. Welding of titanium and its alloys expands the applications of usage of titanium. The idea of this review, is to sum up the welding and fatigue behavior of titanium and its alloys. It has been identified that laser beam welding (LBW) is feasible for titanium and its alloys due to its flexibility, high heat capacity input and efficiency.

1. Introduction
Titanium is that the fourth most bottomless part on earth. Atomic number 22 and its composites have many engaging properties, such as high express quality, excellent consumption obstruction, unmatched biocompatibility, warmth opposition, disintegration opposition, higher exhaustion, and breaking obstruction. The properties mentioned above have prompted enterprises and specialists' enthusiasm for their utilization throughout the most recent 20 years. They’re usually used in aviation, marine, substance, atomic, management plant, therapeutic, transport, and donning businesses. Run of the mill segments incorporates turbine sharp edges, fuel pipelines, orthopedically inserts, fumes conduits, aircraft landing gear, motor casings, careful instruments, head shielded barbecues, mechanical device shafts, and heat exchangers [1–4]. Welding is a fabrication process in which two or more parts are fused together by means of heat, pressure or both forming a joint after the parts get cooled. There are different types of welding techniques such as, shielded metal arc welding (SMAW) uses a metallic consumable electrode for producing arc between itself and the work piece. The molten electrode metal fills the weld gap and merge the work pieces. GTAW, also known as tungsten inert gas (TIG) welding, is a type of arc welding which uses a non-consumable tungsten electrode to perform welding. Gas metal arc welding (GMAW), which uses the electric arc generated between the consumable MIG electrode and the workpiece. The electric arc which is produced between the electrode and the workpiece is used to join the metals. Flux cored arc welding (FCAW), which is both automatic or semi-automatic process. It uses a tubular electrode which is filled with flux. Submerged Arc Welding (SAW) is a process that involves forming an electric arc between a continuous feed electrode and a piece of metal. It uses a blanket of powdered flux to cover the arc and provide electrical conductivity. Electron-beam welding (EBW) is a fusion welding process which uses high velocity electrons to fuse the metals together. The heat produced by the electrons generates the thrust needed to push the metals together. Laser Beam Welding (LBW) is a type of fusion welding that uses a laser to join metals [5–9].
2. Mechanical feedback

Titanium alloys can be welded with distinct types of steels due to its stability at higher temperature and enhanced strength [10]. Ti-6Al-4V is a two-phase titanium alloy with numerous applications in various industries such as oil and gas reprocessing plants, biomedical surgical instruments, and aero-engines. Its robustness and high mechanical strength make it suitable for various industrial applications. [11]. Fusion welding process (FWP) was used to weld the titanium and its alloy. Despite having a vast application, there are some drawbacks with traditional joining process of Ti-Al-4V, such as brittle coarse microstructure, epitaxial growth, coarse β grains, and a significant distortion with a high residual stress. In order to solve this problems, solid state joining methods like diffusion bonding friction welding and explosive welding are performed to join the metal materials [12]. After all, these solid-state welding processes are not capable to produce good quality joints when the titanium is combined with other elements such as aluminium, stainless steel, magnesium etc. [13]. Then the Friction stir welding (FSW) was used to provide quality joints and to eradicate the problems emerged while performing complex joints [14]. Friction stir welding (FSW) is one of the types of solid-state welding process. It is a welding process that uses a non-consumable electrode to join the workpieces without melting it. Here the heat is generated by the friction produced between two workpieces [15]. Several examinations were accounted for on erosion combine attachment (FSW) of atomic number 22 and its mixtures [16]. FSW has all the earmarks of being a tempting robust state technique that stays removed from the larger part of the disadvantages of combination attachment. FSW is used for the connection of auriferous cylinders [17]. However, expensive ultra-hard devices square measure usually needed for atomic number 22. Instrument wear is noteworthy, and device life is restricted to not several meters of fruitful joint [18]. Connection of atomic number 22 could be an elementary necessity to use in primary and alternative individual segments. An enormous vary of combinations and robust state attachment forms square measure usually used for the connection. Atomic number 22 and its compounds show excellent weldability by combination connection ways. The gas metal arc welding (GTAW) method provides wise joint properties. Anyways, it will originate coarse grains within the combination zone, additional in-depth heat affected zone (HAZ), poor flexibility, and bending [19,20]. A high vitality attachment procedure, as an example electron beam welding (EBW) could beat the cutoff points of GTAW [21]. But it will anyways need an attachment at a high vacuum that built the expense of the procedure together. Since EBW is completed in an incased chamber, following the attachment crease is testing. The complete discovery must be maintained during an ultraclean state that evade damage to siphoning unit [22].

Optical device bar attachment (LBW) is considered as a correct technique to affix atomic number 22 and its mixtures [23]. LBW is practiced utilizing an optical device pillar from a lasing supply. The optical device bar could be a lucid, collinear, incorporated and monochromatic lightweight emission radiation. The optical device pillar could have a very high vitality thickness and may be engaged to a far confined space. There's no real contact between the laser supply, optical device head and the workpiece material. An exactly engaged optical device shaft permits high attachment rates once contrasted with alternative ancient combination attachment forms. The potency and recurrence of the procedure is excellent and the mechanism is cheap. Usually, LBW doesn’t require any filler materials and also the problems with likeness of filler material and its utilization square measure during this means nonexistent. LBW produces slender dot pure mathematics and a restricted HAZ. The accidental injury is nominally attributable to lower leftover worries within the joints. A large edge design is not needed for the LBW before the connection. The main noteworthy LBW method parameters measure optical device manangement, attachment speed, episode edge, spot distance, and mid length [24–28]. Some exploration of LBW of atomic number 22 and its mixtures was accounted for in the writing these days.
3. Welding of titanium alloys

In engineering, any method has two or a lot of metal items joined by applying warmth, pressure, or a mix of each. Attachment is employed for creating permanent joints. It is involved in various applications such as automobile parts, structural works, ship building etc. Among the different welding processes, arc welding types are also applied in advanced technical experimental analysis like Carbon arc welding, metal arc welding, MIG, TIG, Plasma arc welding, submerged arc welding, electro slag welding, etc [29]. Infusion welding is done when the base metal is melted to a liquid state, and the metal is filled with filler metal. The metal is then heated using various means, such as electric arc, plasma arc, and inert gases. For materials such as Al, Ti which quickly form oxide layers, the weld puddle should be surrounded by the atmosphere of inert gases like argon, helium etc. [30].

Titanium could be a low-density part (approximately an hour of the density of iron) that may be greatly reinforced by deformation and alloying process. Titanium is element having a property such as sensible heat transfer and non-magnetism [31]. It has a less thermal enlargement when compared to iron and aluminium. Titanium and its alloys have higher melting points than steels. However, most helpful temperatures for structural applications typically vary from 425 to 595°C (800 to 1100°F). Nuclear number 22 has the flexibility to be passivated and so exhibits a high degree of immunity against the most mineral acids and chlorides. Atomic number 22 is nontoxic and also biologically adoptable with human tissues and bones. The mix of high strength, stiffness, sensible toughness, density, and sensible corrosion resistance provided by varied atomic number 22 alloys at terribly low to elevated temperatures permits weight savings in part structures and different superior applications. The nuclear number 22 have two phases such as alpha phase (hexagonal crystal structure) and beta phase (body centered cubic). The transformation temperature (beta transformation (i.e.) completion of transformation to beta on heating) is powerfully determined by the opening parts atomic number 8, nitrogen, and carbon (alpha stabilizers), which raise the transformation temperature. The chemical element could be a beta stabilizer and lowers the transformation temperature [32]. Liu et al. joined four-millimetre-thick pure atomic number 22 sheets and explored the reinforcing part within the combination zone. They found that the strength and elongations of the LBW welds are the same as those of the BM, and the fracture rates are the same as those of the HAZ and FZ, implying that the HAZ and FZ are stronger than the BM [33]. Gao et al. joined 0.8-millimeter-thick Ti–6Al–4 V atomic number 22 compound sheets and targeted the elements adding to consistency development. They found that the porous geometry and the weld microstructure of pulsed laser-welded joints are related to the overlapping factor. As the number of overlapping factors increases, the weld's microhardness gradient decreases [34]. Carvalho et al. united one-millimetre-thick pure atomic number 22 sheets to form tubes and assess the weakness [35]. Mouawad et al. combined a pair of millimetre thick pure atomic number 22 sheets and researched the impact of crystallographic surface on the joint properties [36]. Ahn et al. merged a pair of millimetre thick Ti–6Al–4 V sheets and skint down the impact of laser power and attachment speed on the pure mathematics of the mixture zone [37]. Kashaev et al. fused a pair of millimetres thick Ti-6243 atomic number 22 amalgam sheets and evaluated the impact of procedure parameters on the joint microstructure and execution [38]. Zhang et al. joined one-millimetre-thick Ti-22Al-25Nb atomic number 22 amalgam sheets and did a place investigation to understand the disfigurement of the joint throughout the ductile check [39].
Various silver impurities or alloying parts might either raise or lower the transformation temperature. Alpha, near-alpha, alpha-beta, or beta are the four classes that represent the final type of microstructure once a process is finished. Most alpha alloys have a small amount of beta section, which is mainly due to the use of beta-stabilizers. [40]. An example of this is often the atomic number 42 and V additions in Ti-8Al-1Mo-1V. A near-alpha or super-alpha alloy might seem small structurally, kind of like an alpha alloy. An alpha-beta alloy consists of alpha and maintained or remodelled beta. Business beta alloys tend to retain the beta section on initial cooling to temperature [41]. However, they precipitate secondary phases throughout heat treatment is shown in fig 1.

### Table 1. Physical and Mechanical Properties of Titanium [30]

| Property                        | Value               |
|---------------------------------|---------------------|
| Atomic number                   | 22                  |
| Atomic weight                   | 47.9                |
| Atomic volume                   | 1.06 g/m^3          |
| Atomic radius                   | 0.133 nm            |
| First ionization energy         | 661.5 eV/mole        |
| Thermal neutron absorption cross section | 560 fm^2/atom       |
| Crystal structure               | close-packed, hexagonal ≤ 1156 K body-centered, cubic ≥ 1158 K |
| Color                           | Dark gray           |
| Density                         | 4510 kg/m^3         |
| Melting point                   | 1941 ± 25 K         |
| Solubility limits               | 1908 K              |
| Boiling point                   | 3533 K              |
| Specific heat (at 298 K)        | 0.518 J/(kg K)      |
| Thermal conductivity            | 21 W/(m K)          |
| Heat of fusion                  | 440 kJ/kg           |
| Heat of vaporization            | 9.53 MJ/kg          |
| Specific gravity                | 4.5                 |
| Hardness                        | HRB 70 to 74        |
| Tensile strength                | 241 GPa             |
| Modulus of elasticity           | 102.7 GPa           |
| Young’s modulus of elasticity   | 102.7 GPa           |
| Poisson’s ratio                  | 0.41                |
| Coefficient of friction          | 0.8 at 40 m/min     |
| Specific resistance             | 0.68 at 300 m/min   |
| Coefficient of thermal expansion| 0.554 μm^-1         |
| Electrical conductivity         | 3% IACS (copper 100%) |
| Electrical resistivity          | 0.478 μΩm           |
| Electroconductivity             | 1.5 Paunings        |
| Temperature coefficient of electrical resistance | 0.0026 k^-1         |
| Magnetic susceptibility          | 1.25 X 10^-6 μΩm    |
| Machinability rating             | 40 (equivalent to 1, hardness stainless steel) |
4. Effect of welding current and voltage on titanium alloys
The welded workpiece is created into specimen size of concerning two hundred metric linear unit length and 12.5 metric linear unit dimension exploitation EDM method in line with ASTM-E8 standards. The durability worth for all specimens is shown most durability is obtained is 342.2 MPa. For which associate degree specimen with input parameter worth of attachment current of ninety-five Amps, attachment speed at sixty mm/min and arc voltage of seventeen volts [42]. D. K. Gope et al. reported in the empirical inquiry of pug cutter fixed TIG welding of Ti-6Al-4V titanium alloy number seventh sample with a maximum current of 90 ampere and minimum speed of 175 mm/minute. The welded portion of the sample gives the highest hardness values, around 414 HVN. At the same time, the third sample gives failure values when the current 75 ampere and high speed [43]. T. Senthil Kumar et al. found that there is direct relationship between the peak current and pulse frequency which affects the tensile properties of welded joints. If the maximum current is accrued, then the lastinness increases, and a similar result is determined once the frequency is accrued. However, the base current and pulse on time have a reciprocally proportional relationship with the lastinness. From the experiment done by wan et al., it has been found that the final strength and production capacity of twisted metal parts with a maximum of 240 amperes is higher than those with a current 180 amperes [44]. They found that the strength and harvesting power of small TIG lamps welded to the members of the dense titanium alloy was altered by the shape of the test samples. The microhardness values of the fusion zone and the temperature-sensitive area are higher than those of the base metal, and there are higher localized temperature-sensitive values near the base metal. The highest level of microhardness in the heat-affected area was around 349 HV which increased by about 17.9 percent while analyzing the basic meta [45]. CHEN Jian-Chun, et al. the tensile samples of Ti-6Al-4V material were two hundred metric linear unit×50 metric linear unit×7 mm (30 mm within the center), and therefore the impact samples fifty-five mm×10 mm×7mm, severally. The attachment speed was two to three mm/s, and therefore, the opening diameter was one. Eight metric linear units allow maximally current of two hundred A. the height current was elite to be eighty A. the bottom current and its amount were thirty A and 200ms, severally. The experimental results from fracture surfaces and small hardness within the welded zones demonstrate that the dynamically controlled PAW method dramatically improves the hardness of the welded joints. The common small hardness price is 361 HV is measured inside 12mm distance and 349 HV is measured within 25mm distance of samples [46].Jing Liu et al. butt attachment tests were performed on business plant reinforced Ti6Al4V atomic number 22 compound sheets with measurements of 260×110×1.2 metric linear unit utilizing a JHM-1GXY-400X beat Nd: YAG optical device attachment machine with attachment parameters square measure a hundred and eighteen A current, 320mm/min attachment speed, frequency is 15HZ and pulse breadth is five.5ms. The properties of the LBW square measure the yield strength is 968 MPa, strength is 1108MPa. Likewise, the BM properties square measure the yield strength is 856 MPa, strength is 1089MPa [47].

5. Fatigue studies of welded Titanium alloys
Jing Liu et al. the microstructure shows needle-shaped forms are there at fusion zone due to rapid heat removal technique in laser beam welding. The fatigue examination shows fatigue mutilation growth rate is fast at weld beads related to the base metal. At the fusion zone, the martensite structure is a major reason for rapid crack growth at the exact welded area [48]. M. Ramulu et al. from the above-tabulated data, it's obvious the fatigue is improved by further heat treatment after welding compared to the base metal. The welded portion shows improved fatigue strength, specifically the high temperature 871°C and 927°C heat treatment improves the fatigue strength near base metal fatigue strength. Therefore, further in-depth experimentation gives more openings to fatigue strength improvement on titanium alloys [49].
Figure 2. Fatigue studies of welded Titanium alloys [37]

T.S.Balasubramanian et al. show the cyclic load test result of GTAW specimen fatigue strength of non-notched is 110 MPa at 1x106 cycles which is 1.91 times more than BM value. At the same time, the fatigue strength of notched is 45 MPa at 1x106 cycles which is 2.22 times more than BM value. The fine lamellar structure improves the resistance against crack growth and the fatigue strength of LBW joints [50]. Luca Boccarusso et al. experiment results show the crack instigation at the top of the welded surface because of the specific heat input. Here the specific heat input parameter plays an important role in the fatigue behavior of the welded part. After cleaning with H2O–HF–HNO3, the 100x50x3mm size Ti-6Al-4V sheets are welded with Laser beam welding technology [51]. These welded sheets show the varying fatigue behavior concerning variable-specific heat input. The minimum fatigue life value starts from 6,94,228 cycles at 87.5 J/mm specific heat input, and the maximum fatigue life value is 1,74,048 cycles at 133.3 J/mm clear heat input that is increasing in fatigue life with decreasing specific heat input. J. Tao et al. investigation says that the fatigue life of the electron beam welded Ti-6Al-4V sheets are added with hydrogen concentration from 0% wt. to 0.140% wt. The fatigue test result shows that the specimen's fatigue life increases with decreasing hydrogen concentration %wt [52].

6. Titanium at elevated temperatures

The most important properties for higher temperature titanium alloys are high specific strength and toughness divided by density. The peak service temperature of titanium alloys is mainly constrained by the susceptibility to creep and oxidation. Titanium alloys of today are defined to a maximum operating temperature of 600 °C [53]. They are usually used chiefly for temperatures about 540 °C. However, these parts have several thousand times of enlistment. Titanium alloys are also used in high-performance motors for Cylinders [54]. The exhaust manifolds operate at 820 °C but slightly less than the aerospace sample.
Some new high-temperature titanium alloys produce dispersoids of rare earth elements to enhance creep resistance [55]. Such dispersoids, on the other hand, maybe an origin for crack. Work to improve structure and behavior is ongoing [56]. Intermetallic Titanium alloys demonstrate substantially higher tolerance to creep and oxidation. Several intermetallic phases of different forms like TiAl, Ti2AlNb, Ti3Al, and Al3Ti are currently of significant importance. But the most research works are on TiAl [57]. This intermetallic process displays outstanding resistance to creep and oxidation, high strength to fatigue, high modulus, and low density [58]. Moreover, due to the analogous flexibility, a significant change has not yet been achieved. Present alloys of the third generation TiAl show some change [59]. The Ti2AlNb and Ti3Al intermetallic phases are having low density but substantially higher corrosion resistance and strength. It causes both stages to interest in replacing Nickel-based Superalloys. The two-phases must be used for much higher operating temperatures than traditional Titanium alloys. Two-phase titanium alloy systems are well known to experience a sudden decrease in ductility at elevated temperatures ranging from 1000 to 1150 °K. This lack of ductility is demonstrated by the simple decohesion of polycrystalline aggregates across the boundaries of the elevated-temperature beta phase grain [61]. Isothermal compression evaluations have distinguished hot working behavior of Ti60 alloy Ti60 flow stress reduced with higher temperature and lower strain rate [62]. Non-ferrous alloy based materials widely employed in automobile and aerospace applications [63-70].

7. Conclusion

Modern research has shown that laser beam welding is best used with titanium welding because of its flexibility, high thermal conductivity, and efficiency. It is used in many applications such as biomedical, chemical, aerospace, nanoparticle, marine, energy production, and aerospace industries. The literature shows that the specification of laser production greatly affects integrated mechanical properties. However, other repair issues and welding problems, such as low sides, low fatigue features, substrate oxidation, penetration, non-filling, and weld cracks, are listed in titanium alloy laser welds. Therefore, this review provides better clarification for researchers to develop more research work with titanium tubes and its alloys.

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