World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:9, No:11, 2015

Effect of Butt Joint Distortion and Comparison Study on Ti/Al Dissimilar Metal Using Laser Beam Welding

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Abstract**—**In general, it is desirable to finish the weld quickly, before a large volume of surrounding metal heats up and expands. The welding process used, type, welding current and speed of travel, thus, affect the degree of shrinkage and distortion of a weldment. The use of mechanized welding equipment reduces welding time, metal affected zone and consequently distortion. This article helps to define what weld distortion is and then provide a practical understanding of the causes of distortion, effects of shrinkage in butt joint welded assemblies using TI6AL4VA and Aluminium AA2024 alloy sheet. The beam offset position to the joint interface towards titanium and aluminium side. The factors affecting distortion during welding is also given. Test results reveal that welding speed is the significant parameter to decide the extent of distortion. Also welding from Al side reduces the distortion while Ti side increases the distortion.

Keywords**—**Nd:YAG Pulsed laser welding, Titanium/Aluminium thin sheet butt joint, distortion.

I. INTRODUCTION

THE material of Ti6Al4V and AA2024 alloy sheet is widely used in both the aerospace and automobile industries for its high stiffness, strength to weight ratios [1]-[3], high corrosion resistance [4], relative ease of processing [5]-[7] and good mechanical properties [8], [9]. As one type of solid state laser beam welding, Nd:YAG welding has been widely adopted for welding of very thin sections [10].

Distortion is the change in shape, temporary or permanent of welded parts as a result of welding. It may be accompanied by internal stresses of any magnitude up to the point of yield point of the material. Distortion in a weld results from the expansion and contraction of the weld metal and adjacent base metal during the heating and cooling cycle of the welding process. Doing all welding on one side of a part will cause much more distortion. During this heating and cooling cycle, many factors affect shrinkage of the metal and lead to distortion, such as physical and mechanical properties that change as heat is applied. For example, as the temperature of the weld area increases, yield strength, elasticity, and thermal conductivity of the steel plate decrease, while thermal expansion and specific heat increase as shown in Fig. 1. These changes, in turn, affect heat flow and uniformity of heat distribution [11].

When fusion welding is performed, the melted metal quickly contracts on cooling from the liquidus to room temperature, resulting in shrinkage over the weld and exerting eccentric force on the weld cross section.

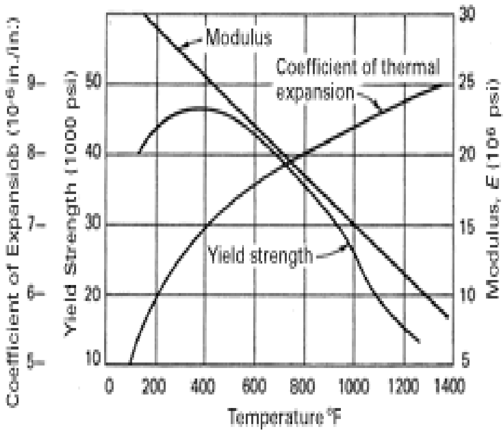

Fig. 1 The factors contributing to weldment distortion.

The weldment elastically strains in response to the stresses caused by the contraction of the weld metal and causes irregular strain with macroscopic distortion. Fig. 2 shows different types in welding distortion such as (a) Transverse shrinkage, (b) Longitudinal shrinkage, (c) Longitudinal distortion, (c) Angular distortion, (d) Fluctuated distortion and (e) Buckling distortion [11].

The principal features of the more common forms of distortion for butt and fillet welds are shown in Fig. 3. Non-uniform contraction through thickness produces angular distortion in addition to longitudinal and transverse shrinkage [11].

Distortion due to elastic buckling is unstable and flattens a buckled plate; it will probably 'snap' through and dish out in the opposite direction. Twisting in a box section is caused by shear deformation at the corner joints. This is caused by unequal longitudinal thermal expansion of the edges. Increasing the number of tack welds to prevent shear deformation often reduces the amount of twisting. This influences the degree of distortion mainly through its effect on the heat input.

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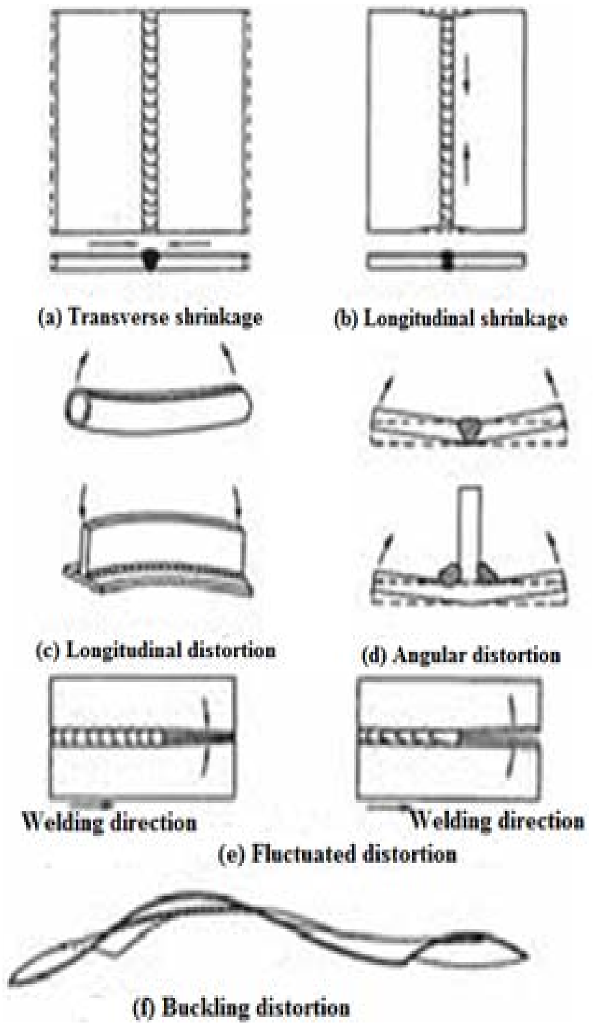

Fig. 2 Variation in welding distortion

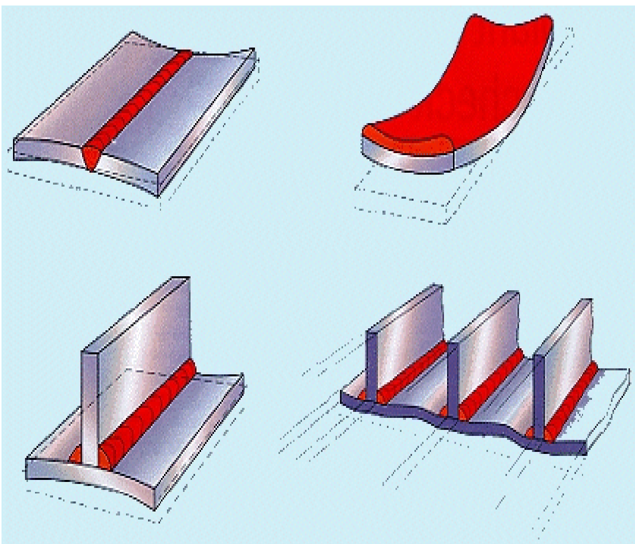

Fig. 3 Forms of distortion for butt and fillet welds

In order to minimize unexpected thermal distortion that is one of the critical problems in laser-manufacturing industries, the welding parameters must be carefully selected. However, they are typically set from experience, which do not ensure the expected welding quality. Most research results are dedicated to the theoretical and discuss the effects of welding parameters and material properties on welding distortions [12]–[15].

There are very few reports in the literature on Nd:YAG welded Ti6Al4V and AA2024 thin alloy sheet. Therefore, the effects of distortion on mechanical properties of titanium and aluminium 1.0mm thickness sheets are studied using various speed and laser focusing towards titanium and aluminium side.

II. Experimental Details

In the present investigation specimens are prepared with butt joint configuration using welding of TI6AL4VA and Aluminium Alloy AA2024 plates with dimensions of 150mm length, 75mm width and 1mm thickness as shown in Fig. 4. The chemical composition in weight percentage is given in Table I and II.

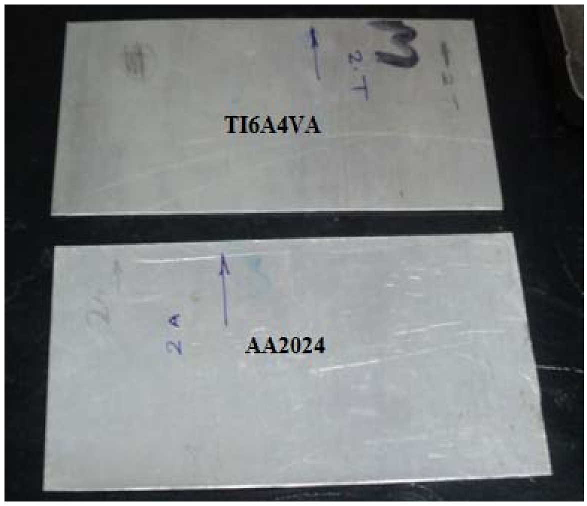

Fig. 4 TI6AL4VA and Aluminium Alloy AA2024

TABLE I
TI6AL4VA Titanium Alloy Chemical Composition

Component	Wt. %
Al	5.5 – 6.75
V	3.5 – 4.5
H	0.015
Ti	Balance

TABLE II
AA2024 Aluminium Alloy Chemical Composition

Component	Wt. %
Si	0.500 -1.200
Cu	3.800 - 5.000
Zn	0.063
Fe	0.700
Mg	0.200- 0.800
Ti	0.010
V	0.001
Pb	0.028
Mn	0.300- 1.200
Al	Balance

A. Laser Welding Unit

The laser welding system of JK600 Nd: YAG supplied by M/S GSI Group is a pulsed laser industrial with average power 600W, maximum frequency 1000Hz, pulse with range 0.2 – 2.0ms, fibre diameter 600µm. The experiments are performed with Energy 21J – 40J, Laser focus 200mm, Gas flow rate 10 l/min, Height 30% - 40%, Width 8.5mm – 9.0mm and Rate 15Hz - 20Hz. The speed of the operations is varied from 200mm/min to 240mm/min in steps of 10mm/min. The working principles of laser welding system are given in Fig. 5.

Fig. 5 Nd;YAG laser welding system

The work pieces are clamped each other tightly in order to get the minimum gap formation between the edges and to reduce the breaking off risk during solidification as shown in Fig. 6. An alternative approach has been suggested [16] and offset distance considered towards titanium and aluminium. This would require to conveniently tilting the laser head to prevent detrimental back reflection of the laser beam [17] as low aluminium absorptance, in addition, dissipation of the provided heat and affecting of fusion.

Fig. 6 Work piece clamping system

Beam offset distance of 0.3mm is fixed to the joint interface towards the titanium sheet and aluminium sheet as shown in Fig. 7. With respect to beam offsetting position of the laser beam is critical and any variation of the beam position with respect to the interface would affect the actual offset. It produces excessive mixing and insufficient bonding.

A system integrated camera is employed for primary fit up while setting the welding path. The robot which moves the laser head provides more accuracy and repeatability of the process. Preliminary trials are conducted to find an adequate power to be used in proper range of welding speed for deep penetrative beads.

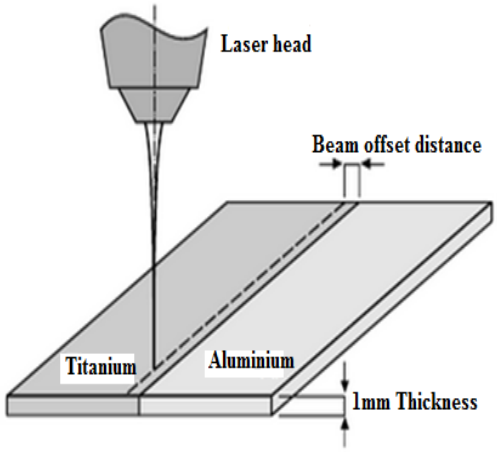

Fig. 7 Beam off set position to the joint interface.

Experiments are carried out by keeping offset distance towards titanium and aluminium side, to study the effect of distortion on both sides. The width of the test piece, frequency, height, focus distance and argon gas flow rate are kept constant and laser welding is performed on dissimilar weld joint. The welding speeds, energy consumed are noted and are given Table III.

TABLE III
WELDING CONDITIONS FOR PULSED 600W ND: YAG LASER

Sl.No	Rate Hz	Width ms	Height %	Energy J	Speed mm/min	Focus mm	Gas flow rate l/min
1	20	8.5	32	24.8	200	200	10
2	20	8.5	32	25.1	210	200	10
3	20	8.5	32	25.0	220	200	10
4	20	8.5	32	24.9	230	200	10
3	20	8.5	32	25.2	240	200	10

III. RESULT AND DISCUSSION

After completion of the welding it is observed on the welded joint smooth uniform and shiny beads. The top and back sides of the specimen are shown in Fig. 8. When thin plates are welded it is noted that residual compressive stresses occur in areas away from the weld and cause distortion. Moreover, the specimen length exceeds the actual length for a given thickness. While studying weld distortion, it is important to determine whether the distortion is being produced by buckling or bending. The expansion coefficient of aluminum alloy is higher than that of titanium alloy. The displacement of aluminium alloys rapidly increases and slowly decreases. But the distortion tendency initiates slowly and then rapidly to the maximum value. Also for titanium Gr5 alloy the distortion is slowly increases until reaching the maximum value after some time. It is noted that the physical properties of two alloys are different and the thermal expansion coefficient of aluminum alloy is higher than titanium. Moreover, the displacement of AA2024 alloy is higher than that of titanium Gr5 alloy. Distortion of titanium and aluminium is measured by using vernier height gauge with magnifying glass as shown Fig. 9.

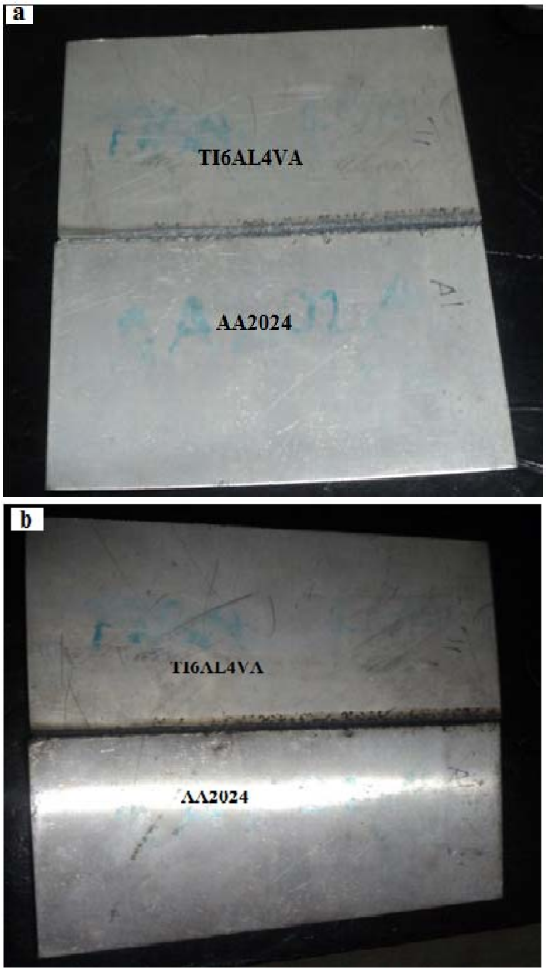

Fig. 8 Welding specimen (a) Top side and (b) Back side

The welded specimen is located on the surface block near vernire height gauge. The probe is touch on the edge of the specimen and indicates the distortion height as shown in Fig. 10. The magnifying glass is used to indicate accuracy of the reading.

Distortion height varies with different welding speeds as shown in Table IV towards titanium side of offset distance 0.3mm. Table V shows distortion towards aluminium side of offset distance 0.3mm.

It is found that distortion occurs during heating and different speed ranges. Test results of two alloys show that the critical states of distortion for titanium alloy and aluminum alloy occur at different time interval.

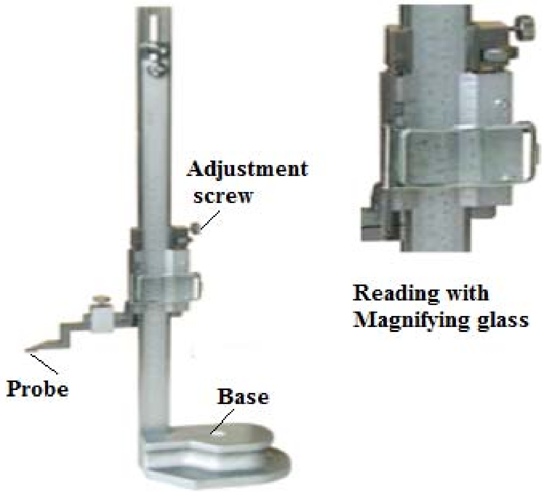

Fig. 9 Vernire height gauge

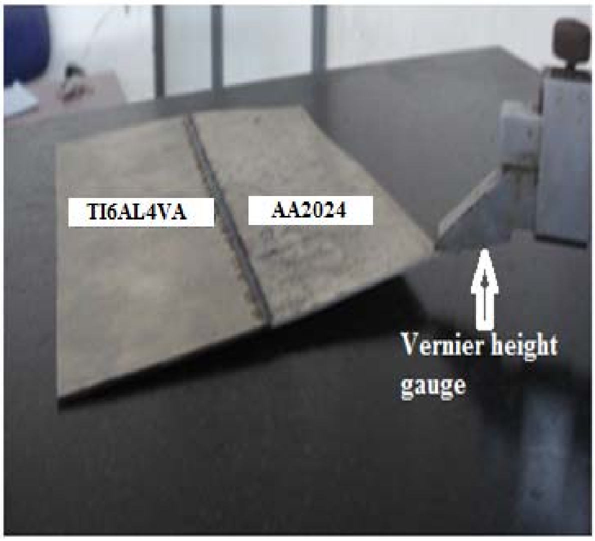

Fig. 10 Distortion of Titanium and Aluminium

TABLE IV
HEIGHT VARIATION USING DIFFERENT SPEED – TOWARDS TI SIDE

Speed (mm/min)	Distortion height (mm)
200	2.00
210	2.17
220	2.30
230	2.82
240	3.18

TABLE V
HEIGHT VARIATION USING DIFFERENT SPEED – TOWARDS AL SIDE

Speed (mm/min)	Distortion height (mm)
200	3.70
210	2.60
220	1.72
230	1.58
240	1.28

Fig. 11 shows the various distortion heights at different speed towards titanium side. Also increase in speed increases distortion. The maximum distortion is noted at 240mm/min.

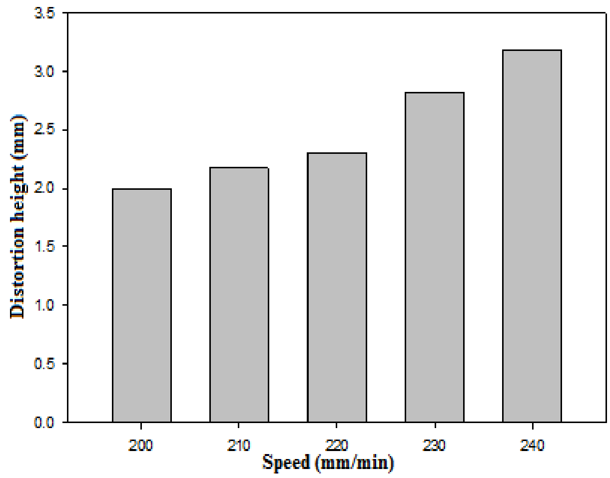

Fig. 11 Distortion towards Titanium

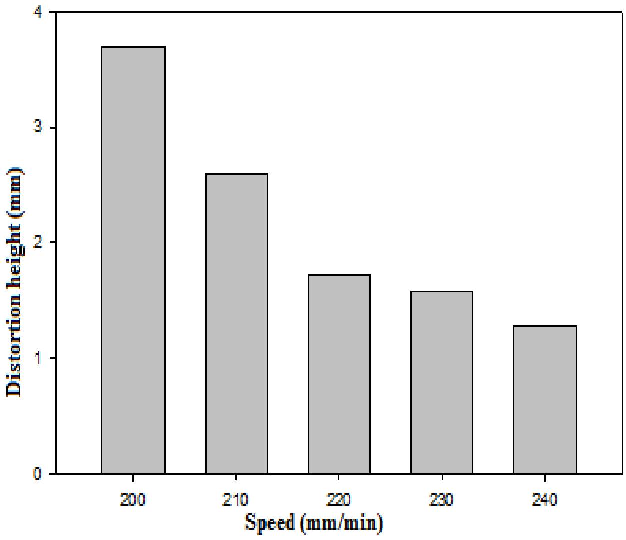

Fig. 12 Distortion towards Aluminium

From Fig. 12, it is observed that increase in welding speed reduces distortion.

IV. Shrinkage Control and Minimize Distortion

To minimize weld distortion, methods must be used both in design and during welding to overcome the effects of the heating and cooling cycle. Shrinkage cannot be prevented, but it can be controlled. Several ways can be used to minimize distortion caused by shrinkage.

A. Do not Over Weld

The more metal placed in a joint, the greater the shrinkage forces. Correctly sizing a weld for the requirements of the joint not only minimizes distortion, but also saves weld metal and time. The amount of weld metal in a fillet weld can be minimized by the use of a flat or slightly convex bead and in a butt joint by proper edge preparation and fit up, Fig. 13.

The excess weld metal in a highly convex bead does not increase the allowable strength in code work, but it does increase shrinkage forces. Fig. 14 shows avoid over welding and it shows excessive reinforcement and increases distortion.

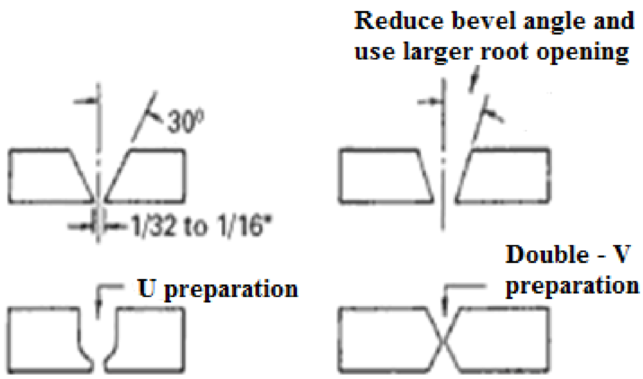

Fig. 13 Edge preparation and Fitup

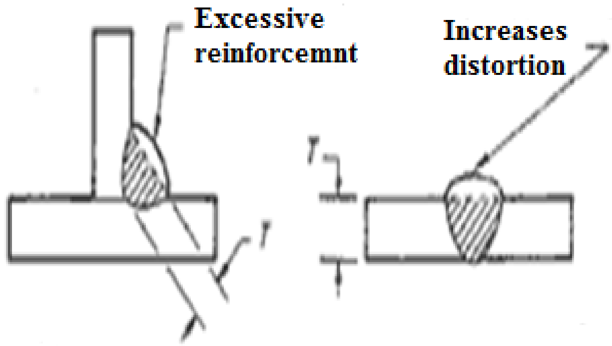

Fig. 14 Avoid overwelding

When welding heavy plate over 1 inch thick bevelling or even double bevelling can save a substantial amount of weld metal which translates into much less distortion automatically. In general, if distortion is not a problem, select the most economical joint. If distortion is a problem, select either a joint in which the weld stresses balance each other or a joint requiring the least amount of weld metal.

B. Use Intermittent Welding

Another way to minimize weld metal is to use intermittent rather than continuous welds where possible as shown in Fig. 15. For attaching stiffeners to plate, for example, intermittent welds can reduce the weld metal by as much as 75 percent yet provide the needed strength.

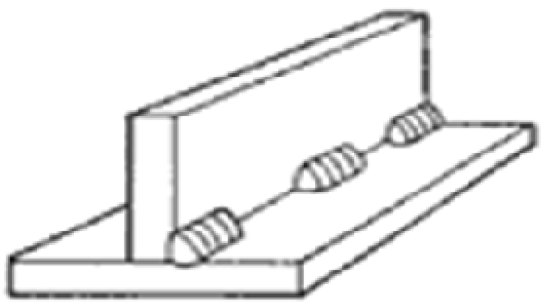

Fig. 15 Intermittent welding

C. Use as Few Weld Passes as Possible

Fewer passes with large electrodes, Fig. 16, are preferable to a greater number of passes with small electrodes when transverse distortion could be a problem. Shrinkage caused by each pass tends to be cumulative, thereby increasing total shrinkage when many passes are used.

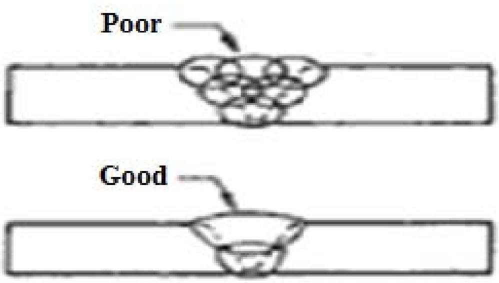

Fig. 16 Minimum number of passes

D. Place Welds near the Neutral Axis

Distortion is minimized by providing a smaller leverage for the shrinkage forces to pull the plates out of alignment. Fig. 17 shows both design of the weldment and welding sequence can be used effectively to control distortion.

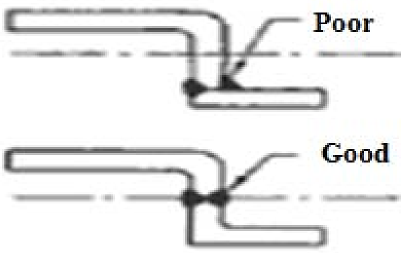

Fig. 17 Welding near Neutral axis

E. Balance Welds around the Neutral Axis

This practice, shown in Fig. 18, offsets one shrinkage force with another to effectively minimize distortion of the weldment. Here, too, design of the assembly and proper sequence of welding are important factors.

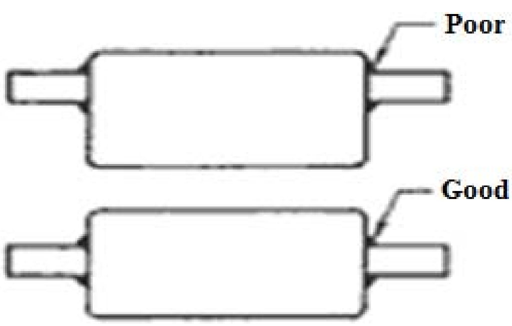

Fig.18 Balancing welds around Neutral axis

F. Use Backstep Welding

In the backstep technique, the general progression of welding may be, say, from left to right, but each bead segment is deposited from right to left as shown in Fig. 19. As each bead segment is placed, the heated edges expand, which temporarily separates the plates at B. But as the heat moves out across the plate to C, expansion along outer edges CD brings the plates back together. This separation is most pronounced as the first bead is laid. With successive beads, the plates expand less and less because of the restraint of prior welds. Backstepping may not be effective in all applications, and it cannot be used economically in automatic welding.

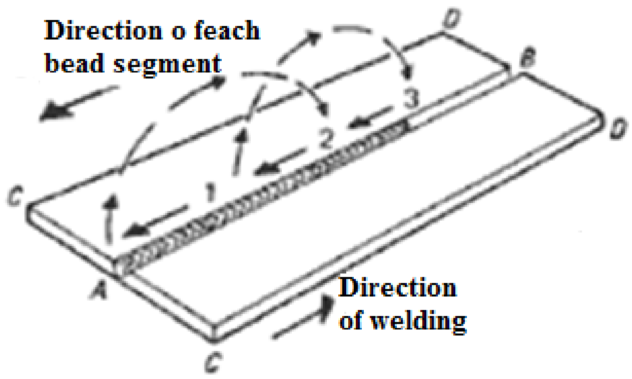

Fig. 19 Backstep welding

G. Anticipate the Shrinkage Forces

Presetting parts at first glance, this was referring to overhead or vertical welding positions, which is not the case before welding can make shrinkage perform constructive work. Several assemblies, preset in this manner, are shown in Fig. 20. The required amount of preset for shrinkage to pull the plates into alignment can be determined from a few trial welds.

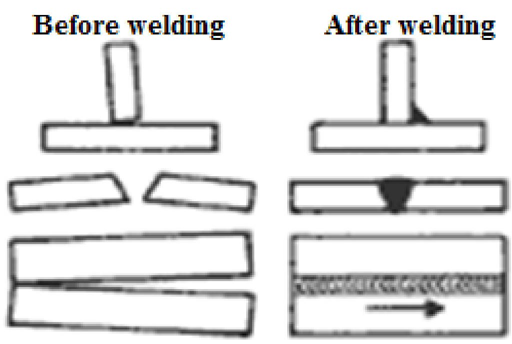

Fig. 20 Presetting parts

Prebending, presetting or prespringing the parts to be welded. Fig. 21 is a simple example of the use of opposing mechanical forces to counteract distortion due to welding. The top of the weld groove which will contain the bulk of the weld metal - is lengthened when the plates are preset. Thus the completed weld is slightly longer than it would be if it had been made on the flat plate. When the clamps are released after welding, the plates return to the flat shape, allowing the weld to relieve its longitudinal shrinkage stresses by shortening to a straight line. The two actions coincide, and the welded plates assume the desired flatness.

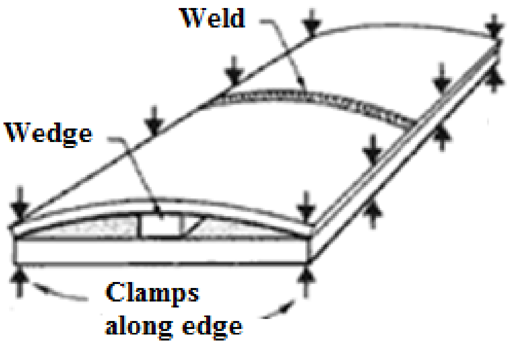

Fig. 21 Prebending

Another common practice for balancing shrinkage forces is to position identical weldments back to back, Fig. 22, clamping them tightly together. The welds are completed on both assemblies and allowed to cool before the clamps are released. Prebending can be combined with this method by inserting wedges at suitable positions between the parts before clamping.

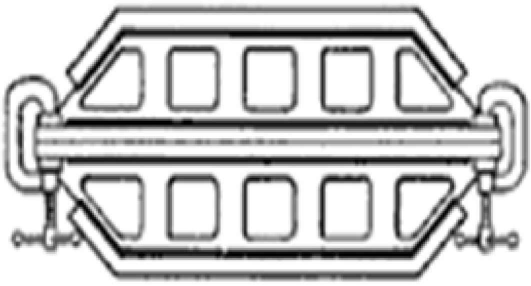

Fig. 22 Back to back clamping

In heavy weldments, particularly, the rigidity of the members and their arrangement relative to each other may provide the balancing forces needed. If these natural balancing forces are not present, it is necessary to use other means to counteract the shrinkage forces in the weld metal. This can be accomplished by balancing one shrinkage force against another or by creating an opposing force through the fixturing. The opposing forces may be: other shrinkage forces; restraining forces imposed by clamps, jigs, or fixtures; restraining forces arising from the arrangement of members in the assembly; or the force from the sag in a member due to gravity.

H. Plan the Welding Sequence

A well-planned welding sequence involves placing weld metal at different points of the assembly so that, as the structure shrinks in one place, it counteracts the shrinkage forces of welds already made. An example of this is welding alternately on both sides of the neutral axis in making a complete joint penetration groove weld in a butt joint. Another example, in a fillet weld, consists of making intermittent welds according to the sequences as shown in Fig. 23.

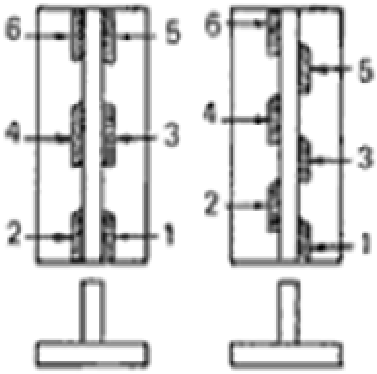

Fig. 23 Sequence welds

Clamps, jigs, and fixtures that lock parts into a desired position and hold them until welding is finished are probably the most widely used means for controlling distortion in small assemblies or components. It was mentioned earlier in this section that the restraining force provided by clamps increases internal stresses in the weldment until the yield point of the weld metal is reached. For typical welds on low-carbon plate, this stress level would approximate 45,000 psi. One might expect this stress to cause considerable movement or distortion after the welded part is removed from the jig or clamps. This does not occur, however, since the strain (unit contraction) from this stress is very low compared to the amount of movement that would occur if no restraint were used during welding.

I. Remove Shrinkage Forces after Welding

Peening is one way to counteract the shrinkage forces of a weld bead as it cools. Essentially, peening the bead stretches it and makes it thinner, thus relieving (by plastic deformation) the stresses induced by contraction as the metal cools. But this method must be used with care. For example, a root bead should never be peened, because of the danger of either concealing a crack or causing one. Generally, peening is not permitted on the final pass, because of the possibility of covering a crack and interfering with inspection, and because of the undesirable work-hardening effect. Thus, the utility of the technique is limited, even though there have been instances where between-pass peening proved to be the only solution for a distortion or cracking problem. Before peening is used on a job, engineering approval should be obtained. Another method for removing shrinkage forces is by thermal stress relieving - controlled heating of the weldment to an elevated temperature, followed by controlled cooling. Sometimes two identical weldments are clamped back to back, welded, and then stress-relieved while being held in this straight condition. The residual stresses that would tend to distort the weldments are thus minimized.

J. Minimize Welding Time

Since complex cycles of heating and cooling take place during welding, and since time is required for heat transmission, the time factor affects distortion. In general, it is desirable to finish the weld quickly, before a large volume of surrounding metal heats up and expands. The welding process used, type and size of electrode, welding current, and speed of travel, thus, affect the degree of shrinkage and distortion of a weldment. The use of mechanized welding equipment reduces welding time and the amount of metal affected by heat and, consequently, distortion. For example, depositing a given-size weld on thick plate with a process operating at 175 amp, 25 volts, and 3 ipm requires 87,500 joules of energy per linear inch of weld also known as heat input. A weld with approximately the same size produced with a process operating at 310 amp, 35 volts, and 8 ipm requires 81,400 joules per linear inch. The weld made with the higher heat input generally results in a greater amount of distortion. note: I don't want to use the words excessive and more than necessary because the weld size is, in fact, tied to the heat input. In general, the fillet weld size is equal to the square root of the quantity of the heat input (kJ/in) divided by 500. Thus these two welds are most likely not the same size.

V. Factors Affecting Distortion

If a metal is uniformly heated and cooled there would be almost no distortion. However, because the material is locally heated and restrained by the surrounding cold metal, stresses are generated higher than the material yield stress causing permanent distortion. The following principal factors affecting the type and degree of distortion are:

A. Parent Materials Properties

Parent material properties which influence distortion are coefficient of thermal expansion and specific heat per unit volume. As distortion is determined by expansion and contraction of the material, the coefficient of thermal expansion of the material plays a significant role in determining the stresses generated during welding and, hence, the degree of distortion. For example, as stainless steel has a higher coefficient of expansion than plain carbon steel, it is more likely to suffer from distortion.

B. Restraint

If a component is welded without any external restraint, it distorts to relieve the welding stresses. So, methods of restraint, such as strong-backs in butt welds, can prevent movement and reduce distortion. As restraint produces higher levels of residual stress in the material, there is a greater risk of cracking in weld metal and HAZ especially in crack-sensitive materials.

C. Joint Design

Both butt and fillet joints are prone to distortion. It can be minimized in butt joints by adopting a joint type which balances the thermal stresses through the plate thickness. For example, a double-sided in preference to a single-sided weld. Double-sided fillet welds should eliminate angular distortion of the upstanding member, especially if the two welds are deposited at the same time.

D. Part Fit-Up

Fit-up should be uniform to produce predictable and consistent shrinkage. Excessive joint gap can also increase the degree of distortion by increasing the amount of weld metal needed to fill the joint. The joints should be adequately tacked to prevent relative movement between the parts during welding.

E. Welding Procedure

This influences the degree of distortion mainly through its effect on the heat input. As welding procedure is usually selected for reasons of quality and productivity, the welder has limited scope for reducing distortion. As a general rule, weld volume should be kept to a minimum. Also, the welding sequence and technique should aim to balance the thermally induced stresses around the neutral axis of the component.

VI. Conclusions

1. The JK600 laser pulsed Nd:YAG laser welding technique has been employed to join TI6AL4VA and Aluminium AA2024 alloys. In general, the results show that it is possible to control the distortion using speed ranges. It has been proved that speed is the most important parameter while determining the distortion.
2. If the speed is increased too much towards titanium side, the work piece distortion exceeds. And is the speed is increased toward the aluminium side, the work piece distortion reduced.

Acknowledgment

The authors are grateful to the Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalainagar, Tamil Nadu, India for extending the facilities of Materials Testing Laboratory to carry out this investigation.

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