Analysis of Dissimilar Metal Welding of 1020 Mild Steel and 304 Stainless Steel

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Abstract— opining of divergent metals has discovered its utilization widely in power age, electronic, atomic reactors, petrochemical and concoction enterprises primarily to get customized properties in a segment and decrease in weight. Anyway productive welding of disparate metals has represented a significant test because of contrast in thermo-mechanical and synthetic properties of the materials to be joined under a typical welding condition. This causes a precarious slope of the thermo-mechanical properties along the weld. An assortment of issues come up in disparate welding like breaking, huge weld leftover anxieties, relocation of molecules during welding causing pressure focus on one side of the weld, compressive and tractable warm burdens, stress erosion splitting, and so on. Weld lingering pressure and warm pressure have been investigated for unique metal welding of 304 treated steel to 1020 mellow steel accepting 302 tempered steel as the filler metal. Likewise taking strain created as a file the powerlessness of the welded joint to pressure erosion splitting have been considered. It is discovered that when the filler metal is supplanted by Inconel 625 critical improvement is acquired in the welded joint as far as decrease in pressure created and stress consumption splitting. Additionally the issue of carbon relocation is disposed of by the utilization of Inconel 625 as a weld filler metal because of the obstruction of nickel-based composites to any carbon dissemination through them.

Keywords: Dissimilar Metal Welding, Mild Steel, Stainless Steel

I. Introduction

Welding is an assembling procedure of making a lasting joint acquired by the combination of the outside of the parts to be consolidated, with or without the use of weight and a filler material. The materials to be joined might be comparable or not at all like one another. The warmth required for the combination of the material might be acquired by consuming of gas or by an electric circular egment. The last strategy is all the more widely utilized in view of more prominent welding speed. Welding is widely utilized in manufacture as an elective strategy for giving or producing and a role as a trade for shot and bolted joints. It is likewise utilized as a fix medium for example to rejoin a metal at a make or to fabricate laugh uncontrollably a little part that has severed, for example, an apparatus tooth or to fix a well used surface, for example, a course surface.

A. Weld Processes

The welding processes may be broadly classified into the following two groups: Welding processes that use heat alone i.e. Fusion Welding. Welding processes that use a combination of heat and pressure i.e. Forge Welding.

B. Fusion Welding

If there should be an occurrence of combination welding the parts to be joined are held in position while the liquid metal is provided to the joint. The liquid metal may originate from the parts themselves for example parent metal or filler metal which ordinarily has the equivalent or almost comparative structure as that of the parent metal. Along these lines, when the liquid metal hardens or wires, the joint is framed. The combination welding, as indicated by the strategy for heat produced, may be classified as:

1) Thermite Welding
2) Gas Welding
3) Electric Arc Welding

C. Forge Welding

In produce welding, the parts to be joined are first warmed to a legitimate temperature in a heater and afterward pounded. Electric Resistance Welding is a case of produce welding. The guideline of applying warmth and weight, either successively or at the same time is generally utilized in the procedures known as Spot, Seam, Projection, Upset and Flash Welding.

1) Welded Joints

The welding joint geometry can be classified primarily into five types. This is based on the orientation between the material surfaces to be joined. The various joints are shown in the figure 1 below:

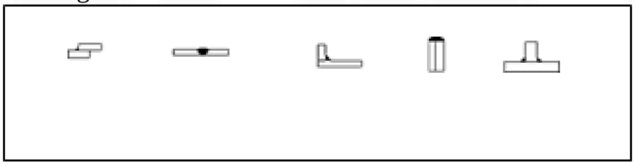

Fig. 1: Types of Welded Joints

1) Lap Joint
2) Butt Joint
3) Corner Joint
4) Edge Joint
5) T-Joint

The main considerations involved in the selection of a particular welded joint are given below:

1) The shape of the welded component required,
2) The thickness of the plates to be welded, and
3) The direction of the forces to which the finished object will be subjected to in the actual working conditions.

D. Metallurgy of a Welded Joint

Metal is warmed over the scope of temperature up to combination and followed by cooling encompassing temperature. Because of differential warming, the material away from the weld globule will be hot yet as the weld dot is moved toward logically higher temperatures are gotten, bringing about a complex smaller scale structure. The ensuing warming and cooling brings about setting up inner anxieties and plastic strain in the weld. Depending upon the incline of temperature inclination three unmistakable zones as shown in Fig. 2 can be identified in

1) welded joint which are:
2) Base metal
3) Heat Affected Zone (HAZ)
4) Weld metal

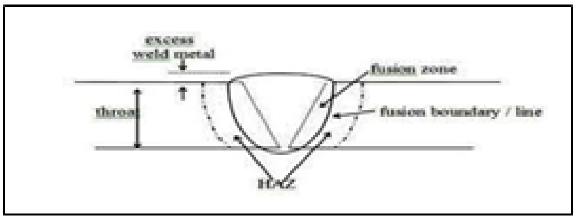

Fig. 2: Zones in a welding joint

A joint delivered without a filler metal is called autogenous and its weld zone is made out of re-cemented base metal. A joint made with a filler metal is called weld metal. Since focal part of the weld globule will be cooled gradually, long columnar grains will created and in the out ward heading grains will get better and better with separation.

So the malleability and durability diminishes away from the weld globule. Anyway quality increments with the good ways from the weld dot. The first structure in steels comprising of ferrite and pearlite is changed to alpha iron. The weld metal in the liquid state has a decent propensity to disintegrate gases which come into contact with it like oxygen, nitrogen and hydrogen. So during cementing, a segment of these gases get caught into the globule called porosity. Porosity is liable for decline in the quality of the weld joint. Cooling rates can be constrained by preheating of the base metal welding interface before welding.

The warmth influenced zone is inside the base metal itself. It has a microstructure unique in relation to that of the base metal in the wake of welding, since it is exposed to raised temperature for a considerable timeframe during welding. In the warmth influenced zone, the warmth applied during welding recrystallizes the lengthened grains of the base metal, grains that are away from the weld metal will recrystallizes into fine equiaxed grains.

E. Dissimilar Welding

Joining of unique metals has discovered its utilization broadly in power age, electronic, atomic reactors, petrochemical and synthetic businesses mostly to get customized properties in a part and decrease in weight. Anyway effective welding of different metals has represented a significant test because of distinction in thermo-mechanical and substance properties of the materials to be joined under a typical welding condition. This causes a lofty angle of the thermo-mechanical properties along the weld. An assortment of issues come up in different welding like breaking, huge weld leftover anxieties, relocation of iotas during welding causing pressure fixation on one side of the weld, compressive and ductile warm burdens, stress erosion splitting, and so forth. Presently before examining these issues coming up during disparate welding, the entries coming beneath illuminate a portion of the reasons for these issues. In different welds, weldability is dictated by gem structure, nuclear measurement and compositional solvency of the parent metals in the strong and fluid states. Dispersion in the weld pool frequently brings about the development of intermetallic stages, most of which are hard and weak and are in this way inconvenient to the mechanical quality and malleability of the joint. The warm extension coefficient and warm conductivity of the materials being joined are extraordinary, which causes enormous oddball strains and subsequently the leftover anxieties brings about splitting during cementing.

F. Stresses for Welded Joints

The worries in welded joints are hard to decide on account of the variable and erratic parameters like homogeneity of the weld metal, warm worries in the welds, changes in physical properties because of high pace of cooling, and so forth. In structure issues, these anxieties are gotten on the accompanying suspicions:

The heap is disseminated consistently along the whole length of the weld, and The pressure is spread consistently over its successful area.

G. Residual Stress

Residual pressure is a pressure or pressure that exists in a material with no outside burden being applied, and the remaining worries in a part or structure are brought about by contradictory inward lasting strains. Welding, which is one of the most critical reason for leftover pressure, commonly creates huge malleable burdens, the greatest estimation of which is roughly equivalent to the yield quality of materials that are joined by lower compressive remaining worries in a segment. The leftover worry of welding can essentially disable the exhibition and dependability of welded structures. Two of the serious issues of any welding procedure are remaining pressure and twisting. Remaining pressure is essentially brought about by the compressive yielding that happens around the liquid zone as the material warms and grows during welding. At the point when the weld metal cools it contracts which causes an elastic leftover pressure, especially in the longitudinal bearing. In the wake of welding a lingering malleable pressure stays over the weld centreline and causes an adjusting compressive pressure further from the weld zone. The tractable lingering weight on the weld line diminishes the exhaustion quality and the strength, especially when joined with any indents or deformities related with the weld dot. To alleviate a portion of the leftover anxieties brought about by the welding procedure, the structure misshapes, causing bending. There are a few methods of contortion, however the one that is generally normal, especially in slim welded structures is clasping bending, which is brought about by the compressive worry in the parent material. The lingering pressure created in the wake of welding is appeared in Fig 3 (b).

H. Thermal Stresses

In divergent metal welding, one of the metals in contact at the weld metal interface is compelled by development or constriction of the other. The two metals being welded have diverse coefficient of warm development. The metal having a higher coefficient of warm extension, with its inclination to grow more than the other is compelled by the fixed limit.

Because of which compressive warm pressure is created in the metal having a higher coefficient of warm extension while ductile warm pressure is created in the metal with the lower coefficient of warm development. The warm pressure created during the welding is appeared in Fig 3 (a).

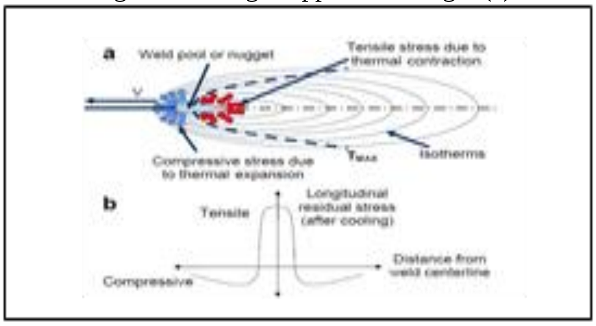

Fig. 3: Stress in welds (a) warm worry during and (b) leftover worry in the wake of welding.

1) Warm Stress Superimposed under Residual Stress

The welded metal parts are exposed to a various patterns of warm development and constriction. As aftereffect of which these warm burdens get superimposed over the leftover pressure prompted in the wake of welding.

A right gauge of warm worries under superimposed condition with the remaining pressure is important to decide the most vulnerable zone or the region generally defenseless to splitting. The cyclic warm anxieties superimpose on the weld remaining pressure and working ductile burdens can advance fragile break, increment the weakness of a weld to weariness harm and stress consumption splitting (SCC) during administration. This will guarantee a sound plan of the joint and auxiliary respectability.

2) Stress Corrosion Cracking (SCC)

Stress consumption splitting is breaking because of a procedure including conjoint erosion and stressing of a metal because of remaining or applied anxieties. The effect of SCC on a material for the most part falls between dry breaking and the exhaustion limit of that material. SCC as a rule happens in certain particular composite condition pressure mixes. SCC is an erosion instrument that requires the matching of a material with an extremely specific condition and the utilization of an elastic worry over a basic worth.

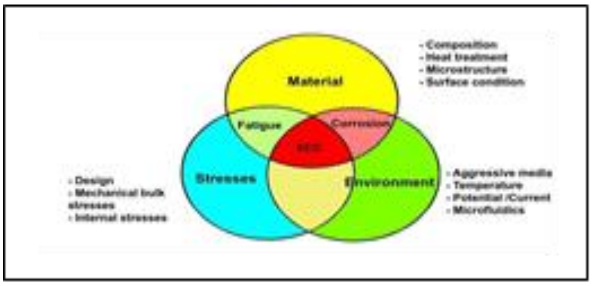

Fig. 4: Factors influencing Stress Corrosion Cracking

As shown in Fig. 4 above Stress Corrosion Cracking is not just a material problem, but it is a combined result of the following three factors:

1) Material Properties
2) Corrosive Environment
3) Stresses

Most of the surface is not attacked, but with fine cracks penetrating into the material. In the microstructure, these cracks can have an intra-granular or a trans- granular morphology. Macroscopically, SCC fractures have a brittle appearance. SCC is classified as a catastrophic form of corrosion, as the detection of such fine cracks can be very difficult and the damage not easily predicted. Typical SCC failures are seen in pressure vessels, pipework, stressed components and systems where an excursion from normal operating conditions or the environment occurs.

Stress Corrosion Cracking can be controlled by the incorporating the measures given below:

Selecting a material that is not susceptible to the service environment Ensuring that any changes to the environment caused by cleaning are not detrimental to the material.

Controlling the service stresses through careful design and minimizing stress concentrations to keep them below the critical value. Heat Treatment reduces the residual stresses in the material and in turn decreases the susceptibility to Stress Corrosion Cracking. Using corrosion inhibitors during cleaning operations or to control the environment in a closed system. Coating the material and effectively isolating the material from the environment.

I. Carbon Migration

Carbon migration across the weld interface is considered a significant factor in the "life" of a transition joint, since time dependent property changes occur in the regions where carbon movement occurs.The carbon migration causes loss of strength in the ferrite material adjacent to the weld interface and an increase in hardness (and probably also in strength with a change in the modulus of elasticity possible) in the filler metal (carbon-enriched zone). These zones are immediately adjacent to one another and provide a significant change in properties across a narrow region.

However, some generalizations can be stated concerning carbon migration in a welded joint: Carbon migration is directly dependent on time, temperature and carbon content of the base metals. Carbon diffuses five to ten times faster in ferrite than in austenite at the same temperature.

Thermal stresses acting on the weld interface enhance carbon diffusion, thus the metals having larger co-efficient of thermal expansion like stainless steel will experience more rapid formation of the carbon depleted zone.

The carbon depleted zone exhibits low tensile and creep strength and reduced recrystallization temperature. However, the properties are not specifically defined.

The carbon-depleted soft zone is restrained by the harder and stronger carbon-enriched zone immediately adjacent during thermal cycling. The development of a complex stress state involving shear along the interface, thus inhibiting uniform strain and tends to create deformations in the soft zone.

II. LITERATURE SURVEY

Over the years a lot of research has been done in the area of dissimilar welding and many interesting results have been brought up with regards to the problems encountered in dissimilar welding. With dissimilar welding finding its use in nuclear, petrochemical, electronics and several other industrial domains, this section brings into account the work of the predecessors in this field.

A. Research papers

Chengwu et al. [1] in their work on weld interface microstructure and mechanical properties of copper-steel unique welding, the microstructure close to the interface between Cu plate and the intermixing zone was examined. Test results demonstrated that for the welded joint with high weakening proportion of copper, there was a change zone with various filler particles close to the interface.However, if the weakening proportion of copper is low, the progress zone is just produced close to the upper side of the interface. [1] At the lower side of the interface, the fierce blasting conduct in the welding pool prompted the entrance of fluid metal into Cu. The welded joint with lower weakening proportion of copper in the combination zone displayed higher ductile strength.Jiang and Guan [2] contemplated the warm pressure and leftover worry in unique steels. They proposed that enormous remaining burdens are instigated by welding in the weld metal and warmth influenced zone (HAZ), which superimpose and increment the warm pressure. Gyun Na, Kim and Lim [3] contemplated the lingering pressure and its forecast for different welds at atomic plants utilizing Fuzzy Neural system models. The elements that have an effect upon weakness quality are remaining pressure, stress focus, the mechanical properties of the material, and its miniaturized scale and full scale structure. Gyun Na et al. [3] expressed that remaining pressure is one of the most significant factors yet its impact on high-cycle weariness is of more worry than different components. Remaining pressure is a strain or pressure that exists in a material with no outside burden being applied, and the lingering worries in a segment or structure are brought about by contrary inside perpetual strains.Welding, which is one of the most critical reasons for leftover pressure, commonly creates huge malleable anxieties, the greatest estimation of which is around equivalent to the yield quality of materials that are joined by lower compressive lingering worries in a part. [3] The remaining worry of welding can essentially hinder the exhibition and dependability of welded structures. The uprightness of welded joints must be guaranteed against exhaustion or erosion during their long use in welded segments or structures. On stress consumption splitting Gyun Na et al. [3] expressed that pressure consumption splitting typically happens when the accompanying three elements exist simultaneously: defenseless material, destructive condition, and tractable pressure including lingering pressure. Accordingly, lingering pressure turns out to be basic for stress-erosion breaking when it is hard to improve the material destructiveness of the segments and their condition under working conditions. Khan et al. [4] examined laser pillar welding of disparate tempered steels in a filet joint arrangement and during the investigation metallurgical examination of the weld interface was finished. Combination zone microstructures contained an assortment of complex austenite ferrite structures. Nearby miniaturized scale hardness of combination zone was more noteworthy than that of both base metals. The welding combination zone microstructure comprises of for the most part essential ferrite dendrites with a between dendritic layer of austenite. [4] This austenite frames through a peritectic–eutectic response and exists at the ferrite solidification limits toward the finish of solidification. Some lathy ferrite morphology is additionally seen right now. This is because of confined dispersion during ferrite–austenite change that outcomes in a lingering ferrite design. Khan et al. [4] reached the resolution that arrangement of ferrite along the austenite grain limit in the warmth influenced zone on austenite side is watched. Simultaneously, microstructures are made out of two-stage ferrite and martensite with intra-granular carbide on ferrite side. Likewise the variety in nearby miniaturized scale hardness saw over the weld relies upon the division intermix of each base metal and the redistribution of austenite-and ferrite-advancing components in the weld. Itoh et al. [5] got a patent on the joined structure on the disparate metallic materials. This creation relates for the most part to a joined structure of unique metallic materials having various qualities. All the more explicitly, the innovation identifies with a joined structure of a current conveying contact or angling contact which are utilized for, e.g., a force breaker, or a covering end structure of a metal base and a covering material for improving conductivity and warmth opposition. Delphin, Sattari-Far and Brickstad [6] considered the impact of warm and weld leftover weights on CTOD (Crack Tip Opening Displacement) in flexible plastic break examination. They expressed that structures may come up short as a result of break development both in welds and in the warmth influenced zone (HAZ). The welding procedure itself prompts leftover worries in the weld and HAZ, which add to split development. Delphin et al. [6] utilized a non-direct thermoplastic limited component model to reenact the circumferential weld in a generally slender walled treated steel pipe. After the funnel had chilled off in the wake of welding a circumferential surface split was presented. The split, situated in the focal point of the weld, was exposed to two kinds of burdens. Right off the bat, the welded pipe was exposed to an essential elastic burden, and afterward to an optional warm burden. Delphin et al. [6] expressed that the decision of solidifying model is significant. It is accepted that kinematic solidifying is a superior decision than isotropic solidifying in low cycle reenactments for example in a couple pass welding process, as in the present investigation. For the instance of weld leftover worries in blend with high warm burdens, it is discovered that the versatility prompted by the warm anxieties isn't adequate to smother the impact of weld remaining weights on CTOD, in any event, for extremely high warm loads. The remaining anxieties can be loose by emptying from an essential malleable burden. Mai and Spowage [7] accomplished their work on characterisation of divergent joints of steel-kovar, copper-steel and aluminum-copper. It was expressed in their work that joining of unique materials is one of the difficult undertakings confronting present day makers. Different metal welding innovations find application in numerous areas, for example, smaller scale gadgets, clinical, optoelectronics and microsystems. [7] The little geometry of the joints and the distinctive optical and warm properties of the materials makes laser welding one of the most reasonable creation techniques. Likewise high temperature angles in a welding may result in martensitic responses prompting over the top hardness in the combination zone. [7] The X-beam pressure examination procedure couldn't resolve the pressure varieties created by the distinctive preparing parameters utilized. In comparable steel welds the lingering worry at the focal point of the weld pool has been accounted for to be near the material yield quality. Colegrove et al. [8] examined the welding procedure sway on remaining pressure and twisting. Their work looks to comprehend the connection between heat input, combination region, estimated twisting and the leftover pressure anticipated from a straightforward numerical model, and the lingering stresses is approved with exploratory information. Remaining pressure is brought about by the compressive yielding that is happening around the liquid zone when the material is warmed and its development during welding. [8] When the weld metal cools it gets contracted which results to an elastic remaining pressure, fundamentally in the longitudinal heading. After the welding is more than, a lingering elastic pressure is available over the weld centreline which causes an adjusting compressive pressure away from the weld zone. [8] The malleable remaining weight on the weld centreline diminishes the exhaustion quality and sturdiness, particularly when joined with any of the scores or different deformities identified with the weld dab. The other primary finding of Colgrove et al. [8] is that the warmth information and bending go with one another in about a direct relationship. The outcomes acquired for the remaining pressure show that the width of the pinnacle elastic increments with heat input. At long last the leftover pressure estimations show how the malleable pinnacle extends up with expanding the warmth input. There is an extremely little distinction in the size of the pinnacle tractable for the diverse welding forms. Arunkumar, Duraisamy and Manikandan [9] considered the mechanical properties of unique metal cylinder welded joints and named a portion of the alloying components that improve the weldability or the welded joint. Compound Steels, for example, that contain chromium and molybdenum. This piece conveys great weldability and high hardenability for the above expressed alloys.Chromium gives improved oxidation and consumption obstruction. What's more, molybdenum expands quality at raised temperature. [9] The blend of chromium and molybdenum additionally builds protection from high temperature hydrogen assault and to crawl. Arunkumar et al. [9] likewise expressed that inordinate infiltration of a weld root can be amended by legitimate arrangement of cylinders in base of weld joint; concentric bore at closes, right welding current. Porosity in welded joint can be decreased by utilizing low hydrogen welding process, expanding protecting gas stream, expanding heat info and utilizing clean joint appearances. Chung et al. [10] examined microstructure and stress erosion splitting conduct of the weld metal in divergent welds and powerlessness to push consumption breaking regarding flexibility misfortune is needy in expanding request of seriousness is; undiluted weld metal, the change zone and the weld interface. This implies powerlessness to stretch erosion splitting is increasingly identified with the instance of fragile cracks. Chung et al. [10] expressed that interface splitting is regularly connected with a solidified interface locale in the weld, suggesting that the weld interface assumes a significant job in deciding SCC vulnerability. Chung et al. [10] likewise saw that the microstructures close to the weld interface are muddled, comprising of martensite. The more Ni and Cr contents, the less the specimen would be susceptible to SCC. Lundin [11] did his research on dissimilar welds with its emphasis on carbon migration, stress/strain state of welds and transition joint failure mechanism. The study stated that the majority of failures have been associated with austenitic stainless steel filler metal joints, and it is considered that the failure mode exhibited by the nickel-based filler metals is fundamentally different than that with the austenitic stainless fillers. Lundin [11]said that the cracking most often initiates at or near the outside surface. The cracking results directly from void linkup, grain boundary separation or tearing. It is generally parallel to the weld interface. The cracking is associated with or exacerbated by oxidation- oxide notching. The relative expansion coefficients of the various weld metal regions are extremely important with regard to thermal stress generation. Increasing the Ni content of the filler metal alters carbon solubility, makes carbides less stable, changes diffusivity and in general retards carbon migration from the ferritic material. [11] The influence of time, temperature and material composition influences the nickel rich weld metals reduces carbon migration. Further, the use of stabilizing elements in the ferritic component is effective in combatting migration but neither so easily with nickel is the principal alloying elements

III. Problem Formulation

The aim of this research project has been to study dissimilar metal joint using a filler metal. Dissimilar welding is used to fabricate the pressure vessels and piping in power plant but failures occur frequently due to:

1) Thermal Stress which is generated due to difference in co-efficient of thermal expansion.
2) Difference in mechanical properties, the local heating and subsequent cooling results in large residual stress. This thermal stress superimposed on weld residual stress and operating tensile stress promotes brittle fracture, increase susceptibility to fatigue and stress corrosion cracking during its service life. The domain of this research covers cause, effect and elimination of problems caused due to stresses, carbon migration and stress corrosion cracking. The metals to be welded are 304 stainless steel and 1020 plain carbon steel and the filler metal used is 302 Stainless steel whose properties has been taken similar to 304 stainless steel for the purpose of analysis. The welding process has been simulated using finite element analysis. The software used for this analysis is ANSYS 13.0 using its Workbench module. It is because Workbench is a very powerful tool to simulate a welding joint and infer the results. Also it has a reputation of coming up with results very close to the practical values. The input parameters are easily fed and boundary conditions, simulation programmes and geometrical modelling is very convenient due to its user-friendly graphic interface.

A. Input Parameters

The input parameters in this analysis are the thermo-mechanical properties of the materials getting into the welding joint. All the properties used in this analysis are temperature dependent.

1) Composition

The composition of the metals used in this simulation of welding joint is given below:

a) 304 Stainless Steel

The composition of 304 stainless steel is shown in table 1. Chromium along

Table 1: *Composition of 304 Stainless Steel*

Fe	C	Si	Mn	S	P	Cr	Ni
71.433	0.058	0.35	1.32	0.007	0.032	18.52	8.28

b) 1020 Mild Steel

In plain carbon steel, carbon is the principle alloying element. Composition of 1020 mild steel is shown in table

Table 2: *Composition of 1020 Mild Steel*

Fe	C	Mn	P	S
99.31	0.2	0.4	0.04	0.05

c) 302 Stainless Steel

The composition of 302 stainless steel is almost similar to that of 304 stainless steel and the composition has been taken same for the purpose of analysis. 302 stainless steel has been used as the weld metal in the first analysis and subsequently replaced by Inconel 625 in the second analysis.

d) Inconel 625

Inconel 625 is a non-magnetic, corrosion and oxidation resistant, nickel-based alloy. This alloy has high fatigue strength, exhibits excellent resistance to stress corrosion cracking. Nickel and Chromium provide stabilizing effect from oxidizing environments. The nickel based alloys like Inconel also resist problems caused due to carbon migration. Pitting and crevice corrosion are prevented by Molybdenum stabilizes the alloy against sensitization during welding. Due to these properties, Inconel is widely used in dissimilar welding. The composition of Inconel 625 which has been used in this analysis has been shown in Table 3

Table 3: *Composition of Inconel 625*

Ni	Cr	Mo	Fe	Mn	C	Cu	Si
61.5	23.0	8.0	6.5	0.25	0.08	0.2	0.25

2) Mechanical Properties

The mechanical properties that have been chosen for the purpose of analysis are density, Poisson's ratio, modulus of elasticity and yield strength. The mechanical and thermal properties of the materials used in this analysis have been extrapolated from the graph published by Jiang and Guan [2] in their study on residual stress in a welded joint.

a) 304 Stainless Steel

The mechanical properties of 304 stainless steel that have been used in this analysis have been given in table 4

Table 4: *Mechanical Properties of 304 Stainless Steel*

Variation of properties with temperature	Density (kg/m^3) * 10^3	Poisson's Ratio	Modulus of Elasticity (Pa) * 10^{11}	Yield Strength (Pa) * 10^8
0 ^{0}C	7.9	0.295	2.0	2.7
200 ^{0}C	7.78	0.3	1.9	1.9
400 ^{0}C	7.67	0.31	1.8	1.6
600 ^{0}C	7.55	0.315	1.7	1.2
800 ^{0}C	7.43	0.32	1.5	0.8
1000 ^{0}C	7.32	0.327	1.0	0.6
1200 ^{0}C	7.2	0.335	0.4	0.55
1400 ^{0}C	7.12	0.341	0.5	0.5
1600 ^{0}C	7.04	0.346	0.5	0.5

3) Thermal Properties

The thermal properties of the materials that were necessary for this analysis were melting point, thermal conductivity, specific heat and co-efficient of thermal expansion.

a) 304 Stainless Steel

The thermal properties of 304 stainless steel that have been used in this analysis have been given in table 7. The melting point of 304 stainless steel is taken as 14270C

Table 7: *Thermal Properties of 304 Stainless Steel*

Variation of properties with temperature	Thermal Conductivity (W/m^{0}C)	Specific Heat (J/Kg^{0}C)	Thermal Expansion Coefficient (^{0}C^{-1}) * 10^{-5}
0 ^{0}C	15	501	1.8
200 ^{0}C	18	530	1.9
400 ^{0}C	21	580	2.0
600 ^{0}C	26	620	2.05
800 ^{0}C	34	650	2.1
1000 ^{0}C	36	680	2.15
1200 ^{0}C	36	690	2.2
1400 ^{0}C	36.1	700	2.25
1600 ^{0}C	36.1	705	2.29

b) 1020 Mild Steel

The thermal properties of 1020mild steel that have been used in this analysis have been given in table 8. The melting point of 1020 Mild Steel has been taken as 15150C.

Table 8: *Thermal Properties of 1020 Mild Steel*

Variation of properties with temperature	Thermal Conductivity (W/m^{0}C)	Specific Heat (J/Kg^{0}C)	Thermal Expansion Coefficient (^{0}C^{-1}) * 10^{-5}
0 ^{0}C	48	480	1.2
200 ^{0}C	32	510	1.3
400 ^{0}C	30	550	1.3
600 ^{0}C	29	600	1.3
800 ^{0}C	29	640	1.2
1000 ^{0}C	29	680	1.2
1200 ^{0}C	30	690	1.2

c) Inconel 625

The thermal properties of Inconel that have been used in this analysis have been given in table 9. The melting point of Inconel 625 is taken as 14040C

Table 9: *Thermal Properties of Inconel 625*

Variation of properties with temperature	Thermal Conductivity (W/m^{0}C)	Specific Heat (J/Kg^{0}C)	Thermal Expansion Coefficient (^{0}C^{-1}) * 10^{-5}
0 ^{0}C	12.5	456	1.31
200 ^{0}C	15.4	501	1.35
400 ^{0}C	18.2	552	1.39
600 ^{0}C	20.1	597	1.44
800 ^{0}C	23.1	649	1.51
1000 ^{0}C	26.8	682	1.57
1200 ^{0}C	29.4	707	1.66
1400 ^{0}C	31.2	718	1.74
1600 ^{0}C	32.1	725	1.81

For cooling of the parts after the welding is over the convective heat transfer co-efficient has been taken as 15 W/m2 0C. The ambient air temperature has been taken equal to 27 0C.

IV. Finite Element Analysis

Finite element analysis has been done in the case of this welding to predict stresses, susceptibility to stress corrosion cracking and the location where failure is most likely to occur. Some of the other methods of analysis were not used due to the following given reasons:

1) Accurate measurement of stresses is very difficult using conventional testing techniques.
2) X-ray method can be used for analysis but it is capable of giving only surface stresses.
3) Neutron Diffraction Method can give the through thickness stress but not the stress distribution. So, this is the reason why finite element analysis has been used because it is capable of predicting highest risk zone and the stress distribution throughout the parent metals, heat affected zone and the weld metal.

V. Problem Statement

The problems which have been analysed in this research are three. First aspect is reduction in stresses developed, second is minimization of carbon migration and the third is decreasing the susceptibility to Stress Corrosion Cracking. Considering the above objectives two metal plates, equal in size with a dimension of 300 x 150 x 8 mm are butt welded with filler between them. The parent metal plates are of 304 stainless steel and 1020 mild steel material. The welding arrangement has been The welding simulation has been done firstly by studying the welding temperature field followed by incrementally applying the temperature results to simulate the weld. After the welding process is over residual stresses get developed inside the welded parts. This welded part when kept under operating conditions which are taken as high as 600 0C, results in development of thermal stresses inside the welded part.

The analysis has been done considering three models. Model A is analysed only for thermal stresses and the results are inferred. Model B is analysed only for residual stresses and the results are inferred. Model C is analysed for thermal stresses superimposed with residual stresses. That means mathematically-Model A + Model B = Model C.And all the results are taken along the line of length 30mm which lies 5mm above the weld root. Now in the second case, the weld metal A302 Stainless Steel is changed to Inconel 625 and then again the thermal, residual and thermal stress superimposed on residual stresses are calculated.

A. *Assumptions and Conditions*

1) Heat flow inside the welded parts is assumed to be by conduction using the fundamental equation of conduction as given in equation (i);

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_{int}=\rho c\frac{\partial T}{\partial t} \qquad \text{(i)}$$

where k is the thermal conductivity, T is the transient temperature field which is a function of time t and Cartesian co-ordinates (x, y, z) with Q as internal heat source rate, ρ as density and c as specific heat capacity.

2) Heat loss from the welded part to the ambient air is assumed to occur by convection following the governing equation of cooling(ii);

$$= -hA(Ts - Ta) \qquad \text{(ii)}$$

where Qc is the rate of cooling, h is the convection co-efficient taken here 15 W/m2 oC for all the cases, Ts is the surface temperature and Ta is the temperature of ambient air taken 27 oC.

3) Thermal stress is calculated from the start up at 27 oC to 600 oC. Thermal stress simulated in the welding using its global modelling matrix reduced to give thermal stress at any two nodes is given in equation (iii);

$$\begin{bmatrix}-E\alpha T\\-E\alpha T\\0\end{bmatrix}=\frac{AE}{L}\begin{bmatrix}1&-1&0\\0&1&-1\\0&0&0\end{bmatrix}\begin{bmatrix}d_1\\d_2\\d_3\end{bmatrix} \qquad \text{(iii)}$$

where E is the Young's Modulus of Elasticity, T is the transient temperature field, α is the co-efficient of thermal expansion, A is the cross sectional area, L is the length of the section and (d1, d2, d3) are the nodal displacements caused due to temperature load at any three nodes.However displacement boundary condition d1=0 is taken to avoid rank deficiency. In this case of modelling the welded part is assumed to be fixed normal to the weld.

4) For residual stress analysis the elements are activated and deactivated by element birth and death technique. This means that after a weld pass is over on an element, after solidification the element gets structurally activated.The material properties are set to zero for the deactivated elements. The welding has been carried out at 1500 oC. Therefore, the initial condition for an element after reactivation is its melting point. When an element gets reactivated i.e. born then its mass, element load, etc. are set to their original values.

VI. Results and Discussion

The results that are obtained after the weld simulation can be taken considering two cases. In the first case 302 stainless steel has been taken as the weld filler metal whose properties are taken the same as 304 stainless steel which is one of the parent metals. So the results inferred from all the three models viz. A, B and C which will be taken one by one.

A. Case I

1) 302 Stainless Steel as Weld Filler Metal

Thermal stress has developed inside the welded part as both of its ends across the weld have been fixed against any kind of motion by setting up in nodal displacement in all directions as zero. This is the boundary conditions used in model A and model C.Considering Model A, where only the part has been subjected to thermal stresses the results are explained in the figures below. The figures below show the stress contour near the weld metal and the graphs which are path results along the line of length 30 mm at the centre of the filler metal and at a distance of 5 mm from the weld root. The line is called line P in the subsequent paragraphs.

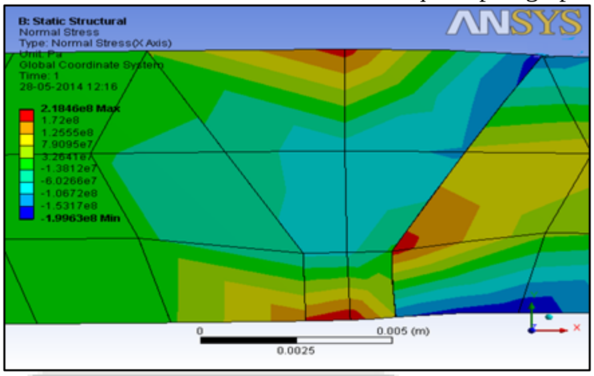

Fig. 6: Normal stress contour of Model A

The normal stress varies from 218 MPa tensile to 199 MPa compressive. The peak of the tensile lies along the centreline of the weld metal. However peak of the compressive stress lies in the weld interface of weld filler metal and 1020 mild steel.

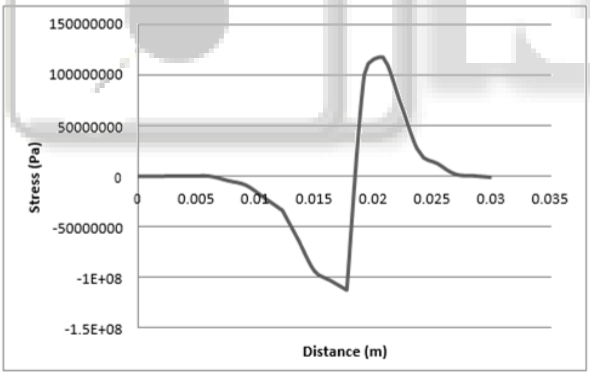

Fig. 7: Normal stress distribution along line P

The normal stress along the line P in both directions is found in the weld interface near the 1020 mild steel. The maximum stress is found to be 118 MPa in the tensile direction.

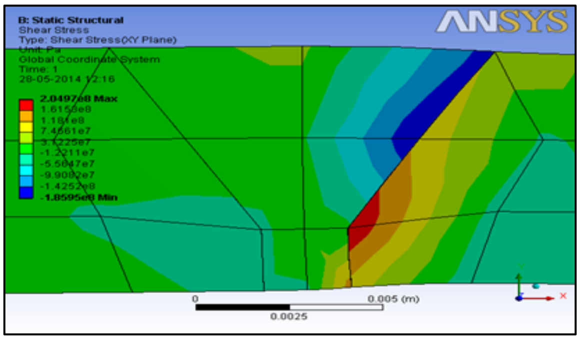

Fig. 8: Shear stress contour of Model A

The shear stress varies from 204 MPa positive to 186 MPa negative. However peak of the shear stress lies in the weld interface of weld filler metal and 1020 mild steel. From the above two cases it is very clear that the weld interface on the 1020 mild steel is the highest risk zone, where the failure is most likely to occur. The shear stress distribution along the line P is shown in Fig. 9.

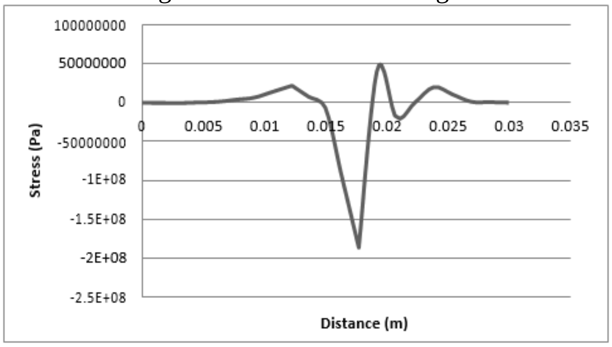

Fig. 9: Shear stress distribution along line PThe maximum shear stress along the line P is 186 MPa along the negative direction and also is located in the weld interface on 1020 mild steel side. Now taking up the case where residual stresses have developed as a result of heating and subsequent cooling during the welding process.

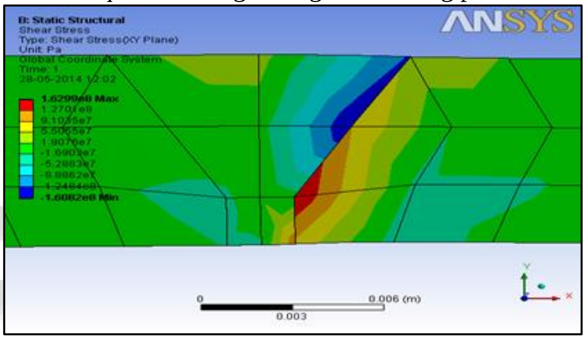

Fig. 10: Normal stress contour of Model B

The normal stress varies from 192 MPa tensile to 157 MPa compressive. The peak of the tensile lies on the 1020 mild steel and compressive stress lies in the 304 stainless steel side. This is due to larger coefficient of thermal expansion of 304 stainless steel. The stress gradient in the filler metal is very steep due to rapid change in the direction of stresses.

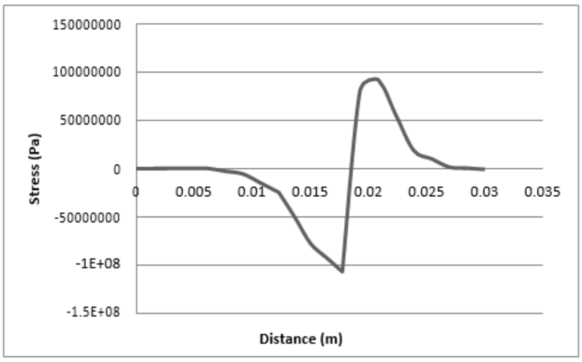

Fig. 11: Normal stress distribution along line P

The maximum stress is induced in the weld interface on the 1020 mild steel side and its magnitude is 107 MPa and is of compressive nature. The steep gradient in the stress in this zone represents the vulnerability of this zone to cracking.

Similarly the shear stress contour in the XY-plane developed in the model B is shown in the Fig. 12.

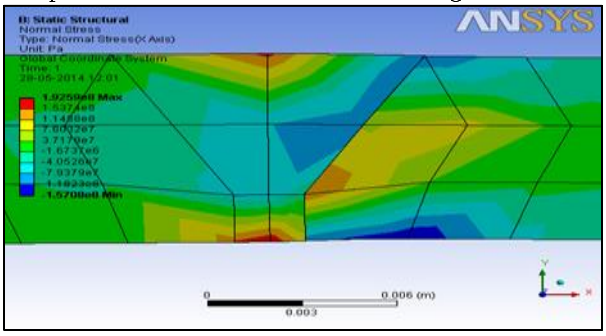

Fig. 12: Shear stress contour of Model B

The shear stress varies from 204 MPa positive to 186 MPa negative. However peak of the shear stress lies in the weld interface of weld filler metal and 1020 mild steel. The extremes of stress in both directions also lie in the same location making it the weakest part.

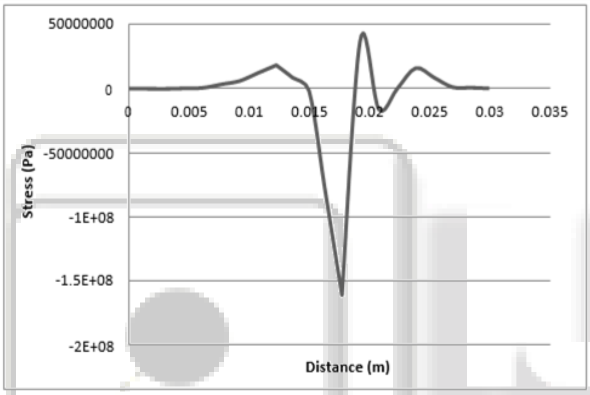

Fig. 13: Shear stress distribution along line P

The maximum value of shear stress along the line P is found to be 161 MPa, and the stress is in clockwise direction which is assumed to be negative direction. At the weld interface on 1020 mild steel side, shear stress rises falls very rapidly.

In the model C, where the thermal stress is superimposed on residual stress the normal stress contour developed is shown in Fig. 14.

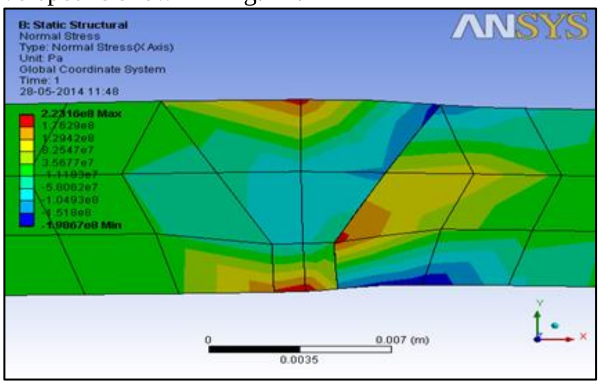

Fig. 14: Normal stress contour of Model C

The value of normal stresses developed in the welded joint in the model C is 223 MPa of the tensile nature and 198 MPa of the compressive nature. The maximum tensile stress is located at the centre of the welded joint and is much localised.

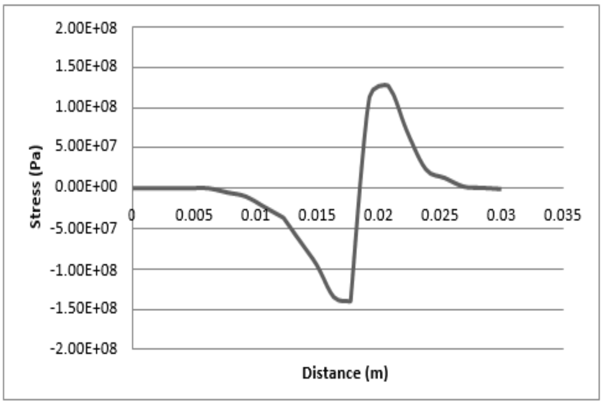

Fig. 15: *Normal stress distribution along line P*

The stress distribution graph that normal stress value is highest i.e. 140 MPa near the weld interface on the 1020 mild steel side. The magnitude of stress is highest in both the directions at this very location.

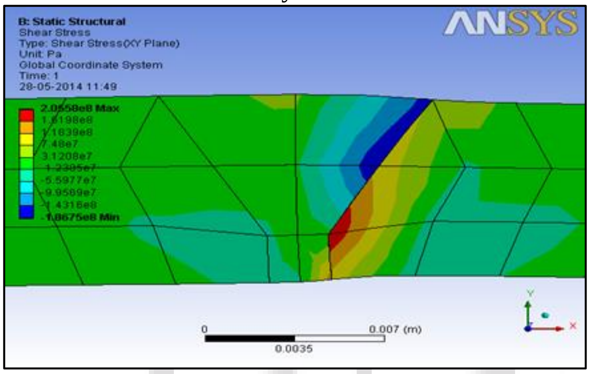

Fig. 16: Shear stress contour of Model C

Similarly the shear stress contour in XY-plane as shown in Fig. 16 indicates a high cyclic reversal of stresses at the weld interface on 1020 mild steel side. The value of stress here varies from 205 MPa counter-clockwise to 186 MPa in the clockwise sense. By the virtue of shear stress developed it is quite clear that the welded joint is most likely to break at the weld interface on 1020 mild steel side.

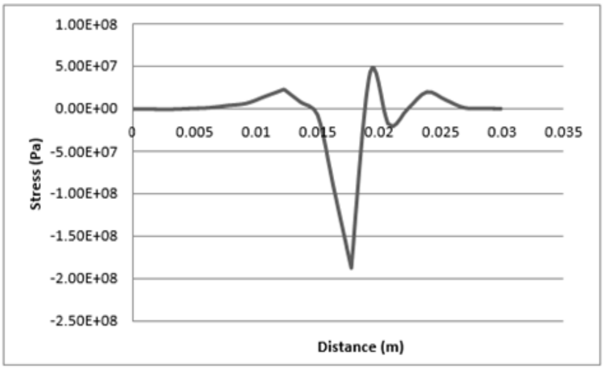

Fig. 17: *Shear stress distribution along line P*

The path results obtained on the line P also confirm that there is a huge cyclic reversal of stresses in the zone mentioned above. The maximum value of shear stressi.e. 187 MPa is also present on this particular line.The analysis of strain which is a parameter in deciding the susceptibility of stress corrosion cracking is discussed in the next paragraph.

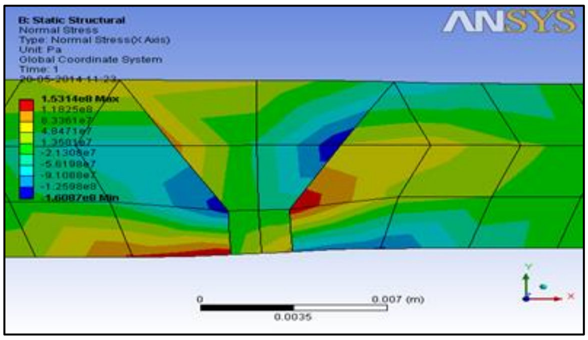

Fig. 18: Equivalent strain contour in Model C

In line with the stresses the contour of equivalent strain also depicts that a maximum strain of 0.01 m/m is also located in the weld interface on the 1020 mild steel side. This means that this interface has the highest deformation.

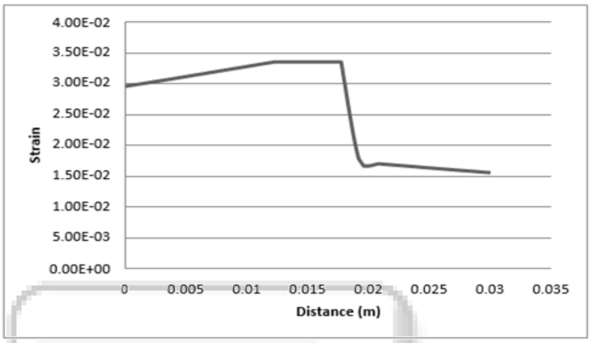

Fig 19: *Equivalent strain distribution along the line P*

The value of maximum equivalent strain is 0.0335 m/m and its value remain almost constant in the HAZ of 304 stainless steel and reach its peak in the weld metal zone and then recede rapidly in the 1020 mild steel side. Having seen these problems of high stress and strain with 302 stainless steel as the weld metal, Inconel 625 replaces it for the next analysis.

B. *Case II*

Inconel 625 as Weld Filler Metal-Now the weld metal is changed from 302 stainless steel to Inconel 625. Inconel 625 has been chosen because of its material properties, which are intermediate between 304 stainless steel and 1020 mild steel. Again the welded joint is simulated as in case I, keeping all the other boundary condition same.

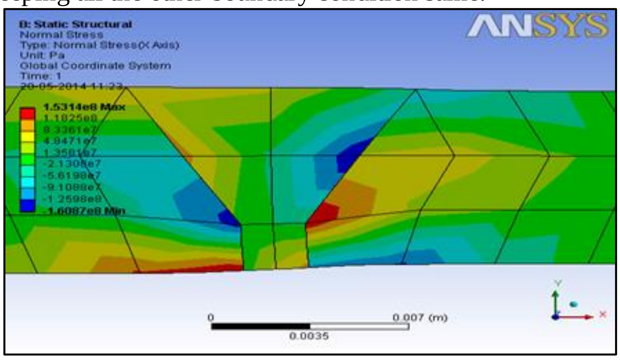

Fig. 20: Normal stress contour of Model A

The value of stress varies from 153 MPa tensile to 160 MPa compressive. A notable change that can be observed from the previous case is that the rise in stress is not limited only in 1020 stainless steel side but a somewhat lower but appreciable rise is also seen in the 304 stainless steel side.

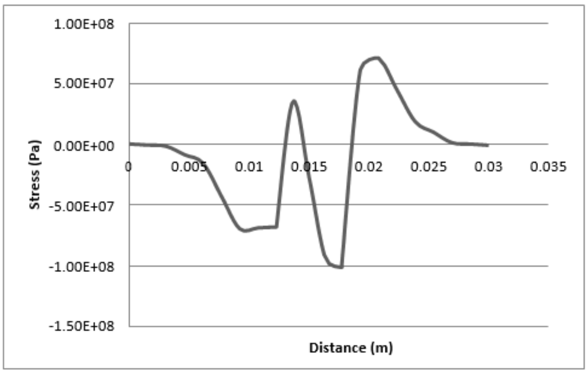

Fig 21: *Normal Stress distribution along line P*

The values of maximum stress on 304 stainless steel side is 71 MPa and while a maximum of 101 MPa is found on 1020 mild steel side.

Fig. 22: Shear stress contour of Model A

Shear stress values in the XY-plane vary from 119 MPa counter-clockwise to 172 MPa in the clockwise sense. It is to be noted that high cyclic shear stresses have developed in the weld interface on 1020 mild steel side and in terms of shear stress this side of weld metal is still the highest risk zone.The maximum value of shear stress which is 172 MPa falls on the line P, which depicts that the weakest point falls at a distance of 5 mm from the weld root near the 1020 mild steel side.

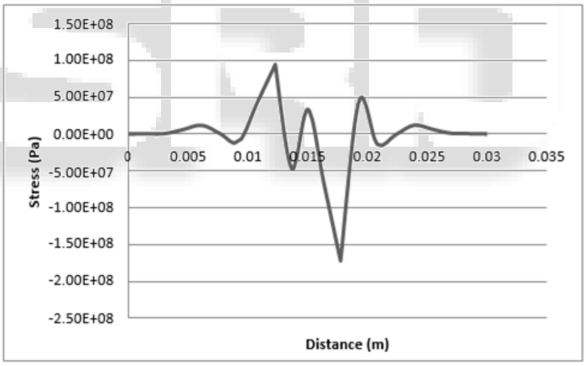

Fig 23: *Shear stress distribution along line P*

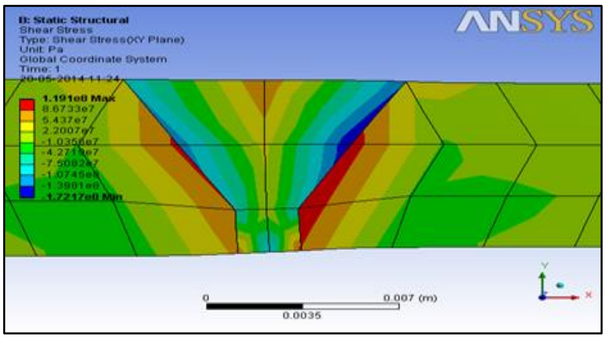

Fig. 24: Normal stress contour of Model B

For the case wherein residual stress has developed due to cooling after welding the value of stress varies from 150 MPa in tensile sense to 156 MPa in the compressive sense.

As shown in the contour diagram tensile stresses have developed on 1020 side while 304 stainless steel and Inconel have compressive stress developed in their region.

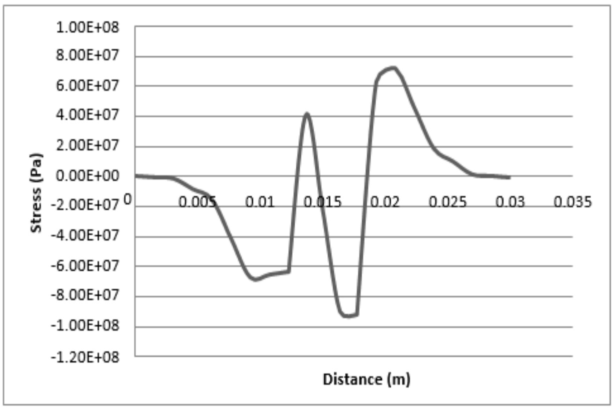

Fig 25: *Normal stress distribution along line P*

The maximum value of normal stress is found in the weld interface near the 1020 mild steel and its value is 91 MPa which is compressive in nature. However the value of stress in terms of magnitude is found to be uniformly increasing and decreasing along the weld metal.

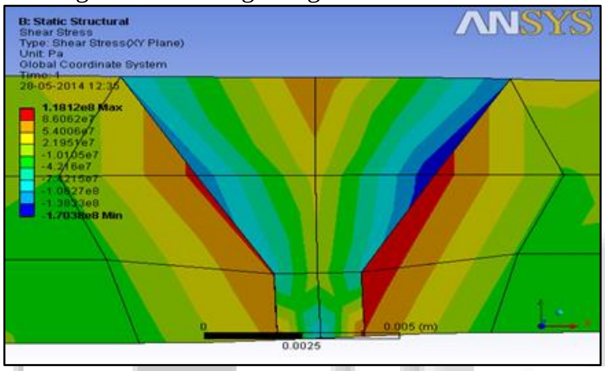

Fig. 26: Shear stress contour of Model B

The shear stress developed in the welded part in XY-plane is 118 MPa in the counter-clockwise sense and 170 MPa in the clockwise sense. Both the peaks of clockwise and counter-clockwise are present on the weld interface on the 1020 mild steel side.

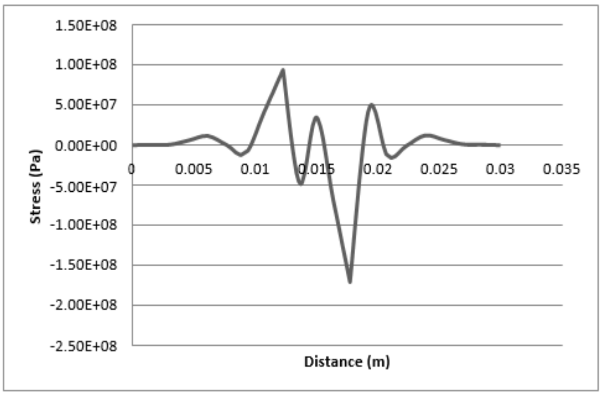

Fig. 27: *Shear stress distribution along line P*

The variation in shear stress along the weld metal is very rapidly changing in a cyclic fashion. The value of maximum shear stress in clockwise sense is located at the weld interface on 1020 mild steel side on the line P and its value is 170 MPa.

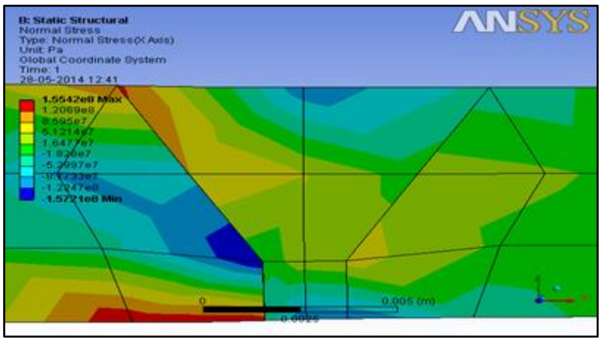

Fig. 28: Normal stress contour of Model C

The model C which is superimposed thermal stress on residual stress the maximum normal stress has shifted away from the weld metal zone towards the side of 304 stainless steel. Even if the highest value of stress is about 155 MPa tensile and 157 MPa compressive, but still the value of normal stress in the weld metal zone is very low as depicted by Fig. 29.

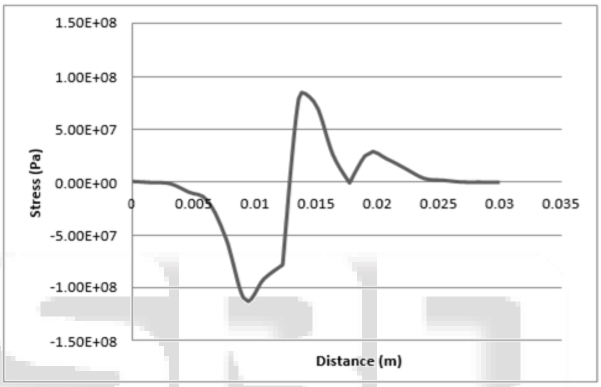

Fig. 29: *Normal stress distribution along line P*

Fig. 29: shows the value of maximum normal stress of around 102 MPa along the line P, which is almost half of the maximum stress developed in the entire welded part. Almost entire of the weld zone has nearly equal value of stress as shown in Fig. 28. This is the advantage by using Inconel 625 as a weld metal which reduces the stress developed in the weld metal zone and makes the joint safer.

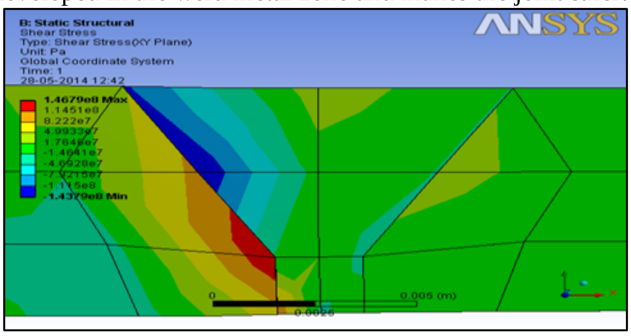

Fig. 30: Shear stress contour of Model C

The value of the shear stress in the XY-plane developed is highest in the weld interface on the 304 stainless steel side. The value of the stress varies from 146 MPa in counter-clockwise sense and 143 MPa in clockwise sense. Even if the highest stress has changed places between the interfaces, but still its value has decreased.

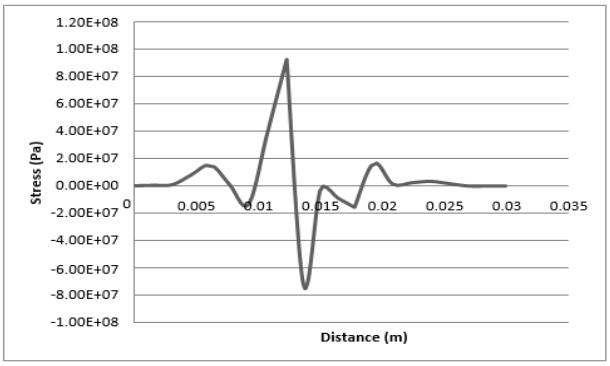

Fig. 31: *Shear stress distribution along line P*

The same is depicted by Fig. 31, as the highest value of stress along the line P is found to be 92.6 MPa. The cyclic variation of stress is near the 304 stainless steel side but still the value of stress is appreciably lower than that in case of 302 stainless steel as the weld metal.

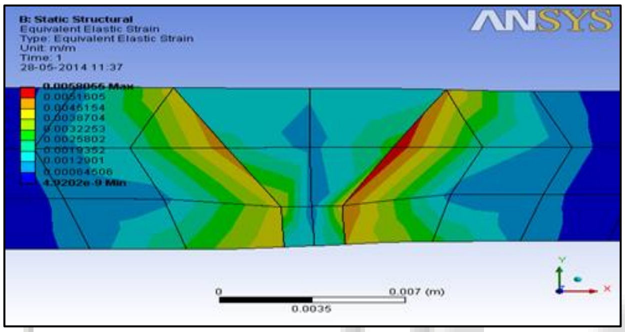

Fig. 32: Equivalent strain contour for Model C

Now, finally considering the strain developed in the model C, it is found that the value of equivalent strain varies from 0.0058 to a minimum of 4.92e-9. The peak value of strain lies in the weld interface on the 1020 mild steel side. The values of strain are found higher only in the HAZ of parent metals and most of the weld metal has developed negligible strain.

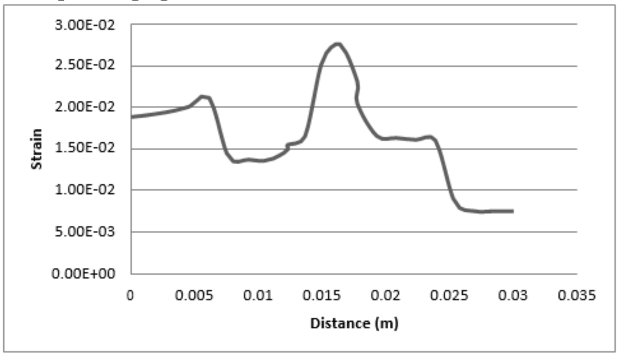

Fig. 33: *Equivalent strain distribution along line P*

The equivalent strain along the line P shows higher values of strain in the heat affected zone of the parent metal and whose values decrease within the weld metal. The peak value of strain along the path is 0.0276 m/m.After getting the results, the data regarding the maximum values of normal stress along the line P is tabulated comparing both the cases of welding;

Models Nature of Stress Case I: 302 Stainless Steel Case II: Inconel 625

Table 10: *Comparison of normal stress values in the two cases of welding*

Models	Nature of Stress	Case I: 302 Stainless Steel	Case II: Inconel 625
A	Tensile	118 MPa	71 MPa
	Compressive	112 MPa	101 MPa
B	Tensile	92 MPa	63 MPa
	Compressive	107 MPa	91 MPa
C	Tensile	127 MPa	82 MPa
	Compressive	140 MPa	112 MPa

From the above table some of the results that can be inferred are mentioned

1) The maximum value of superimposed stress i.e. Model C is greater than the maximum values of both the thermal stress and weld residual stress in all the cases.
2) This explains the reason why it is necessary to consider the weld residual stress while exposing a welded part to cyclic thermal stresses. It will be an underestimation of the maximum working stress and result finally into an unsafe joint.
3) The values of stress both either of compressive or of tensile nature are found to be reduced significantly when the weld metal is changed from 302 stainless steel to Inconel 625.

It is obvious from the stress contour diagrams in the case I the highest values of stresses were in the weld interface on the 1020 mild steel side. Hence it is the weakest location the welded part. Now from table 1 and table 2 it is clear that the carbon concentration in 1020 mild steel is much higher than that in 304 stainless steel. As a result of which, during welding or any other subsequent high temperature operation carbon atoms will diffuse from 1020 mild steel into the weld metal. So a carbon depleted zone is formed in the HAZ of 1020 mild steel and a carbon enriched zone is formed in the weld metal. The carbon diffusion will change the material properties and will greatly influence life of the joint [12]. Since the value of stress as shown in the contour diagrams change drastically in this interfacial zone, the resultant stress gradient will accelerate carbon diffusion. [11].Therefore, carbon diffusion, thermal and residual stress which plays an important role in the service life of a component needs to be reduced. One method of solving this problem is to choose a weld metal having co-efficient of thermal expansion intermediate between 1020 mild steel and 304 stainless steel, and other is to choose a weld metal that can reduce carbon diffusion. Sireesha et al. [12] suggested that Inconel as a filler material is the best option available in welding dissimilar steels. This is because nickel-based consumable alloys exhibit better tensile strength, resistance to hot cracking and thermal stability compared to steels. Also carbon movement activity is also retarded due to low diffusivity of carbon in nickel-based alloys.

This is the reason why Inconel 625 has been used for welding in the second case and the results obtained have clearly proved the theory behind. Only exception that can be taken is shifting of high stress zone in both the interfaces which was earlier only on the 1020 mild steel side. But the value of these stresses is very low i.e. 15- 30% lower than those obtained by using 302 stainless steel as the weld metal.

In dissimilar welding joint, Stress Corrosion Cracking. To appreciate the susceptibility to Stress

Corrosion Cracking, hardness is an important factor which goes hand in hand with strain hardening. So the values of strain have also been calculated in this research. [13]. From Fig. 19, the strain developed in the weld metal and the HAZ of parent metals is found to have a maximum value of 0.0335 m/m in the weld metal zone. After Inconel 625 is used as the weld metal, the highest value of strain is reduced to 0.0276 m/m as shown in Fig. 33.

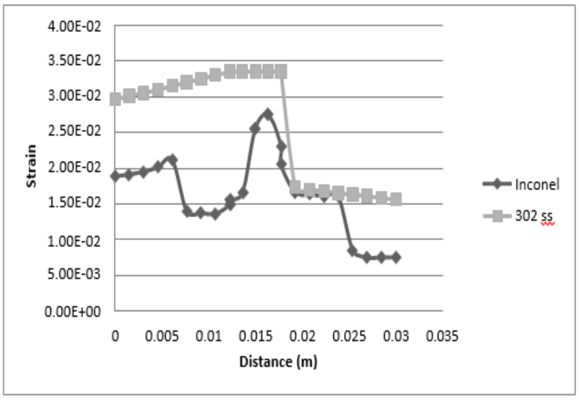

Fig. 34: *Comparison of strain values between case I and case II*

Fig. 34 shows that the value of strain induced in Inconel weld metal is significantly lower than that induced in 302 stainless steel weld metal throughout the path line P. The reduction in maximum strain is 17%.

VII. Conclusions

This research presents a study of thermal stress in a dissimilar welding joint between 1020 mild steel and 304 stainless steel, and the effect of weld residual stress on the thermal stress has been discussed. From the results above we arrive at the following conclusions:

1) Welding which is a significant cause of residual stress generates a large amount of residual stress in the weld metal and HAZ of the parent metals, which increases the final thermal stress and should be considered while determining the strength of the joint.
2) If the residual stresses are not considered, due to lower co-efficient of thermal expansion, 1020 mild steel develops tensile thermal stress while compressive thermal stress is generated in 304 stainless steel during operating conditions.
3) The peak of the stress is reached in the weld interface of 1020 mild steel and weld metal near the mild steel side, which becomes the highest risk zone.
4) If A302 steel is replaced by Inconel 625 then the developed peak stress falls by 15-30%, and hence the welded joint becomes safer.
5) Inconel 625 is recommended to be used as the weld metal, because it also reduces strain which is an index of stress corrosion cracking as result of which the chances of stress corrosion cracking are reduced by 17%.
6) Also by introducing a weld metal which is a nickel-based alloy decreases the carbon activity gradient due to its low carbon diffusivity. Thus there is no abrupt change in material composition and hence a steep stress gradient is avoided.

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