Evaluations and Modelling of Residual Stress of a joining - Sialon to Austenitic Stainless Steel

By

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

It is not easy to join ceramic to metal due to the differences in the coefficient of thermal expansion of the two materials. The residual stress present has caused failure to the joining. Materials with a relatively low elastic modulus can accommodate strain and will tend to deform under the influence of this stress, while brittle materials such as glasses and ceramics, will have a tendency to fracture. The evaluations and modelling of residual stress of a joining-sialon to austenitic stainless steel was simulated using Finite Element Analysis (ANSYS10) software and simple analytical model was used to evaluate the residual stress. The joining process was assumed as direct diffusion bonding. The stress contour plot was discuss based on failure criteria. It is found that at the area nearby the joining interface, stainless steel experiences tensile stress while ceramic experiences compressive stress. The stress intensity is the highest at a few points at the ceramic interface compared to the steel interface. Crack occurred at these points due to the mismatch of thermal expansion and the inability of ceramic to withstand the high concentration of tensile stress.

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INTRODUCTION

1.1 Background of Study

It is not easy to join ceramic to metal due to the differences in the coefficient of thermal expansion of the two materials. When joining these two materials, the residual stress present has caused failure to the joining. Previous study had shown that the joining sialon to ferritic stainless steel is more successful than the joining of sialon to austenitic stainless steel. At the joining of sialon to ferritic stainless steel, a ductile interlayer [1] which able to absorb the residual stress was formed. However, at the joining of austenitic stainless steel to sialon, the ductile layer was not present. This has caused crack at the joint. Effects of the stainless steel thickness during the joining was studied by P.Hussain et al [2] where findings show that below a critical thickness of steel, the residual stress is less than the fracture stress of sialon. Typical applications of ceramic-metal bonding are the assembly of metal shaft to the turbine rotor, the assembly of metal components to heat engines and etc.

1.2 Problem Statement

In an assembly composed of various materials, there is usually a mismatch between the thermal expansion coefficients of the adjoining components. This causes residual stress on cooling from the solidus temperature of the filler metal and is maximum at the lowest temperature that the assembly experiences. Materials with a relatively low elastic modulus can accommodate strain and will tend to deform under the influence of this stress, while brittle materials such as glasses and ceramics, will have a tendency to fracture. Even if the assembly survives the joining operation, the residual stresses arising from the thermal expansion mismatch can cause it to fail by fatigue during subsequent thermal cycling in the field. Through this project, extensive study on sialon ceramic, austenitic stainless steel, joining process and residual stress will be carried out. The present of residual stress at joining of sialon to austenitic stainless steel will be simulated using Finite Element Analysis(ANSYS).

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Ceramic Sialon

2.1.1 Sialon and silicon nitride

Sialon and silicon nitride[3] are a material with similar properties. Silicon nitride (Si_3N_4) exhibits very high resistance to heat and corrosion and is extremely strong. Sialon, a family of silicon-aluminium-silica oxynitrides, has properties comparable to those of silicon nitride and is much easier to manufacture and form into complex shapes. Because of pure Si_3N_4 powders are difficult to sinter, several methods are used to achieve finished parts of desired size and shape. The processing technology used has a significant effect on the physical properties of the finished part. Among the processing technologies are reaction bonding, hot pressing and isostatically hot pressing and sintering and gas-pressure-assisted sintering. Sialon is synthesized by reacting together silicon nitride, silica, alumina and aluminium nitride. Sialon exists in three forms β′ based on β silicon nitride; α′ based on α silicon nitride and O′ sialon which has the crystal structure of silicon oxynitrides and obeys the formula $Si_zAl_{2-z}O_{3-z}N_z$, with z taking values in the range of 1.3 to 2. Materials base on β′ sialon or a mixture of α and β′ sialon are well suited for high-temperature and high stress application.

Table 1: Typical Properties of Sialon compared to Silicon Nitride[3]

Property	**Units**	**Sialon**	**Si_3N_4**
Density	g/cm^3	3.25	3.2
Modulus of Elasticity	GPa	0.28	0.31
Hardness	Knoop,k100	1800	2200
Compressive strength	MPa	>3500	>3500
Toughness	$MPa \cdot m^{1/2}$	7.7	5
Poison's ratio		0.23	0.27
Thermal conductivity at 25°C	$W/(m \cdot K)$	21.3	25
Specific heat at 25°C	$Cal/g \cdot K$	0.15	0.17
Thermal expansion coefficient	10^{-6} /K	3.04	3.2

Silicon nitride (Si_3N_4) is technically the most important nitride of the main group elements. It is the most frequently utilized nitride material and is used for the construction of bearings, pistons, and turbines. It has two forms and usually both forms are obtained together during the preparation, for example by reaction of the elements at 1200°C. The low temperature α- modification is transformed to the β-modification by heating above l650°C. At low preparation temperatures the α-modification predominates. The proportions of α-Si_3N_4 and β-Si_3N_4 in mixtures can be determined by X-ray powder diffraction. A high amount of α-Si_3N_4 is desired because it significantly increases sintering activity.

The α-Si_3N_4 and β-Si_3N_4 have a complex three-dimensional network of corner sharing Si_3N_4 tetrahedral with an average Si-N bond length of 0.174nm. The structure of the low-temperature modification has two crystallographically different silicon atoms, while only one silicon position occurs in the high-temperature modification. In both modifications, the nitrogen atoms have more or less trigonal-planar carbon coordination. The high stability of silicon nitride is due to a complex interaction of mostly covalent bonding and a high degree of condensation of the corner-sharing Si_3N_4 tetrahedral. The high corrosion stability of Si_3N_4 is due to the formation of a thin surface coating of SiO_2.

The most common method used for sintering silicon nitride materials is gas-pressure sintering. The material is sintered to closed porosity (>95% density) at a low gas pressure. Then an outer gas pressure of up to 10 MPa is applied. The difference between the outer pressure and the pressure in the closed pores is a driving force leading to a better healing of defects. α′- SiAlON are formed during liquid-phase sintering by the reaction of Si_3N_4, AlN, Al_2O_3 and a suitable cation which can enter the structure of α′- SiAlON. The amount of liquid available for densification is quickly reduced due to the formation α-SiAlON solid solutions.

2.1.2 Crystal Structure and Properties

The α and β modifications be can be produced under normal nitrogen pressure. A high pressure modification can be produced under 15 GPa pressure by the technique of laser heating in a diamond cell. The α-phase is very stable under sintering conditions but is the main phase in the starting silicon nitride powders. The α and β modifications [4] are based SiN_4 tetrahedral connected at the corners. Every N belongs to 3 tetrahedral. Only one layer of SiN_4 tetrahedral exists in β-Si_3N_4, whereas two layers shifted with respect to each other exist in α-Si_3N_4. This leads to a doubling of the c-axes in the α-Si_3N_4 crystal lattice in comparison to the β-Si_3N_4 lattice. The high-pressure phase has a completely different structure. On the basis of powder diffraction patterns, it is found that this phase has a spinel-type structure, in which one silicon atom is coordinated by four nitrogen and two silicon atoms by six nitrogen atoms.

The Si and N atoms β-Si_3N_4 can be replaced by Al and O atoms to form the β′-SiAlON with the formula: $Si_{6-z}Al_zN_{8-z}O_z$. The range of the β′ solid solution extends from z =0 to 4.2 at 1750°C. Every Si_3N_4 material containing Al_2O_3 as a sintering additive is some kind of β-SiAlON. Most commonly the terminology β-SiAlON is used for z values >0.5. Analysis of the α-Si_3N_4 crystal structure shows that there is an empty position coordinate in the crystal structure. This position can be partially occupied by ions with an atomic radius of about 0.1nm. Furthermore, Si and N must be replaced by Al and O to obtain electro neutrality. The resulting phase is the called α-SiAlON with the formula: $R_xSi_{12-n-m}Al_{m+n}N_{16-n}O_n$. Occupation of the coordinate leads to stabilization of the very stable α-Si_3N_4 phase. The lowest x value for trivalent cations is 0.33 which means that the α′- SiAlON solid solution does not include the composition of pure α-SiAlON. The β modifications have much lower hardness than the α modifications.

2.1.3 Mechanical properties

Table 2: Properties of Sialon [5]

Mechanical	**Units**	**Value**
Density	g/cm^3	3.24
Porosity	%	<1%
Color	—	gray
Flexural Strength	MPa	760
Elastic Modulus	GPa	288
Shear Modulus	GPa	120
Bulk Modulus	GPa	220
Poisson's Ratio	—	0.25
Compressive Strength	MPa	—
Hardness	Kg/mm^2	1430–1850
Fracture Toughness K_{IC}	MPa•m$^{1/2}$	6.0–7.5
Maximum Use Temperature (no load)	°C	1200
Thermal		
Thermal Conductivity	W/m•°K	15–20
Coefficient of Thermal Expansion	10^{-6}/°C	3

2.2 Stainless Steel

Stainless steels [6] are iron-base alloys with a minimum of approximately 11% chromium, which is the amount needed to prevent the formation of rust in a normal environment. A few stainless steels contain more than 30% chromium. They achieve their stainless characteristic by the formation an unseen and adherent chromium-rich oxide surface film. This oxide forms and heals itself in the existence of oxygen. Other alloying elements added to enhance their structure and properties such as formability, strength and cryogenic toughness. These include elements such as nickel, molybdenum, cooper, titanium, aluminium, silicon, nitrogen, and sulfur. Carbon is normally present in amounts ranging from less than 0.03% to 1.0% in certain stainless steel. The main requirement for stainless steels is that they should be corrosion resistant for a specified application or environment. Stainless steel can be classified into five groups namely austenitic, ferritic, martensitic, duplex and precipitation hardening (PH) stainless steel.

Stainless steel can be formed and fabricated in conventional ways. They can be produced and used in the many conditions. The shapes can be produced by powder-metallurgy techniques. The cast ingots can be rolled or forged while the flat products (plate and sheet) can be produced from continuously cast slabs. Meanwhile, the rolled product can be drawn, bent and extruded. It can also be used as an integral cladding on low-alloy steels as well as some nonferrous metals and alloys. Stainless steel can also be further shaped by machining and joined by welding, brazing, soldering and adhesive bonding. Heat treating of stainless steel produces changes in physical condition, mechanical properties and residual stress level and restores maximum corrosion resistance when that property has been adversely affected by previous fabrication or heating. Frequently, satisfactory corrosion resistance and optimum mechanical properties are obtained in the same heat treatment.

Over the years, stainless steels have established as materials for cooking tools, fasteners, cutlery, flatware, decorative architectural hardware and equipment used in chemical plants, food processing plants, health and sanitation application, petroleum production offshore structure and aerospace parts.

2.2.1 Physical and Mechanical Properties

The physical and mechanical properties of stainless steels are quite different from those of commonly used nonferrous alloys such as aluminium and cooper alloys. When comparing the various stainless steel families with carbon steels, many similarities in the properties exist. The density of stainless steels is approximately 8.0g/cm^3, which is about three times greater than that of aluminium alloys. Its high modulus of elasticity (200MPa) is nearly twice of cooper alloys and nearly three times of aluminium alloys[7].

The differences among these materials are evident in thermal conductivity, thermal expansion and electrical resistivity. For stainless steel, alloying additions component especially nickel, copper, and chromium greatly decrease thermal conductivity. Figure 1 shows the comparison thermal expansion, electrical resistivity and thermal conductivity for carbon steel, cooper alloy, aluminium and stainless steel. Thermal expansion is greatest for type 6061 aluminium alloy followed by aluminium bronze and austenitic stainless alloys, and then ferritic and martensitic alloy. For austenitic stainless a1loys, additions of nickel and copper can decrease the thermal expansion. Stainless steels have high electrical resistivity. Alloying additions tend to increase electrical resistivity. Therefore, the ferritic arid martensitic stainless steels have lower electrical resistivity than the austenitic, duplex and PH alloys but higher electrical resistivity than 1080 carbon steel. Electrical resistivity of stainless steels is about 7.5 times greater than aluminium bronze and about 20 times greater than type 6061 aluminium alloy.

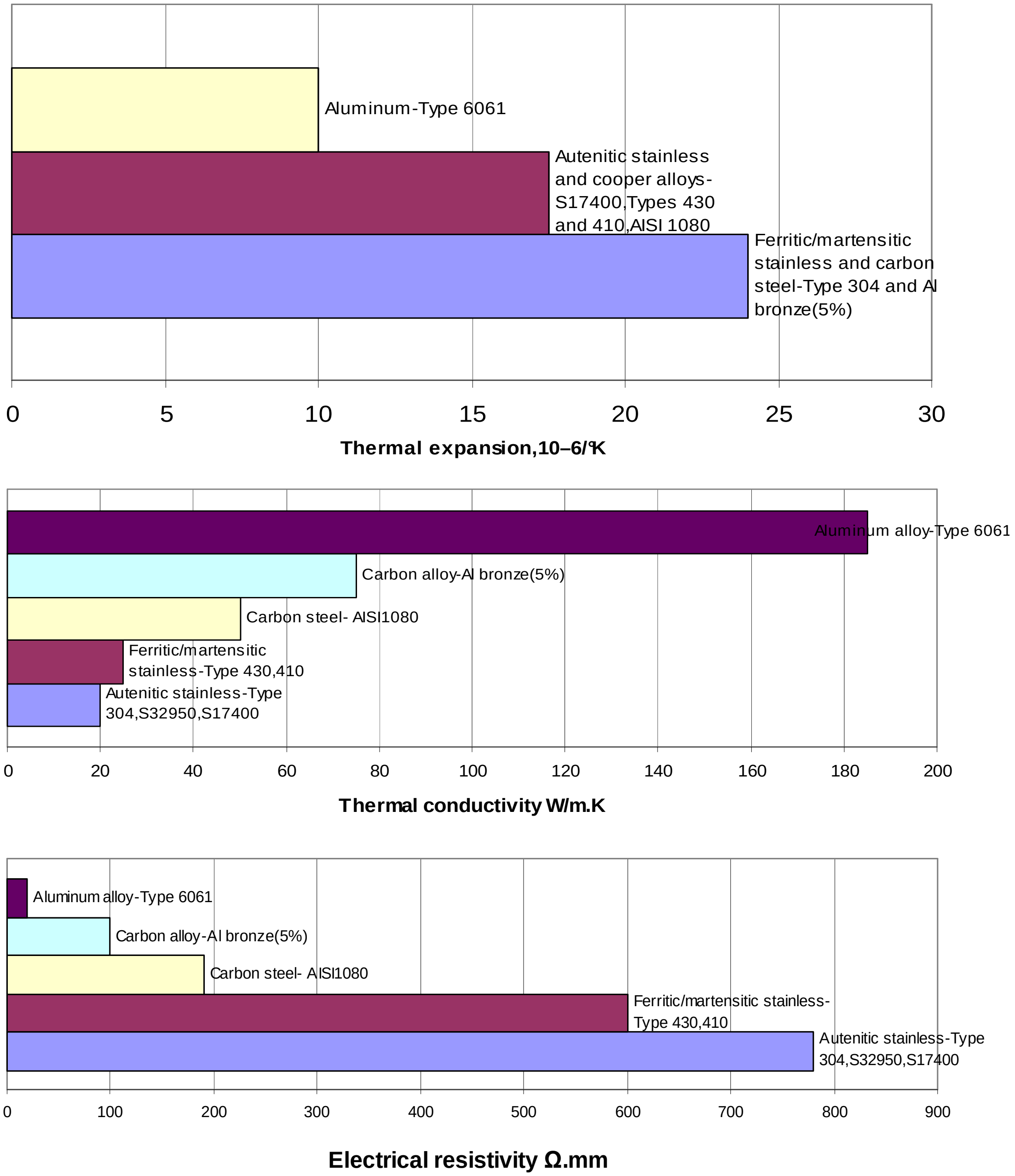

Figure 1: Comparison of thermal expansion, electrical resistivity and thermal conductivity for carbon steel, cooper alloy, aluminium and stainless steel.[8]

The austenitic alloys have relatively low yield strength, compared with the heat-treatable al1oy, but have the highest tensile ductility and toughness. There are also specially developed austenitic alloys to have superior resistance against metal-metal wear.

The ferritic stainless steels have yield strength almost similar to those of the austenitic grades but lower values for ultimate tensile strength, ductility and toughness. However, the strength, ductility, and toughness are still outstanding compared with other material such as aluminium alloy and aluminium bronze. As for the duplex stainless alloys, the tensile yield strength is almost twice of the austenitic and ferritic grades and approximately half the toughness and it toughness is far superior to that of alloys that are heat treated and hardened.

The martensitic alloys have a large variation in strength, ductility, and toughness. In the annealed condition, their properties are similar to those of the ferritic alloys, with strength increasing and ductility decreasing with increasing carbon content. The higher carbon containing alloys are generally tempered at a low temperature (260-650°C) to maximize their strength. The tensile properties are similar to those of carbon steels. The martensitic PH alloys have higher annealed strength and lower ductility than the martensitic alloys and are tempered at temperatures ranging from 480 to 620°C. Their strength is dependent on the hardener material and the aging temperatures used. Their toughness is either similar or superior to the martensitic alloys at a given strength level.

Table 3: Physical Properties of Stainless Steel[6]

Steel Types (AISI)	Density	Modulus		Expansion	Conductivity	Specific Heat	Resistivity
	kg/m^3	kN/mm^2		10^{-6}x K^{-1}	W/m.K	J/kg.K	ohm.mm^2/m
		20C	400C				
Ferritic stainless steels							
410S	7700	220	195	10.5	30	460	0.60
430	7700	220	195	10.0	25	460	0.70
444	7700	220	195	10.4	23	430	0.8
Martensitic and precipitation hardening stainless steels							
410	7700	215	190	10.5	30	460	0.60
440	7700	215	190	10.4	15	430	0.8
630	7800	200	170	10.9	16	500	0.71
Austenitic stainless steels							
304	7900	200	172	16.0	15	500	0.73
316	8000	200	172	16.0	15	500	0.75
Duplex stainless steels							
'2205'	7800	200	N/A	13.0	15	500	0.8

2.2.2 Selection of Stainless Steel

The selection of stainless steels[8] may be based on corrosion resistance, fabrication characteristics, availability, mechanical properties in specific temperature and the product cost. However, corrosion resistance and mechanical properties are usually the most important factors in selecting a specific stainless steel for a given application. The characteristics to be considered in selecting the proper type of stainless steel for a specific application include:

- Corrosion resistance
- Resistance to oxidation and sulfidation(high temperature corrosion)
- Strength and ductility at ambient and service temperatures
- Suitability for intended fabrication techniques
- Suitability for intended cleaning
- Stability of properties in service
- Toughness
- Resistance to abrasion and erosion
- Surface finish and reflectivity
- Physical property characteristics such as magnetic properties, thermal conductivity and electrical resistivity
- Sharpness or retention of cutting
- Rigidity

2.3 Austenitic Stainless Steel

Austenitic stainless steels[9] constitute the largest stainless family in terms of number of alloys and usage. Like the ferritic alloys, they cannot be hardened by heat treatment However, their similarity ends there. The austenitic alloys are nonmagnetic and their structure is face-centered cubic (fcc), like that of high-temperature (900-1400°C) iron. They possess excellent ductility, formability and toughness. In addition, they can be substantially hardened by cold work. Nickel is the chief element used to stabilize austenite. Besides that, carbon and nitrogen are also used because they are readily soluble in the fcc structure. A wide range of corrosion resistance can be achieved by balancing the ferrite-forming elements, such as chromium and molybdenum with austenite-forming elements.

Austenitic stainless steels can be subdivided into two categories; chromium-nickel alloys and chromium-manganese-nitrogen alloys. The second group generally contains less nickel and maintains the austenitic structure with high levels of nitrogen. Manganese (5 to 20%) is necessary in these low-nickel alloys to increase nitrogen solubility in austenite and to prevent martensite transformation. The addition of nitrogen also increases the strength of austenitic alloys. Typical chromium-nickel alloys have tensile yield strengths from 200 to 275MPa in the annealed condition, whereas the high-nitrogen alloys have yield strengths up to 500 Mpa. The compositions of standard austenitic stainless steels are shown in Table 4.

Austenitic stainless steels can be further divided into five groups:

- **Conventional austenitic**, such as types 301, 302, 303, 304, 305, 308, 309, 310, 316, and 317
- **Stabilized compositions**, primarily types 321, 347, and 348
- **Low-carbon grades**, such as types 304L, 316L, and 317L
- **High-nitrogen grades**, such as AISI types 201, 202, 304N, 316N and the Nitronic series of alloys
- **Highly alloyed austenitic**, such as 317LX, JS700, JS777, 904L, AL-4X and 254 SMO

Table 4: Composition of standard austenitic stainless steel[10]

Type	Composition, %						
	C	Mn	Si	Cr	Ni	S	Other
201	0.15	5.5-7.5	1.0	16.0-18.0	3.5-5.5	0.03	0.25N
205	0.12-0.25	14.0-15.5	1.0	16.5-18.0	1.0-1.75	0.03	0.32-0.40N
302	0.15	2.0	1.0	17.0-19.0	8.0-10.0	0.03	-
302Cu	0.08	2.0	1.0	17.0-19.0	8.0-10.0	0.03	3.0-4.0Cu
316H	0.04-0.10	2.0	1.0	16.0-18.0	10.0-14.0	0.03	2.0-3.0Mo
316L	0.03	2.0	1.0	16.0-18.0	10.0-14.0	0.03	2.0-3.0Mo
317	0.08	2.0	1.0	18.0-20.0	11.0-15.0	0.03	3.0-4.0Mo
317L	0.03	2.0	1.0	18.0-20.0	11.0-15.0	0.03	3.0-4.0Mo
330	0.08	2.0	0.75-1.5	17.0-20.0	34.0-37.0	0.03	-
347	0.08	2.0	1.0	17.0-19.0	9.0-13.0	0.03	10x%C min Nb
384	0.08	2.0	1.0	15.0-17.0	17.0-19.0	0.03	-

As mention before, austenitic alloys can be substantially hardened by cold working. The degree of work hardening depends on the alloy content, with increasing alloy content decreasing the work-hardening rate. Austenitic stainless steels that have low alloy content often become magnetic because of the transformation to martensite when sufficiently cold worked or heavily deformed in machining or forming operations. Cooper is intentionally added to lower the work hardening rate for enhanced headability in the production of fasteners.

Another property that depends on alloy content is corrosion resistance. Molybdenum is added enhance corrosion resistance in chloride environments. High-chromium grades are used in oxidizing environments and high-temperature applications while a high-nickel grade is used in severe reducing acid environments. To prevent inter-granular corrosion after elevated-temperature exposure, titanium or niobium is added to stabilized carbon in austenitic stainless steels. The lower- carbon grades (AISI L or S designations), have been established to prevent intergranular corrosion. Some of the more corrosion-resistant alloys, have nickel levels high enough (32 to 38% Ni) to be classified as nickel-base alloys. Alloys containing nickel, molybdenum (6%) and nitrogen (0.20%) are sometimes referred to as superaustenitics which has a very high corrosion resistance.

Austenitic stainless steels have a face-centered-cubic (fcc) structure. This structure is attained through the liberal use of austenitizing elements such as nickel, manganese and nitrogen. These steels are essentially nonmagnetic in the annealed condition and can be hardened only by cold working. They usually possess excellent cryogenic properties and good high-temperature strength. Chromium content generally varies from 16 to 26%, nickel up to about 35% and manganese up to 15%. The 200-series steels contain nitrogen, 4 to 15.5% manganese and up to 7 % nickel while the 300-series contain larger amounts of nickel and up to 2% manganese. Molybdenum, cooper, silicon, luminium titanium and niobium may be added to give certain characteristics such as halide pitting and oxidation resistance. Sulfur or selenium may be added to certain grades to improve machinability.

2.3.1 Basic Metallurgy

Austenitic stainless steel compositions are based on a balance between alloy elements that promote ferrite formation and those that promote austenite formation. The prototype ferritizing element is chromium, but molybdenum, niobium, titanium, aluminium, tungsten and vanadium also promote ferrite. The prototype austenitizing element is nickel but carbon, nitrogen, and copper all promote transformation of ferrite to austenite at high temperatures. In addition, although manganese does not seem to promote transformation of ferritic to austenitic at high temperature but it does tend to stabilize austenite with respect to transformation to martensite at low temperatures. Further, manganese promotes the solubility of nitrogen in steel, making possible a low-nickel family of austenitic stainless steels that are high in manganese and nitrogen.

Austenitic stainless steels can be best described in terms of iron-chromium-nickel ternary alloy system. The commercial alloys also contain a certain amount of carbon, silicon, manganese, sulfur and so on. These elements might change somewhat the phase balance. The structure is determined by three primary constituents iron, chromium and nickel. The maximum temperature of austenite stability is 1100°C and is used as the optimum annealing temperature for the 18-8 chromium-nickel steels. Above 1150°C, some δ-ferrite will form. If the chromium content increases above 18%, it becomes necessary to raise the nickel content. Otherwise, increasing amounts of ferrite will be formed.

Sensitization or carbide precipitation at grain boundaries can occur when austenitic stainless steels are heated for a period of time in the range of about 425 to 870°C. Time at temperature will determine the amount of carbide precipitation. When the chromium carbides precipitate in grain boundaries, instantly the area adjacent is depleted of chromium. The carbide formed in conventional austenitic steels is $(Cr,Fe)_{23}$ or $M_{23}C_6$ carbide. When the precipitation is relatively continuous, the depletion renders the stainless steel susceptible to intergranular corrosion which is the dissolution of the low-chromium layer or envelope surrounding each grain. Sensitization also lowers resistance to other forms of corrosion, such as pining and crevice(crack) corrosion. Time-temperature-sensitization curves are used as guidance for avoiding sensitization. Besides that, stabilized steels are also used for avoiding sensitization. Such stainless steels contain titanium or niobium. These elements have an affinity for carbon and form carbides readily. This allows the chromium to remain in solution even for extremely long exposures to temperatures in the sensitizing range. The only way to correct a sensitized stainless steel is through annealing.

2.3.2 Properties and Applications

Most of the austenitic stainless steels are the 300-Series Steels which the first letter of the type name is denoted with ‘S’. The yield strengths of austenitic stainless steels are rather modest and are comparable to those of mild steels. Typical minimum mechanical properties of annealed 300-Series steels are yield strength 205 to 275MPa, ultimate tensile strength of 520 to 760MPa and elongations of 40 to 60%.

Austenitic stainless steels cannot be hardened by heat treatment. Therefore, high strength is possible in cold-worked form, especially in drawn wire, in which a tensile strength of 1200MPa or higher is achievable. The heat of welding will soften a heat-affected zone in heavily cold-worked austenitic stainless steel.

The leanest austenitic stainless steels such as types 302 and 304, which can be considered the base alloys of austenitic stainless steels offer general corrosion resistance in the atmosphere, in many aqueous media, in the presence of foods, and in oxidizing acids such as nitric acid. Types 321 and 347 are essentially type 304 with additions of either titanium or niobium respectively, which stabilize carbides against sensitization.

The addition of molybdenum in type 316L provides pitting resistance in phosphoric and acetic acids and dilute chloride solutions, as well as corrosion resistance in sulphurous acid. An even higher molybdenum content, as in type 317L (3%), and even richer alloys further enhance pitting resistance.

Nitrogen is added to enhance strength at room temperature and especially at cryogenic temperature. Nitrogen is also added to reduce the rate of chromium carbide precipitation and therefore, the susceptibility to sensitization. Molybdenum-containing alloys are also added with nitrogen to increase resistance to chloride-induced pitting and crevice corrosion.

Higher amounts of chromium, nickel or both are used to enhance high-temperature oxidation resistance (as in types 309, 310 and 330). Cooper and nickel can be added to enhance resistance to reducing acids, such as sulphuric acid. Nickel and molybdenum when present in sufficient amounts, promote resistance to chloride-induced stress-corrosion cracking.

There are several other groups of austenitic stainless steels for specific applications or processing requirements. Each of the wrought austenitic stainless steels has a counterpart cast alloy with a specific cast alloy designation. For example, CF-3, CF-8, CF-3M and CF-8M correspond to the wrought types 304L, 304, 316L and 316, respectively. The cast austenitic stainless steels are designed for good castability and therefore the composition ranges may be varying from those of their counterpart wrought steels. In particular, the chromium and silicon contents are higher and the nickel contents are lower in the cast alloys compared to wrought alloys.

Many cast heat-resisting grades of steel also have austenitic structures. The cast heat resisting grades have much higher chromium and nickel contents for scaling resistance and greater high-temperature strength compared to the 18Cr- 8Ni types of stainless steel. Again there are counterpart wrought and cast grades of heat-resisting stainless steels. However, there are many other cast grades of heat resistance alloys and these alloys have much higher carbon contents (020 to 0.75%) than wrought grades. Thus alloy carbides which contribute substantially to creep resistance are an important component of the microstructure of the cast austenitic high-temperature alloys. The heat-resistant austenitic stainless steels are used at elevated temperature applicants.

2.3.3 Heat Treatment

In furnace loading, the high thermal expansion of austenitic stainless steels (about 50% higher than that of mild carbon steel) should be considered. The spacing between parts should be adequate to accommodate this expansion. Stacking should be employed when necessary to avoid deformation of parts at elevated temperatures.

Conventional austenitics[10]cannot be hardened by heat treatment, but will harden as a result of cold working. These steels are usually purchased in an annealed or cold-worked state. Following welding or thermal processing, a subsequent anneal may be required for optimum corrosion resistance, softness and ductility. During annealing, chromium carbides which obviously decrease resistance to intergranular corrosion are dissolved. Cooling from the annealing temperature must be rapid but it must also be consistent with distortion limitations. Whenever distortion considerations permit, water quenching is used, thus ensuring that dissolved carbides remain in solution. When distortion considerations rule out such a fast cooling rate, cooling in an air blast is used. With some thin-section parts, even this intermediate rate of cooling produces excessive distortion and parts must be cooled in still air. If still air does not provide a cooling rate sufficient to prevent carbide precipitation, maximum corrosion resistance will not be obtained. A solution to this is to use of a stabilized grade or low carbon alloys.

Stabilized austenitics alloys (types 321, 347, and 343) contain controlled amounts of titanium or niobium, which render the steel nearly immune to intergranular precipitation of chromium carbide and its poor effects on corrosion resistance. However, these alloys may require annealing to relieve stresses, to increase softness and ductility or to provide additional stabilization. Unlike the unstabilized grades, these steels do not require water quenching or other acceleration of cooling from the annealing temperature to prevent subsequent intergranular corrosion. Air cooling is generally adequate.

When maximum corrosion resistance of the stabilized austenitic grades is required, it may be necessary to employ a heat treatment known as a stabilizing anneal. The treatment consists of holding at 845 to 900°C for up to 5hours depending on the section thickness. It may be applied prior to or during fabrication and may be followed by short- time stress relieving at 705°C without danger of harmful carbide precipitation. Certain restrictions on furnace atmosphere are compulsory. The furnace combustion must be carefully controlled to eliminate carburizing or excessively oxidizing conditions. Because the properties of the stabilized steels are based on their original carbon content, carbon absorption cannot be tolerated. Excessively oxidizing conditions cause the formation of a scale that is difficult to remove in subsequent rescaling operations. Direct impingement of flame on the work must also be prevented. The sulfur content of the furnace atmosphere, particularly in oil-fired furnaces, must be kept low.

Low-carbon austenitics are intermediate in their tendency to precipitate chromium carbides to the stabilized and unstabilized grades. Their carbon content (0.03%max) is low enough to reduce precipitation of intergranular carbides. This characteristic of limited sensitization is of particular value in welding, flame cutting and other hot-working operations. These materials do not require the quenching treatment that unstabilized grades require to retain carbon in solid solution. However, the low-carbon alloys are not satisfactory for long-time service in the sensitizing temperature range of 540 to 760 °C because they are not completely immune to the formation of carbides deleterious to corrosion resistance. The effects of sensitization and susceptibility to general corrosion vary among the low-carbon alloys, depending on their chemical composition. Because they contain molybdenum, types 316L and 317L are subject to σ-phase formation as a result of long-time exposure at 650 to 870°C. However, the corrosion resistance of these grades can be improved by emp1oying a stabilizing treatment consisting of holding at 885°C for 2hours, prior to stress relieving at 675°C. After undergo the stabilizing heat treatment, these alloys must get the copper-copper sulfate l6% sulfuric acid test for to ensure free from intergranular carbide precipitation.

The low-carbon alloys are frequently used in the production of part requiring low magnetic permeability. These materials are nonmagnetic in the fully annealed condition, with permeabilities below 1.02T but they may develop ferromagnetic qualities as a result of cold working during fabrication. Cold working may generate some low-carbon martensite, which is strongly magnetic. Fusion welding with a low-nickel filler rod is another possible cause of magnetism. Magnetism due to any of these causes can be eliminated by a full anneal to restore the alloy to its fully austenitic condition.

2.3.4 Stress Relieving

Austenitic stainless steels have good creep resistance. Consequently these steels must be heated to about 900°C to attain adequate stress relief. In some instances, heating to the annealing temperature may be desirable. Holding at a temperature lower than about 870°C results in only partial stress relief. The most effective stress-relieving results are achieved by slow cooling. Quenching or other rapid cooling, as is normal in the annealing of austenitic stainless steel, will usually reintroduce residual stresses. Stress relieving is only necessary when austenitic stainless parts are subjected to corrosive conditions conducive to stress corrosion or intergranular corrosion failures.

Selection of an optimum stress-relieving treatment is difficult because heat treatments that provide adequate stress relief can damage the corrosion resistance of stainless steel and heat treatments that are not harmful to corrosion resistance may not provide adequate stress relief.

The metallurgical characteristics[11] of austenitic stainless steels that may affect the selection of stress-relieving treatment are discussed below:

- **Heating in the range from 480 to 815 °C***: Chromium* carbides will precipitate in the grain boundaries of wholly austenitic unstabilized grades. In partially ferritic cast grades, the carbides will precipitate initially in the discontinuous ferrite pools rather than in a continuous grain-boundary network. After prolonged heating grain-boundary carbide precipitation will occur. For cold-worked stainless, carbide precipitation may occur temperatures as low as 425 °C. For types 309 and 310, the upper limit for carbide precipitation may be as high as 900 °C. In this condition, the steel is susceptible to intergranular corrosion. By using stabilized or extra-low-carbon grades, these intergranular precipitates of chromium carbide can be avoided.
- **Heating in the range from 540 to 925°C**: The formation of hard, brittle σ-phase may result, which can decrease both corrosion resistance and ductility. During the times necessary for stress relief, σ-phase will not form in fully austenitic wrought, cast or welded stainless. However, if the stainless partly ferritic, the ferrite may transform to σ-phase during stress relief. This is generally not a problem in wrought stainless steels because they are fully austenitic. However some wrought grades particularly types 309, 309Cb, 312 and 329 may contain some ferrite. Furthermore, the composition of most austenitic stainless welds and castings is intentionally adjusted so that ferrite is present as a deterrent to cracking. The niobium-containing cast grade CF-8C normally contains 5 10 20% ferrite, which is more likely to transform to σ-phase than the niobium-free ferrite in the unstabilized CF-8 grade.
- **Slow cooling an unstabilized grade (other than an extra-low-carbon grade)**: Through either of the above temperature ranges, slow cooling may allow sufficient time for these detrimental effects to take place.
- **Heating at 815°C to 925°C**: The coalescence of chromium carbide precipitates or σ-phase will occur, resulting in a formless harmful to corrosion resistance or mechanical properties.

- **Heating at 955°C to 1120°C**: This annealing treatment causes all grain boundary chromium carbide precipitates to redissolve, transforms σ-phase back to ferrite and fully softens the steel. Long heating times (>1 hour) may even dissolve some of the ferrite present and further reduce the probability that σ-phase will reform upon slow cooling.
- **Stress relieving to improve notch toughness**: Unlike carbon and alloy steels, austenitic steels are not notch-sensitive. Consequently, stress relieving to improve notch toughness would be of no benefit. Notch-impact strength may actually be decreased if the steel is stress relieved at a temperature at which chromium carbide is precipitated or σ-phase is formed.

Although stabilized alloys do not require high-temperature annealing to avoid intergranular corrosion, the stress-relieving temperature has an influence on the general corrosion resistance of these alloys. The corrosion of type 347 is better when the material is treated at 8l5 to 870°C than when treated at 650 to 705°C. The 650 to 705°C stress relief may promote the formation of a small quantity of chromium carbides as a result of free carbon not earlier tied up as niobium carbides.

The selection of the proper stress-relieving treatment involves consideration of the specific material used, the fabrication procedures involved and the design and operating conditions of the equipment. Stress relieving generally is not advisable unless the service environment is known or suspected to cause stress corrosion. If stress relieving seems necessary, appropriate consideration should be given to the metallurgical factors and their effect on the steel in the intended service. The use of stabilized or extra-low-carbon grades is an advantage in view of the greater latitude allowed in stress relieving.

2.4 Joining Process

The joining of dissimilar materials to make products best suited to particular applications is very common. Using joining processes as part of a manufacturing route can offer considerable technical and economic advantages to the designer and fabricator, provided careful and informed decisions are made about the processes to be applied, materials to be selected, joint configurations and the process parameters to be employed. Ceramics in comparison to metals usually have low densities, strong and hard but brittle, poor electrical and thermal conductors, refractory and expand little when heated. It is a common performance requirement that the joints between both similar and dissimilar materials used to manufacture products are both permanent and strong. Examples include the joining of copper piping in central heating systems, attachment of electronic components to circuit boards and the sealing of metal spark-plug electrodes to their ceramic insulators.

In general, a very wide range of processes can be used to join both similar and dissimilar materials, but in practice the number that can be employed for a specific product application is always limited by economics as well as technical factors such as the characteristics of the particular materials that have to be joined and the service conditions that must be go through. Processes that form permanent joints[12] either produce bonding directly between the component materials or make use of foreign materials introduced between mating surfaces. The type of joining processes for permanent bonding includes:

- fusion welding, in which mating surface regions of components are melted and mixed before solidifying to form a permanent bond
- diffusion bonding, in which solid mating surfaces are pressed together and heated to cause bonding by interdiffusion of the components
- brazing, in which liquid metal flows into a narrow gap between the mating surfaces and solidifies to form a permanent bond
- glazing or glass sealing, which uses a fluid glass to bond mating surfaces in processes analogous to brazing or fusion welding
- adhesive bonding, in which component gaps are filled by fluid organic compounds that polymerize to form rigid bonding interlayer.

Effective application of brazing and diffusion bonding depends on careful selection of materials and fabrication parameters. One of the most important technical factors that must be considered is the type of material that has to be joined. When using brazing or diffusion bonding as the joining process, the materials that can be joined are metals or ceramics, or both types of material. While selecting component and joining materials for a particular application, attention must be given to the effects of their individual and separate characteristics on both the suitability of any proposed joining process as well as the ability of the bonded product to withstand the intended service conditions. Bulk properties such as yield strength affect the easiness of diffusion bonding, while surface characteristics affect both brazing and diffusion bonding. The melting temperatures of brazes and other bonding materials must be reviewed in terms of what is achievable with the bonding equipment, the refractoriness of the component materials and the proposed maximum service temperatures. The detailed chemistry of the joining materials also needs consideration if unwanted diffusion of foreign species into the components is to be avoided and for certain types of brazing it is also necessary to select a flux which can aid the joining process and provide a protective environment during its operation.

After selecting the materials and the type of joining process to be employed, decisions must be made about joint designs, which are usually the butt, T, lap or sleeve configurations. Before assembling the preferred joint designs it is necessary to prepare the component mating surfaces if successful brazing or diffusion bonding is to be achieved. Specification of this preparation procedure often involves decisions about the mechanical finish or roughness of the mating surfaces. The decisions must be made based on how to ensure the surfaces are free from chemical blemishes that can impede joining, which can range from paint or rust layers to oil stains, finger prints and other almost invisible mobile organic contaminants.

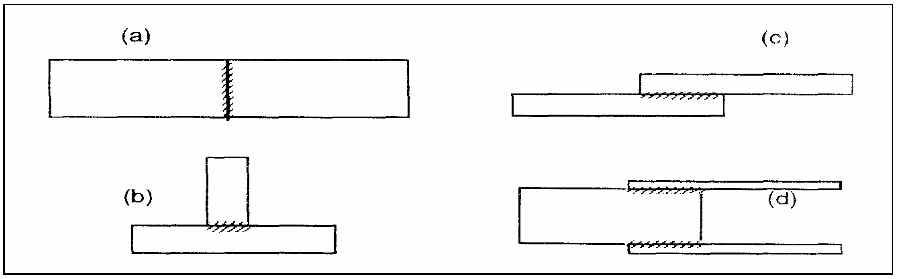

Figure 2: Cross-sections of configurations often used when brazing or diffusion bonding: (a) butt, (b) T, (c) lap and (d) sleeve joints. The bonded areas are shaded.

Brazing is a high-temperature process and in practice the temperatures used range from a minimum of 450°C to a maximum of about 1300°C, a limit governed by the melting temperatures of the most refractory commercial brazes. Although there are no limits in principle to the temperatures that can be used for diffusion bonding, those in use in practice so far also normally lie within the range of 450 to 1300°C.

Some brazing and diffusion bonding processes can be conducted in air in the open workplace but others need fabrication chambers that can be evacuated or filled with inert gaseous atmospheres and some brazing techniques require the component mating surfaces to be covered with an inorganic flux that plays an active role in the joining process. Brazing is a relatively fast process with joint filling being achieved within a few minutes, but the heating and cooling stages can be slow. Similarly, the selection of diffusion bonding process and the equipment employed must take account of the fact that the cycle times can be hours long because joint formation depends on the operation of slow solid-state diffusion processes.

2.4.1 Diffusion Bonding

Diffusion bonding is a solid state process for the fabrication of metal-metal, ceramic-ceramic and ceramic-metal joints that is conceptually simple. In principle, the process requires no localized melting of components or introduction of foreign bonding materials but simply that the mating surfaces are brought into intimate, atomic scale contact so that an interface can be formed by interdiffusion to create a structural continuum. Such interfaces, whether between metals, between ceramics or between a metal and a ceramic, can have good mechanical integrity even at high temperatures.

The simplest form of diffusion bonding[12] involves the application of a low pressure at a high temperature, usually at least 0.75 T_M, where T_M is the melting temperature in degrees Kelvin, to achieve bonding of metal components that have smooth and well-matched mating surfaces. There must be no macroscopic deformation of the components but contacting asperities on the mating surfaces grows to create initially separate microscopic areas of contact. These are then transformed into interfaces by interdiffusion which removes barriers to structural continuum such as oxide films and enlarges the bonded area.

This effect a sintering process that closes the small voids, no more than a few microns across, that are residues of the valleys and pits originally present on the mating surfaces.

If the mating surfaces are not flat but wavy, there can also be regions where the mating surfaces curve away from each other, as shown in Figure 3, and these substantial voids can be slow to close. While very idealized, this simple picture reflects some of the mechanism that has led to the development of differing diffusion bonding techniques. In the figure, the heavy marking of the mating surfaces is reduced as contact area grows as the dissolution of oxide and other films on the mating surfaces or the desorbtion of separated impurities and solutes that is an often necessary condition for successful diffusion bonding.

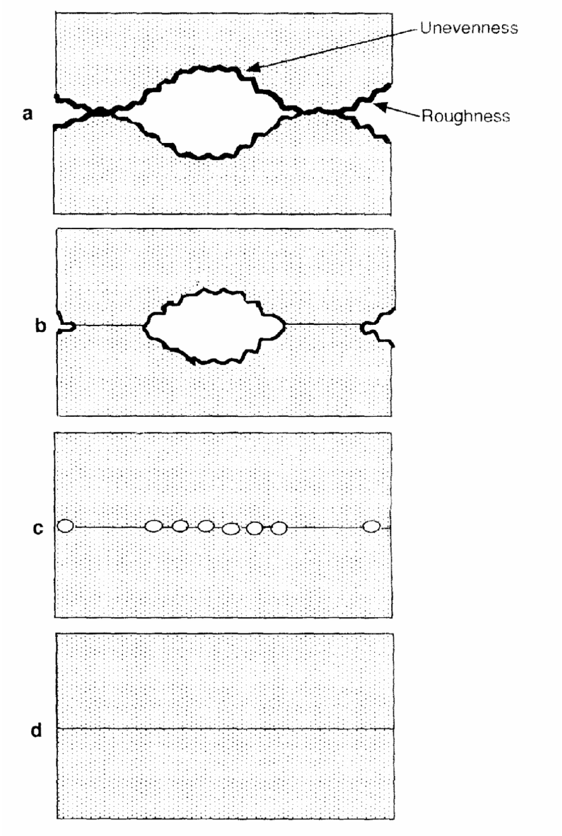

Figure 3: Schematic illustration of diffusion bonding induced growth of the contact area between to microscopically rough and wavy mating surfaces: (a) initial contact, (b), (c) and (d) progressive growth due to plastic flow and diffusion

The process is best suited for the bonding of components made from the same ductile metal whose surfaces are oxide free. However, dissimilar metal combinations can be bonded provided they satisfy a number of additional conditions. The bonding temperature must not be as high as to cause melting of the less refractory component, but it is desirable that it should be high enough to permit beneficial diffusion within the refractory component to promote sealing of microscopic isolated porosity at the bond line and dissolution of soluble surface oxide films. Once metal-metal contact has been achieved, beneficial interdiffusion will occur if the two metals are mutually soluble and the bonding temperature is high enough, but for some systems interdiffusion should be restricted because it will result in the growth of easily broken layers of intermetallic compounds.

Uniaxial pressing has been used widely to produce butt joints by diffusion bonding metal components that already machined to their final shape and dimensions and prepared with smooth and flat mating surfaces. There are a few examples of diffusion bonding being performed in an open workshop but the normal practice is to use a chamber that is evacuated and then sometimes back filled with inert gas before the components are raised to the proposed bonding temperature using heating elements or induction coils. The pressures used to bring the mating surfaces into contact are low to avoid macroscopic deformation and can be generated by applying a dead load, by using jigs made of low expansion materials that put the components under pressure when they are heated or by using hydraulically operated rams that pass through the chamber walls.

Such processing has permitted successful diffusion bonding[12] of a wide range of similar and dissimilar metals including Cu, Fe, Mo, Nb, Ta, Ti, W and some of their alloys. When wishing to bond Al, Be and other metals that form chemically stable oxides, it can be advantageous to coat their mating surfaces with Ag which will dissolve in the substrate during the diffusion bonding cycle. Coatings can also be useful when bonding some dissimilar metal combinations to avoid harmful effects of oxide films and the formation of easily broken intermetallic. Cu and Ni have been bonded successfully to steel and Mo, Nb, W even without the use of coatings by careful choice of the fabrication temperature.

Bonding of ceramics by uniaxial pressing has been achieved. The plasticity of ceramics is generally so poor that deformation of asperities to obtain an initial contact and conformity of the mating surfaces is seldom possible and the refractoriness of ceramics means that the fabrication temperatures often can be unacceptably high for the equipment that is available. However, some success has been achieved by using very smooth and very flat mating surfaces. Other examples of successful ceramic-ceramic joining has been achieved by using component materials with glassy binder phases that flow to form a glazed joint at the bonding temperature and by the introduction between the components of a ceramic powder that is so fine that it creates a bond by sintering to their surfaces.

When ceramics have to be bonded to metals, it is a common practice to introduce a metal interlayer between the components, producing a joint structure similar to that created by brazing. Interlayers have also been used in laboratory studies of ceramic-ceramic bonding. For both requirements, the interlayer should be ductile so that it can deform readily to achieve intimate contact with both mating surfaces at pressures and temperatures that do not cause any macroscopic deformation of the components. The interlayer should act as a stress relieving buffer layer if the thermal expansion of the metal and ceramic components differs significantly and it should stick on strongly to both the metal and ceramic components. Many metals and alloys should be able to satisfy these requirements but those used in practice are usually Al, Au, Ni and Ni-Cr alloys.

Adherence to the metal component can be relatively easy to achieve provided care has been taken to clean the mating surfaces of both the component and the interlayer, but adherence to the ceramic often depends on the formation of a reaction product layer that acts as a bridging compound and this reaction can proceed too far to produce thick and easily broken reaction layer. The technique has been applied so far mainly for the joining of Al_2O_3 and SiO_2 but its utility has also been demonstrated in laboratories for the joining of SiN_4 and other engineering ceramics. Optimization of the product designs and process parameters have allowed fabrication of very high-quality joints. The requirement of the uniaxial pressing method of diffusion bonding for a very high-quality finish towards the mating surfaces are significant technical and economic disadvantages that have led to the development of some others techniques.

2.4.2 Brazing

Brazing is a joining process in which liquid metal flows into a narrow gap between the mating surfaces and solidifies to form a permanent bond. Brazing is a widely used industrial process for fabricating products to meet service demands ranging from those of simple domestic utensils to complex structures for the aerospace and nuclear industries. No matter what the application, the requirements for successful fabrication of brazed joints are the same: the braze metal or alloy must melt and flow over the surfaces of the components to be joined, form a fillet or more usually fill a narrow gap between the components, and then form a permanent bond by remaining adherent while solidifying.

The formation of brazed joints depends on the flow of a liquid experiencing an attraction exerted by the component surfaces and therefore anything that affects this attraction is of crucial importance to the success of the brazing process. The surfaces of clean metal components should be readily wetted by liquid brazes in principle because similar material interfaces have low energies. However, difficulties can arise[12] in practice due to surface pollution and the presence of chemically stable and physically stubborn oxide films. Thus cleaning procedures are of critical importance when defining a brazing procedure. Joint design is of almost equal importance because the extent and rate of penetration of a gap by a wetting liquid depends on its width. The preferred gap for practical brazing of metal components is usually about 0.1 mm.

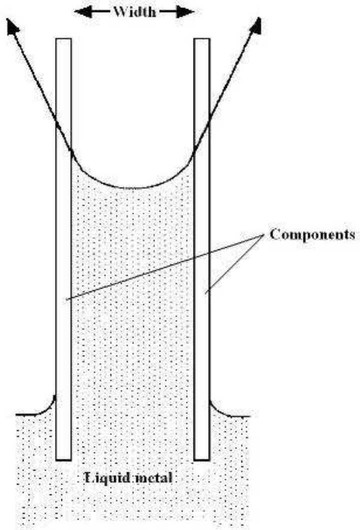

Figure 4: Basic configuration of brazing

Braze alloys and procedures have been developed to promote the wetting of a very wide range of metallic components. Ideal flow of liquid into the capillary gaps of components will be impeded only by viscous and gravitational drag and joints of a few millimeters in length should be filled in a fraction of a second. In practice, filling of joints can take a few minutes when the liquid braze experiences additional impedance due to unwetted oxide films present on component surfaces. However, joint formation times are usually a small part of the total cycle time which includes heating and cooling stages and may also accommodate holds of typically 10 to 30 minutes to achieve a uniform component temperature when heating or to encourage interdiffusion between the braze and the component material when cooling.

If the liquid braze does not wet, the gap will not be filled and no joint will be formed. It is technically important that few brazes wet ceramics and they also spread very slowly over the surfaces. This slowness not only affects the brazing cycle time but also the placing of the braze. While brazes for metal components can be placed at gap entrances and will flow to fill them, those for ceramics are normally placed within the gaps. The widths of gaps are determined not only by capillary factors but by the thickness of available braze sheet or thickness of the layer of braze powder that has been applied to the surface.

A brazed joint has a different composition compared to the components and this affects not only chemical characteristics such as corrosion resistance but also technically important physical properties. The generally lower yield strengths and elastic modulus of braze materials can give the joints with a desirable ductility, but also a undesirable weakness. Also, the low melting temperatures of brazes relative to the components means that brazed joints normally have a lower maximum service temperature than those produced by fusion welding or direct diffusion bonding of the components. Brazing can be used to join ceramic as well as metal components although the two types of materials require quite different brazing practices. The fact that ceramics are wetted by very few braze metals or alloys makes it necessary either to coat their surfaces with a metal before attempting brazing or to use an ‘active metal braze’ alloy that could react chemically with the ceramic to produce a wettable reaction product layer on its surface.

2.4.3 Brazing Techniques

The main techniques used to braze metal components involve the use of localized heating applied by gas torches, induction heaters, or of generalized heating produced by dipping components in salt, flux or metal filled baths, or placing them in controlled atmosphere or vacuum furnaces.

Torch Brazing

Torch brazing by hand is the simplest and also possibly the most used brazing technique for joining metal components and this is particularly true for one-off and short run production applications. The perform is similar to that of fusion welding with the torch flames being directed close to but not at the joint regions. The torch nozzles are usually larger when brazing so that, the exothermic inner flame is not restricted in volume. Gas pressures are generally lower than when fusion welding and sometimes only the outer cool flame is allowed to intrude on the component surface. A variety of gas mixtures are used ranging from oxy-acetylene which produces very hot flames with an inner temperature of about 3500°C to natural gas-air mixtures with a maximum flame temperature of about 1850 °C.

The usual practice when manually using a torch is to supply liquid braze by melting the tip of the braze ‘filler’ rod that touches the component surface near the entrance to the joint. For flow of the liquid to form a joint, it is necessary that the component surface is clean and free of oxide films that slow down wetting. This can be achieved by adjusting the gas mixture to produce a slightly reducing flame when joining components. In practice it is necessary to use a flux, generally a mixture of alkali borates and halides that is applied to the component surface as a powder or paste. During the brazing process, the flux melts at a lower temperature than the braze alloy and then spreads over the component surface and into gaps between components to dissolve the oxide film before itself being displaced by the advancing liquid braze.

Induction and resistance brazing

High-frequency induction brazing is a clean and rapid technique that lends itself to automated and semi-automated joining. As with any form of induction heating, power is transferred by a high-frequency electro-magnetic field from a water-cooled induction coil to the component as a rapidly alternating eddy current. The power source can be used to effect fluxed or fluxless joining using preplaced braze and flux materials and can be conducted in the open workshop or in a controlled environment using a non-metallic chamber such as a glass tube with sealed ends.

In some cases, the resistance brazing technique is even simpler since it is merely a current to flow between electrodes through the joint region. A pressure is needed to achieve good electrical contact between the electrodes and the components, and once again the braze and flux must be placed in the joint region prior to joining. The joint region normally has an initially high electrical resistance so that the resistance heating is localized and often strong. Thus it is important to adjusting the current and design the electrodes to avoid overheating of the braze alloy or the component materials.

Furnace Brazing

Brazing can be performed in batch furnace chambers that are evacuated or filled with a controlled atmosphere of generally, an inert gas such as Ar. Continuous furnaces are particularly suitable for the production of small items such as automobile components. They use a conveyor wire mesh to move components into and out of a heated brazing zone and usually also into and out of controlled atmosphere regions. Batch furnaces find their main applications in the production of short runs, high added value and large components. The assemblies to be brazed are loaded into the furnace via a front opening door and the chamber is then resealed. The closed chamber is then evacuated or evacuated and back filled with a controlled atmosphere and the components are subjected to a temperature cycle.

When furnace brazing it is necessary to place the braze alloy in position before the assembly is in the furnace. The use of fluxing to promote braze flow is rear when using a batch furnace but is when using the continuous furnaces. Fluxless brazing in controlled atmospheres or vacuum has a particular advantage. There is no need to clean the product after brazing. Furthermore, brazing in vacuum or reducing atmosphere enhances the appeal of the products by producing bright clean surface. However, only certain grades of brazing alloy can be used in vacuum furnaces.

Ceramic Brazing

The brazing of ceramics is difficult[12] because they are usually unwetted by the commercial alloys successfully. Thus ceramic surfaces must be coated with pure metals or alloys by vapor deposition but the most developed technique is metallization by the ‘moly-manganese’ process which was originally developed for

Al_2O_3 ceramics. A mixture of Mo, Mn and a glass powder is applied to the ceramic surface and heated to about 1400°C in relatively dry H_2. This causes the glass to become fluid and to wet and bond to both the Mo powder and the ceramic surface, with the bonding to the ceramic being promoted by separation of MnO to the ceramic surface. This coating is sufficiently metallic to be electroplated with Ni and the metallized ceramic is then furnace brazed.

Batch furnaces are very suitable for brazing ceramic components. If the ceramic surfaces have been metallized, they can be treated as metallic components. Ceramic component surfaces can also be painted with TiH_2 which dissociates at 300-500°C to deposit Ti during the subsequent vacuum brazing cycle. Braze flow controlled by growth of a solid reaction product is very slow and hence active metal braze alloys are generally placed between ceramic components rather than being expected to flow into capillary gaps as when joining metal components.

2.5 Residual Stress

Residual stress is the stress that present in an object when no external forces act upon it. It is free basically free from restraint and is in motionless equilibrium. These stresses are caused by internal residual strain where the strain fields in turn are caused by stored elastic energy in the material. The theory of elasticity for an isotropic elastic material can be calculated from the residual stress field at that point by using the generalized form of Hooke’s law[13].

Residual stress occurs when a body is subjected to processes such as thermal expansion or contraction, diffusion, phase changes, rolling, forging, drawing, welding, joining etc. The stress can have a good and bad influence on the life of the component. Residual stress can be beneficial if it acts opposite to the applied stress. The most commonly known example of a residually stressed material is pre-stressed concrete, where the tension in the steel reinforcing rods or pre-stressed cable places the concrete in compression.

Residual stresses have always been a concern for engineers. Manufactured item such as rotors, plates, pressure vessels and automotive parts are plagued by residual stresses that occur during manufacturing or transportation. Just the same as the applied stresses, the residual stresses will add directly to the stress state of the component. While compressive residual stresses countering applied tensile stresses can increase the load bearing capacity of a component, residual tensile stresses severely decrease this capacity. There is no way of knowing the state of that stress field unless the stress field is measured. In fact, the residual stress could be as high as the yield strength of the material.

There are several methods [14] used to determine the residual stress in components. Residual stress in materials can be non-destructively measured by a variety of method including X-ray diffraction and neutron diffraction which determine stress by assuming linear elasticity. Other methods, which based on non-linear properties include ultrasonic, Barkhausen noise and electromagnetic. However, X-ray diffraction remains the most popular method for non-destructively measuring residual stress in metals. For greater measurement penetration, neutron diffraction method is used but this is technique is not portable and it is comparatively expensive.

2.6 Residual Stress Evaluation

According to Giles Humpston [15], the stress in the region of the joint between two isotropic materials designated 1 and 2 with differing thermal expansion that develops on cooling from the bonding(solidus) temperature can be approximated by the following equation:

$$Stress = \left(\frac{E_1 \cdot E_2}{E_1 + E_2} \right) (X_1 - X_2)(T_b - T_s)$$

where

E is modulus of elasticity of 1 and 2
X is coefficient of thermal expansion of 1 and 2
T_b is the bonding (solidus temperature)
T_s is the temperature of the assembly

It is assumed that the materials are only deformed within their elastic limits and the joint is infinitely thin.

CHAPTER 3
METHODOLOGY/PROJECT WORK

3.1 Methodology

This research project is divided into two sections with the scope of study focuses on the residual stress in a joining of ceramic to metal. In this work, the joining sialon to austenitic stainless steel will be studied. The first section included the process identification based on literature review and the evaluation of residual stress using analytical model. The second section is the Finite Element Analysis using ANSYS. The results from both sections will be compared and justified.

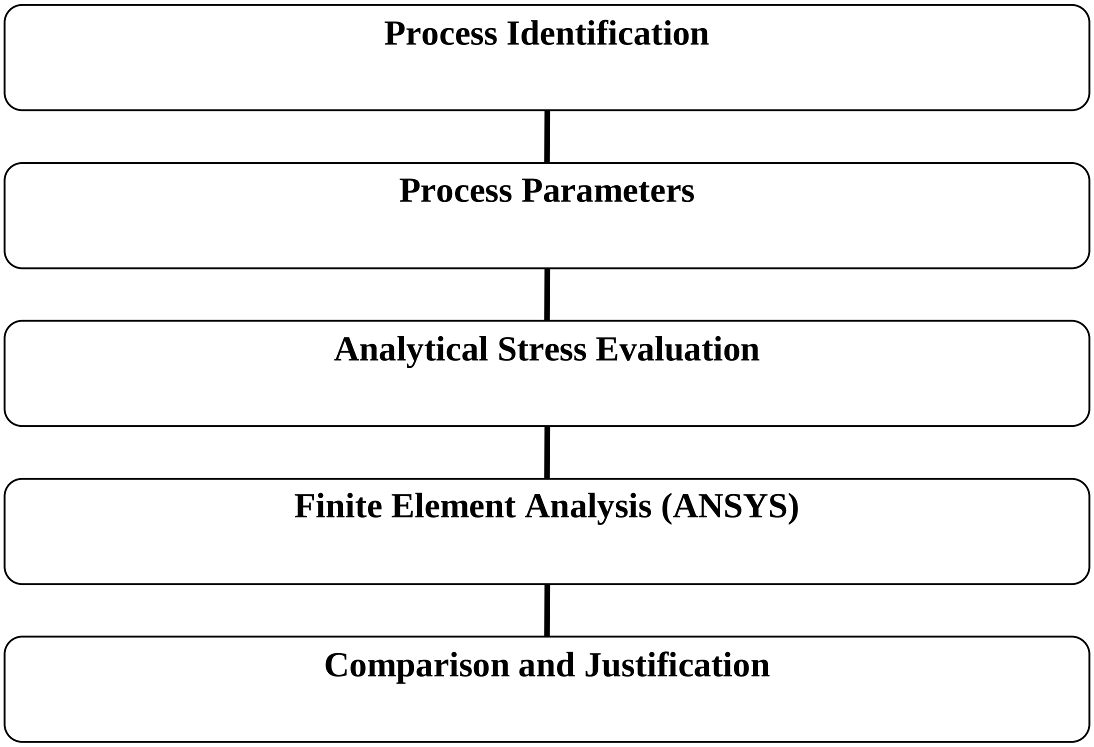

Figure 5: Project work flowchart

3.2 Process Identification and Joining Process Parameters

It was assumed that the joining process is to be done by diffusion bonding. The sialon used has the following properties: a density of 3.30 gcm^{-3}, an elastic modulus of 300GPa, a poison ratio of 0.22, fracture stress of 825MPa and a thermal expansion coefficient of 3.1 X 10^{-6} K^{-1}. The austenitic stainless, AISI 316L which has the following properties: a density of 7.96 g cm^{-3}, an elastic modulus of 200GPa, a poison ratio of 0.25, yield stress of 286 MPa and a thermal expansion coefficient of 16.0 X 10^{-6} K^{-1} was used in the process. Both materials have dimensions of 10mm width, 10mm length and 10mm height. It was assumed that the surfaces of both bars were already machined to have flat smooth mating surface and free from pollutants. The joining process [16] was carried out in a metal chamber high vacuum furnace of about 1 X 10^{-4} Pa. The uniaxial pressing [2] with pressure of 4.5 MPa was applied to the assembly during the heating cycle. At the onset of the cooling cycle, the pressure was removed. Joints were held for 120 minutes at the maximum joining temperature of at 1250°C. The heating and cooling rates were 20°C per minute.

Table 5: Material properties and joining parameters

Properties	**AISI 316L**	**SIALON**
Density(gcm^{-3})	7.96	3.30
Young's Modulus(GPa)	200	300
Poison ratio	0.22	0.25
Thermal Expansion Coefficients(K^{-1})	16.0 X 10^{-6}	3.1 X 10^{-6}
Uniaxial pressure(MPa)	4.5	
Dimension(mm)		
Height	10	10
Width	10	10
Length	10	10

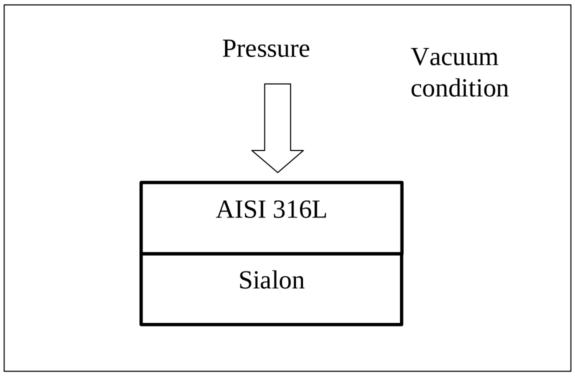

Figure 6: Joining setup

3.3 Finite Element Analysis(ANSYS)

This analysis was carried out using ANSYS 10 according to the material properties and process parameter defined earlier. Thermal analysis was carried out first followed by structural analysis. The results from both analysis were then coupled together to obtain the final solution. The element size used for this analysis is 0.0001m. The maximum and minimum temperature was 1250°C and 25°C respectively. The uniform pressure was 4.5MPa. The joint were held for 120 minutes at the maximum temperature and it took 125 minutes for heating and cooling. The total time used for the whole process was 245 minutes. The following general steps [17] were used:

1. Pre-processing
2. Solution phase
3. Post processing

At the pre-processing stage, the geometry of the model, the element type and the material properties are defined. The mesh size is also defined and the meshing is done in this stage. The type of analysis is defined during the solution stage. The load, boundary condition and constraint are applied during the solution stage and the system is solved. Finally, the results are plot for viewing and analysis at the post processing stage. Refer to appendix for more detail steps.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Residual stress calculations

The stress at the joining interface was calculated using these parameters:

$T_{Bonding}$ = 1250°C = 1523°K

$T_{Assembly}$ = 25°C = 298°K

E_{Sialon} = 300GPa

E_{316L} = 200GPa

$\alpha_{316L} = 16.0 \text{ X } 10^{-6} \text{ K}^{-1}$

$\alpha_{Sialon} = 3.1 \text{ X } 10^{-6} \text{ K}^{-1}$

Residual stress at joining interface

$$= \left(\frac{E_{316L} \cdot E_{Sialon}}{E_{316L} + E_{Sialon}} \right) (\alpha_{316L} - \alpha_{Sialon}) (T_{bonding} - T_{assembly})$$

$$= \left(\frac{200 \cdot 300}{200 + 300} \right) (16 - 3.1)(10^{-6})(1513 - 298)$$

$$= 1896.3 MPa$$

It is assumed that the materials are only deformed within their elastic limits and the joint is infinitely thin.

4.2 Finite Element Analysis (ANSYS)

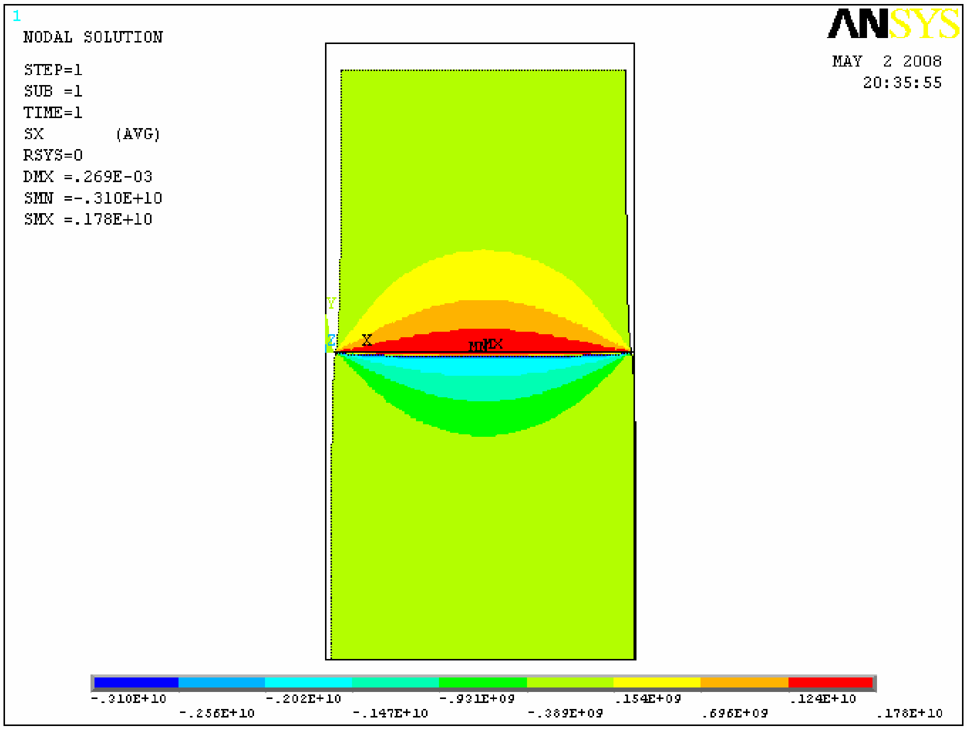

Figure 7: Residual stress contour plot at joining interface (room temperature)

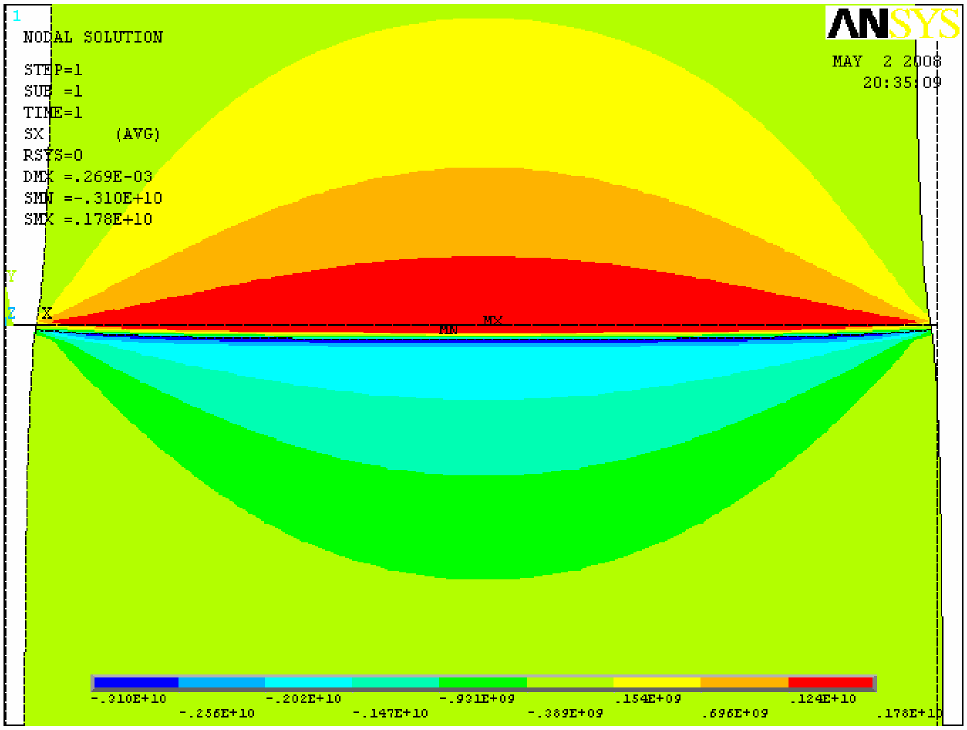

Figure 8: Residual stress contour plot at joining interface (zoomed view)

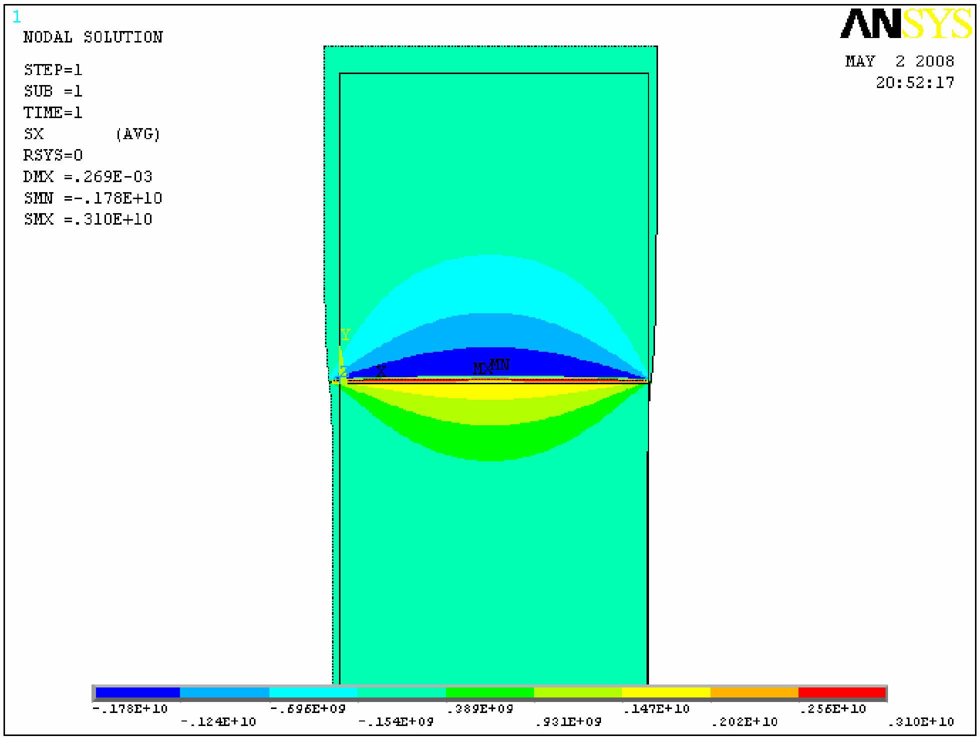

Figure 9: Stress contour plot at maximum temperature 1523°K

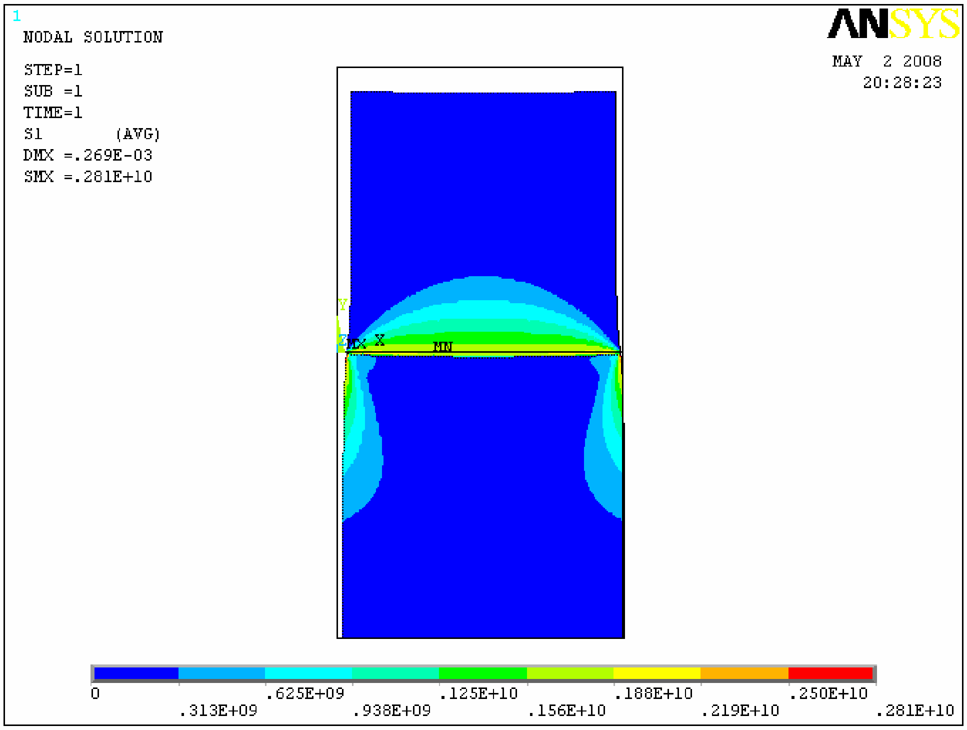

Figure 10: Principle stress contour plot – Maximum normal stress

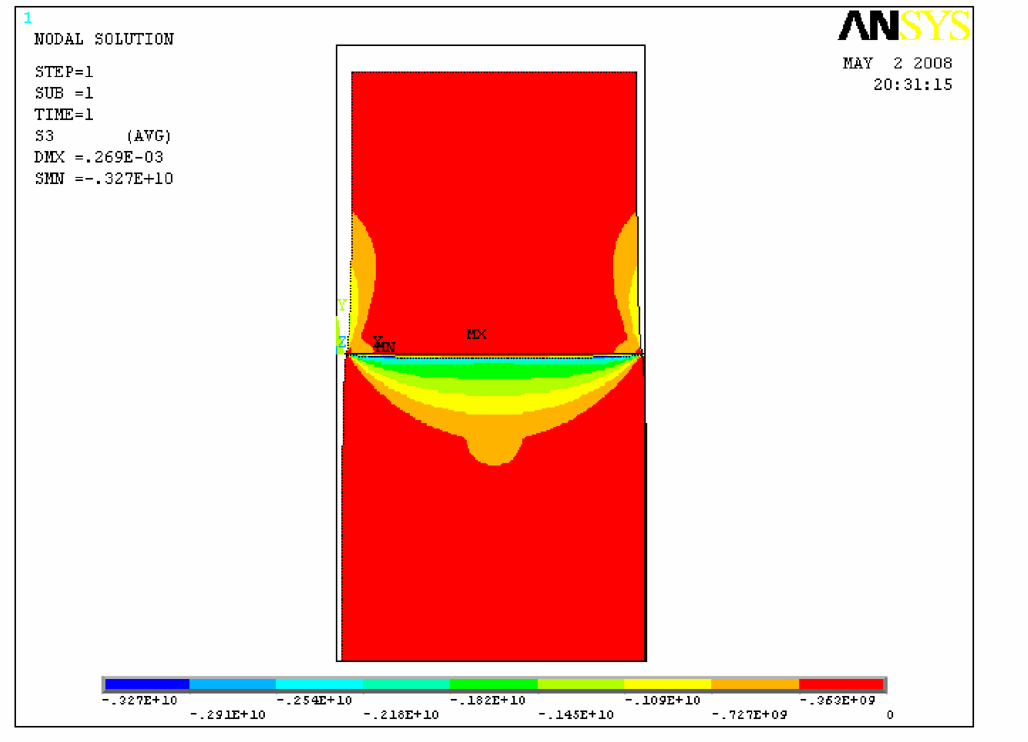

Figure 11: Principle stress contour plot – Minimum normal stress

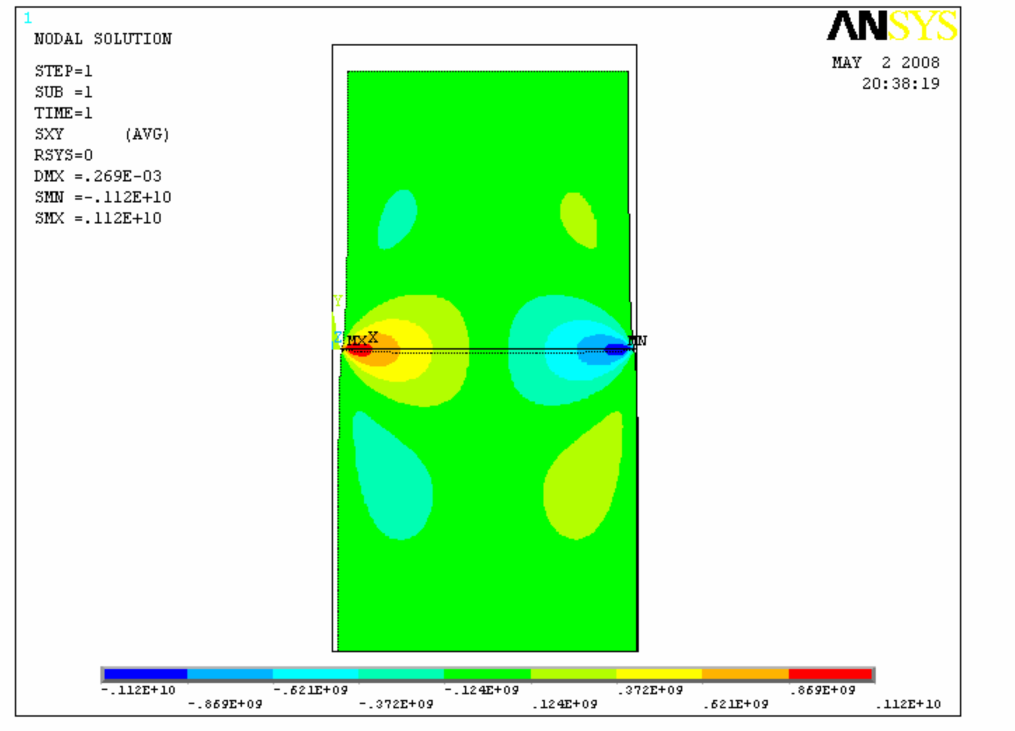

Figure 12: Shear stress contour plot

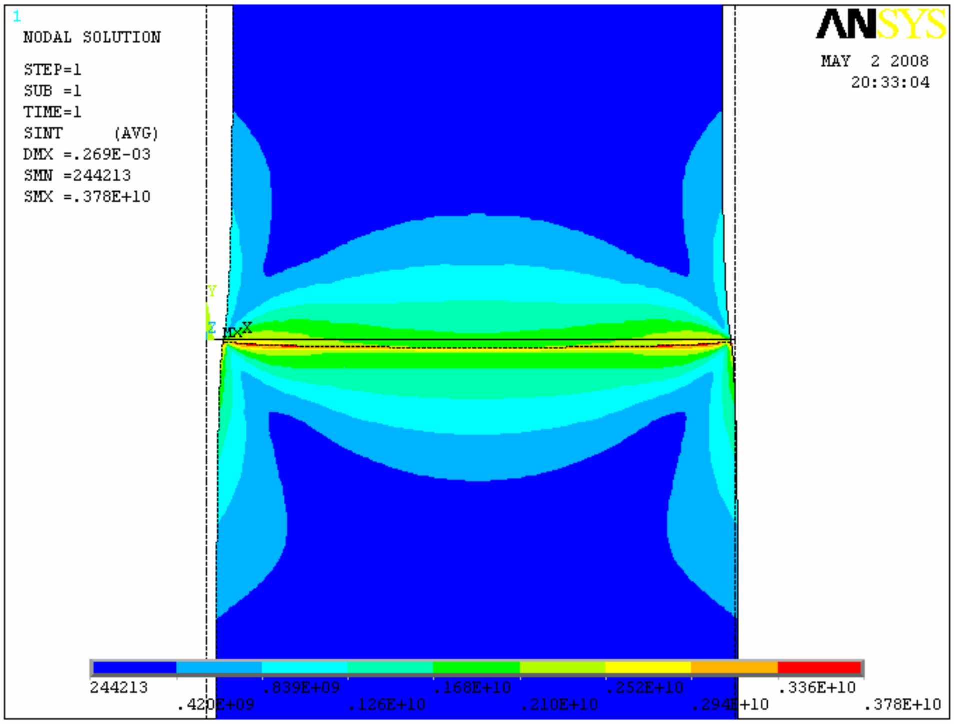

Figure 13: Residual stress intensity at room temperature

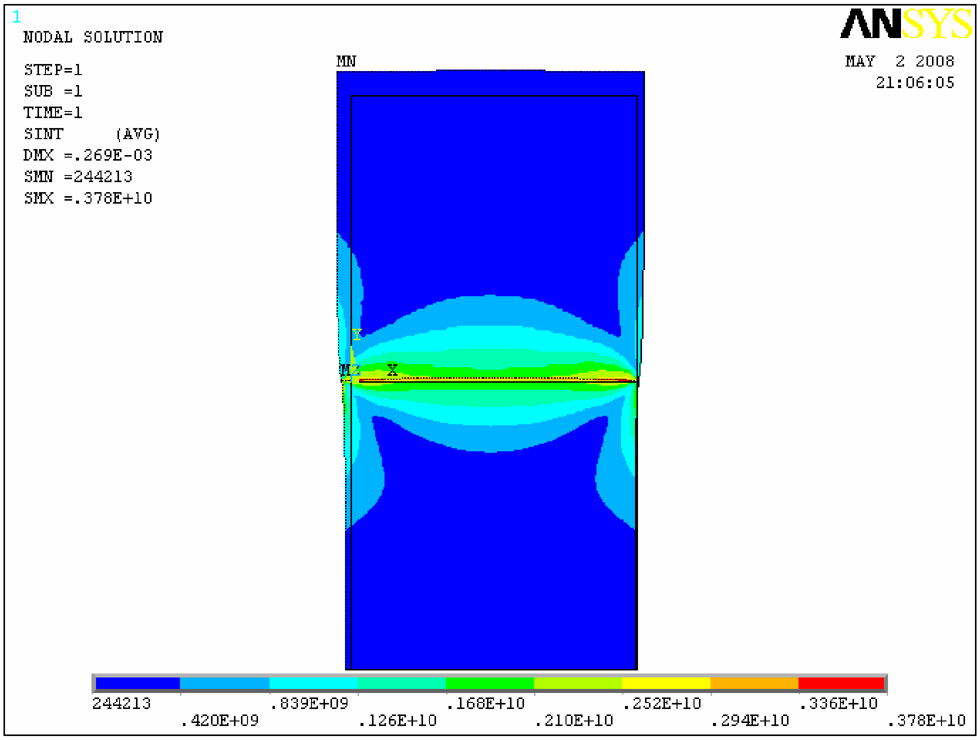

Figure 14: Stress intensity contour plot at maximum temperature

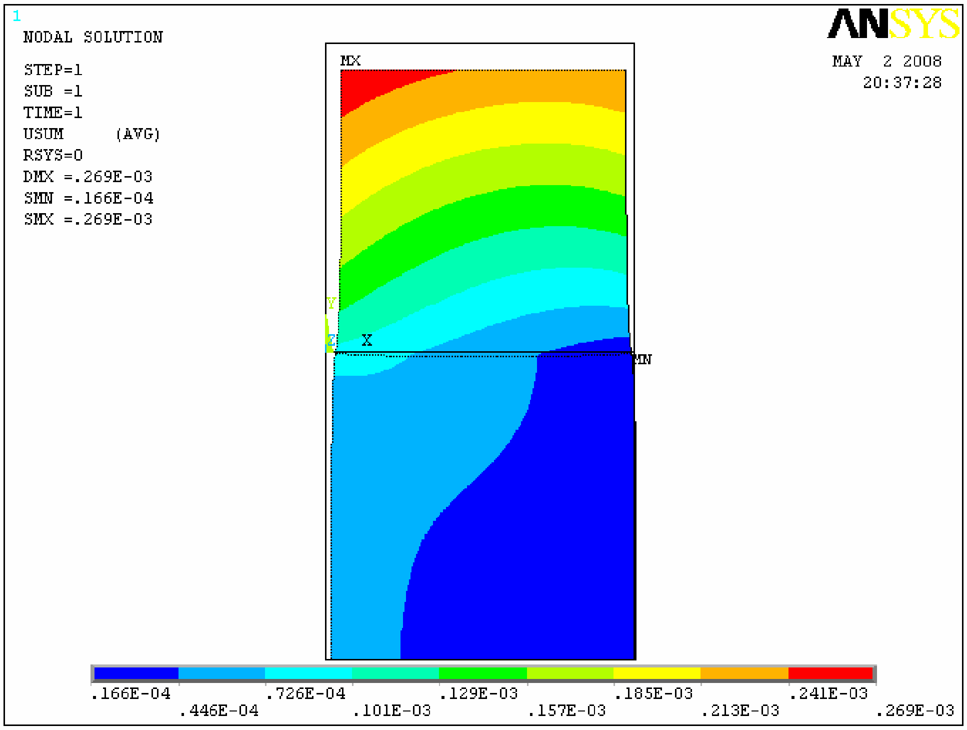

Figure 15: Shape deformation contour plot

4.3 Discussions

Residual stresses are stress fields that exist in the absence of any external load. All mechanical processes can cause deformation that may lead to residual stress. The state of a residual stress depends on both the prior processes it has undergone and the material properties that relate the current mechanical process or environment to deformation.

In diffusion bonding between ceramic and metal, residual stress at the ceramic-metal interface usually occurs during the cooling process from the solidus temperature (joining temperature) of the metal to the lowest temperature of the assembly. The residual stress is maximum at the lowest temperature of the assembly. This stress might cause the joint to fail during cool down.

Compressive residual stress is found to be beneficial to a body while tensile residual stress degrades the strength of a part. High compressive residual stress near the surface greatly increases the resistance to fatigue crack initiation. However, when a surface flaw is already present and if the size of the flaw is larger than the depth of the zone of the compressive stress, the crack tip will be under a tensile stress. Hence the fracture strength is greatly lowered and might leads to failure.

From the finite element analysis, the residual stress of the assembly range from positive 1780MPa to negative 3100MPa. Positive value indicates tensile stress while negative value is compressive stress. The stress concentration is high at the area of the joining interface. The maximum value of compressive stress, which is negative 3100MPa presents at the ceramic while the maximum tensile stress, positive 1780MPa is in the stainless steel.

It can be seen at the area nearby the joining interface that stainless steel experiences tensile stress while ceramic experiences compressive stress. Ceramic by nature has high strength and is brittle. It is possible for ceramic to withstand the compressive stress induced by the cooling process. On the other hand, steel by nature has lower strength than metal and is ductile. It can undergo extensive plastic deformation before failure compared to ceramic which usually fails with about 0.2% of strain. Hence, it is possible for the steel to withstand the tensile stress without failure.

However, at the joining interface between steel and ceramic, there is tensile stress on the ceramic which range from 154MPa to 1240MPa. From literature, the fracture stress of ceramic sialon is 825MPa. Hence this causes crack to the ceramic interface region where the tensile stress is more than 825MPa. As mention before, ceramic cannot withstand tensile stress but compressive stress. There is no crack at the steel interface as the maximum tensile stress at the steel is below the tensile strength of the AISI 316L, which is 1450MPa. Tensile strength is the maximum stress that can be sustained by a structure in tension.

The residual stress at the joining interface estimated from analytical method is 1893MPa. This value is within the range of the result from the finite element analysis. However, this model does not indicate the type of stress that is present. It only shows the magnitude of the residual stress. The finite element analysis shows the distribution of stress and the deformation of the body for better understanding.

From the intensity contour plot, it is clearly show that the stress intensity is the highest at a few points at the ceramic interface compared to the steel interface. Those are the points where the crack occurs due to the mismatch of thermal expansion and the inability of ceramic to withstand the high concentration of tensile stress.

Furthermore, this result also agrees with the previous work done by P.Hussain[1] who compared the joining of sialon to austenitic stainless steel and ferritic stainless steel and found that joining of ferritic stainless steel to sialon was successful due to the natural present of a ductile interlayer between the joint which can absorb the residual stress. This ductile layer was not present at the joining of sialon to austenitic stainless steel and this caused the joint to fail with crack at the ceramic interface.

The temperatures employed at diffusion bonding are always below those needed to melt the component .The melting points of AISI 316L is about 1370 - 1400°C. From that range, the maximum joining temperature of 1250°C employed is relevant. The component temperature of 25°C is also relevant because maximum stress usually occurs at room temperature.

In practice, it is common to introduce a ductile metal interlayer between the components when joining ceramic to ceramic or ceramic to metal. The ductile interlayer can deform to achieve intimate contact with both mating surfaces at pressures and temperatures that do not cause any macroscopic deformation of the components. The interlayer also functions to relieve and absorb the mismatch stress. Those common use ductile metals and alloys interlayers are Al, Au, Ni and Ni-Cr alloys. However in this work, no interlayer was introduce to absorb the residual stress.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The residual stresses arising from the thermal expansion mismatch during direct diffusion bonding of sialon and austenitic stainless steel has been successfully simulated using Finite Element Analysis (ANSYS). It can be seen at the area nearby the joining interface that stainless steel experiences tensile stress while ceramic experiences compressive stress. The stress intensity is the highest at a few points at the ceramic interface compared to the steel interface. Those are the points where the crack occurs.

The analysis shows that the tensile stress presents during the cooling down of the assembly has cause high concentration of tensile stress at the ceramic interface. This causes crack to the ceramic interface as ceramic cannot withstand tensile stress which is more than its fracture stress, 825MPa. There is no crack at the steel interface as the maximum tensile stress at the steel is below the tensile strength of the AISI 316L.

It is highly recommended that future work will be focusing on direct diffusion bonding of sialon and austenitic stainless steel using ductile interlayer. Also the effects of the thickness of the interlayer and materials should be analyzed using finite element analysis to obtain the stress distribution in the future.

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Appendix A

Finite Element Analysis (ANSYS)

Steps for residual stress analysis

Preprocessing

Thermal Environment - Create Geometry and Define Thermal Properties

1. **Give a title** -Utility Menu > File > Change Title > example Thermal Stress
2. **Open preprocessor menu-**ANSYS Main Menu > Preprocessor
3. **Define Keypoints-**Preprocessor > Modeling > Create > Area > Rectangle >By two corners. we use (0,0) W=0.01, H=0.01 and (0,0) ,W=0.01 , H=-0.01
4. **Glue-** Preprocessor > Modeling > Operate > Booleans > Glue> Area. Pick the two areas.
5. **Define the Type of Element -**Preprocessor > Element Type > Add/Edit/Delete For this problem we will use the Thermal Mass>Solid> Quad 4node 55
6. **Define Element Material Properties-** Preprocessor > Material Props > Material Models > Thermal > Conductivity > Isotropic
   In the window that appears, enter the following material properties for steel:
   KXX: 15
   Add a new model and enter the material properties for Sialon.
7. **Define Mesh Size** -Preprocessor > Meshing > Size Cntrls > ManualSize > Global > Size
   Use an element edge length of 0.0001 meters
   Preprocessor > Meshing > Mesh Attributes > Picked Areas > Pick
   Upper area is steel –Material 2, Lower area is Sialon –Material 1
8. **Mesh the frame** -Preprocessor > Meshing > Mesh > Areas > Free> Selected all the areas.
9. **Write Environment**
   The thermal environment (the geometry and thermal properties) is now fully described and can be written to memory to be used at a later time.
   Preprocessor > Physics > Environment > Write

In the window that appears, enter the TITLE Thermal and click OK.

10. **Clear Environment** -Preprocessor > Physics > Environment > Clear > OK
    Doing this clears all the information prescribed for the geometry, such as the element type, material properties, etc. It does not clear the geometry however, so it can be used in the next stage, which is defining the structural environment.

Structural Environment **-** Define Physical Properties

11. **Switch Element Type** -Preprocessor > Element Type > Switch Element Type
    Choose Thermal to Struc from the scoll down list.
    A warning saying you should modify the new element as necessary will pop up. In this case, only the material properties need to be modified as the geometry is staying the same.
12. **Define Element Material Properties**
    Preprocessor > Material Props > Material Models > Structural > Linear > Elastic > Isotropic
    In the window that appears, enter the following geometric properties for Sialon and AISI316L:
    <u>Sialon</u>
    Young's Modulus EX: 300e9
    Poisson's Ratio PRXY: 0.22
    Preprocessor > Material Props > Material Models > Structural > Thermal Expansion Coefficient> Isotropic
    ALPX: 3.1e-6

    <u>Steel</u>
    Young's Modulus EX: 200e9
    Poisson's Ratio PRXY: 0.25
    Preprocessor > Material Props > Material Models > Structural > Thermal Expansion Coefficient> Isotropic
    ALPX: 16e-6

13. **Write Environment**

    The structural environment is now fully described.

    Preprocessor > Physics > Environment > Write

    In the window that appears, enter the TITLE Struct

Solution Phase: Assigning Loads and Solving

1. **Define Analysis Type -** Solution > Analysis Type > New Analysis > Static
2. **Read in the Thermal Environment**

   Solution > Physics > Environment > Read

   Choose thermal and click OK.

   If the Physics option is not available under Solution, click Unabridged Menu at the bottom of the Solution menu. This should make it visible.
3. **Apply Constraints -**Solution > Define Loads > Apply > Thermal > Temperature > On All Lines

   Set the temperature of all the lines to 298 Kelvin.
4. **Solve the System -**Solution > Solve > Current LS
5. **Close the Solution Menu -**Main Menu > Finish

   The thermal solution has now been obtained..This information is saved in a file labelled Jobname.rth, were .rth is the thermal results file. Since the jobname wasn't changed at the beginning of the analysis, this data can be found as file.rth. We will use these results in determine the structural effects.
6. **Read in the Structural Environment -**Solution > Physics > Environment > Read

   Choose struct and click OK.
7. **Apply Constraints -**Solution > Define Loads > Apply > Structural > Displacement > On lines

   Select the lowest line and set constrain to 0Y.
8. **Apply Constraints -**Solution > Define Loads > Apply > Structural > Thermal > On lines

   Select the joining interface line and set the temperature to 1523K
9. **Include Thermal Effects -**Solution > Define Loads > Apply > Structural > Temperature > From Thermal Analysis

Enter the file name File.rth. This couples the results from the solution of the thermal environment to the information prescribed in the structural environment and uses it during the analysis

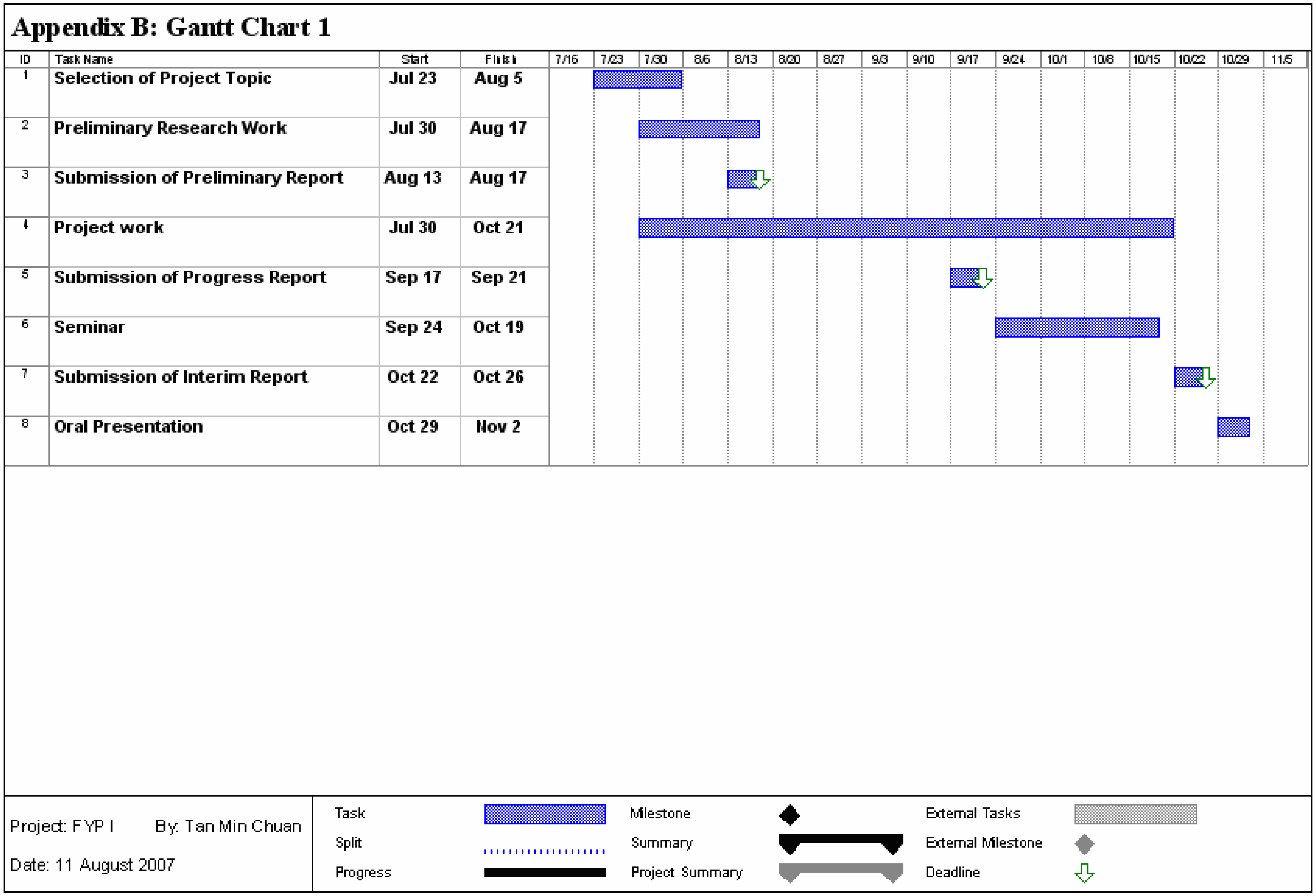
10. **Define Reference Temperature** -Preprocessor > Loads > Define Loads > Settings > Reference Temp
    Set the reference temperature to 1523 Kelvin
11. **Solve the System** -Solution > Solve > Current LS

Post processing: Viewing the Results

1. **General postproc**> Plot Results > Contour Plot > Nodal Solution
   Select the desired results to view

2. **General postproc**> List Results > Contour Plot > Nodal Solution
   Select the desired results to list in command form.

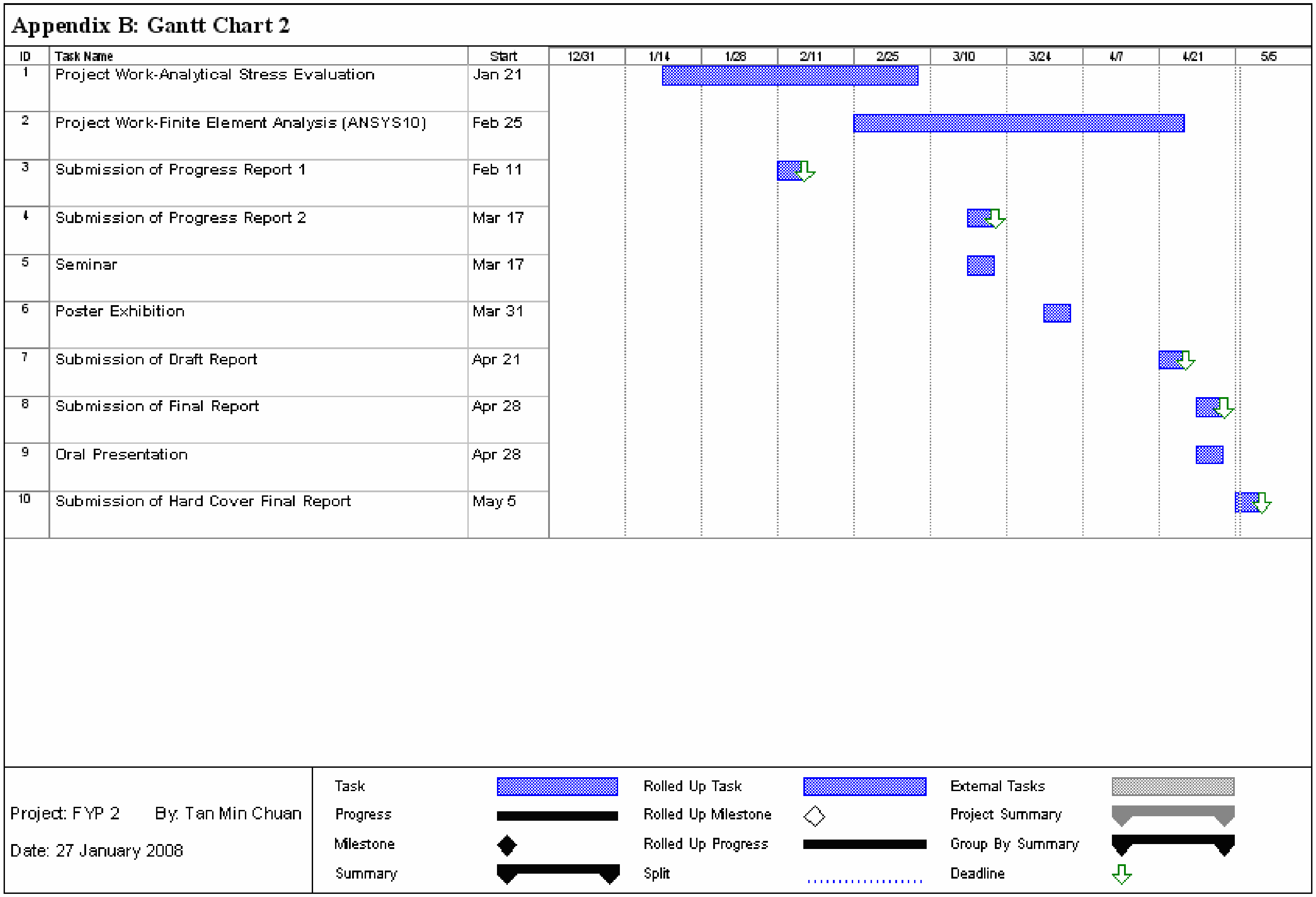
Appendix B: Gantt Chart 1



ID	Task Name	Start	Finish
1	Selection of Project Topic	Jul 23	Aug 5
2	Preliminary Research Work	Jul 30	Aug 17
3	Submission of Preliminary Report	Aug 13	Aug 17
4	Project work	Jul 30	Oct 21
5	Submission of Progress Report	Sep 17	Sep 21
6	Seminar	Sep 24	Oct 19
7	Submission of Interim Report	Oct 22	Oct 26
8	Oral Presentation	Oct 29	Nov 2

Project: FYP I By: Tan Min Chuan

Date: 11 August 2007



Appendix B: Gantt Chart 2

ID	Task Name	Start
1	Project Work-Analytical Stress Evaluation	Jan 21
2	Project Work-Finite Element Analysis (ANSYS10)	Feb 25
3	Submission of Progress Report 1	Feb 11
4	Submission of Progress Report 2	Mar 17
5	Seminar	Mar 17
6	Poster Exhibition	Mar 31
7	Submission of Draft Report	Apr 21
8	Submission of Final Report	Apr 28
9	Oral Presentation	Apr 28
10	Submission of Hard Cover Final Report	May 5

Project: FYP 2 By: Tan Min Chuan

Date: 27 January 2008