**RESEARCH ARTICLE** **OPEN ACCESS**

# Steady State Thermal Analysis Of Friction Stir Welded Stringer Panel Of An Aircraft Wing

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**Abstract—**
Welding is a wide range multistate permanent fastening method of fabrication. Globally welding technology has numerous applications. The present project deals with the calculation of the steady state thermal analysis and fatigue life of the friction stir welded stringer panel.

The stringer panel is a device used for supporting the upper and the lower skin of the aircraft wing. The equivalent stresses and life cycles are calculated theoretically referring to many journals, the theoretical inputs are given to the analysis software ANSYS Workbench i.e. heat flux, temperature, and speed of rotation of the friction stir tool.

The resultant equivalent stress and the total deformation apart from that the life cycles are also generated. The theoretical values of stress and fatigue life are computed. The best welding conditions are predicted by suitable analysis in ANSYS Work bench software by providing suitable working conditions as inputs.

**Keyword** – ANSYS, Friction stir welding, Thermal analysis, Fatigue life.

## I. INTRODUCTION

Friction Stir Welding was invented and patented by The Welding Institute in1991. The process uses a spinning, non-consumable tool, similar to a taper reamer, to generate frictional heat in the work piece. By pressing this tool into contact with a seam to be welded, the base metal heats up and once it reaches about 80% of its melting point it becomes soft and deforms easily. A typical FSW system is shown in Fig 1.1.
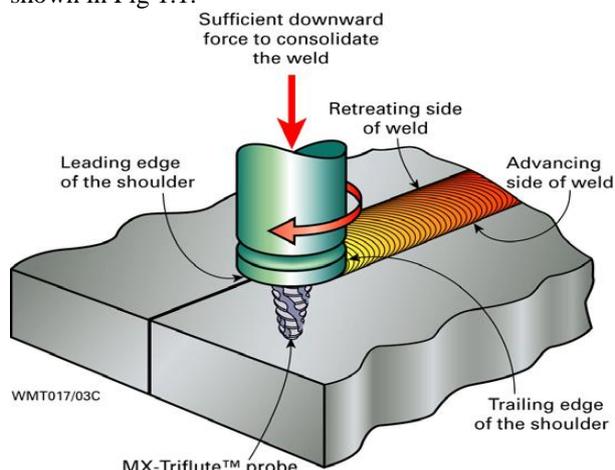


Fig 1.1 The principle of Friction Stir Welding

By keeping the tool rotating and moving it along the seam to be joined, the softened material is literally stirred together forming a weld without melting. These welds require low energy input and are without the use of filler materials and distortion. Initially developed for non-ferrous materials such as aluminum, by using suitable tool materials the use of the process has been extended to harder and higher melting point materials such as steels titanium alloys and copper. Since its conception in 1991 there have been considerable advances in process technology and there are now over 135 licensees of the process and over 1500 subsidiary patents have been filed. This paper will concentrate on improvements for tooling for the friction stir welding of aluminum alloys.

### 1.1 INTRODUCTION TO THE AIRCRAFT STRUCTURE:

Aircraft Structural weight has always been important in aircraft manufacturing industry. Aircraft structural design is a subset of structural design in general, including ships, land vehicles, bridges, towers, and buildings. All structures must be designed with care because human life often depends on their performance.

Metal structures are subject to corrosion, and some kinds of corrosion are accelerated in the presence of stress. Aircraft structures are designed with particular attention to weight, for obvious reasons. If we could see beneath the interior fittings of passenger aircraft, we would see numerous lightening holes in the frames as well as regions where the skins have been thinned by chemical milling.

## 1.2 LAYOUT OF THE AIRCRAFT WING
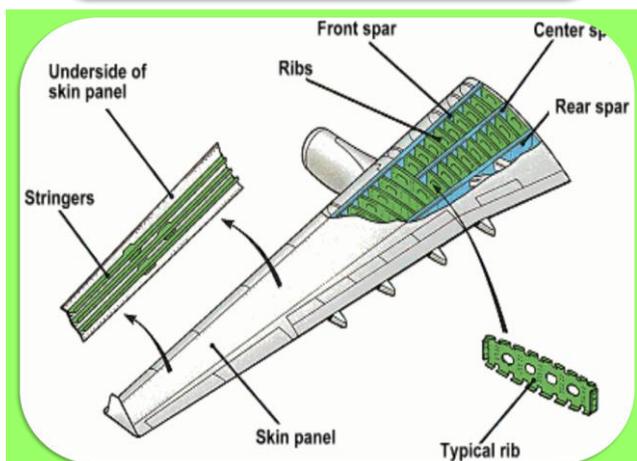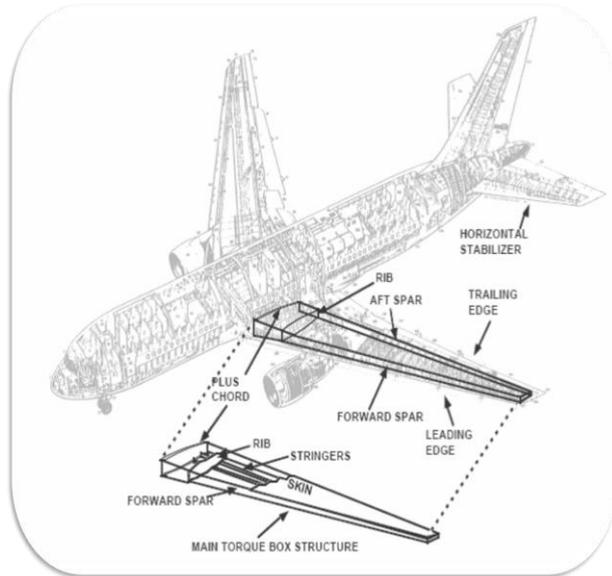




The first aircraft had two wings made of light weight wood frames with cloth skins, held apart by wires and struts.

In the 1920s, metal began to be used for aircraft structure. A metal wing is a box structure with the skins comprising the top and bottom, with front and back formed by I-beams called spars, interior fore-aft stiffeners called ribs, and in-out stiffeners called stringers. In level flight, the lower skin is in tension while the upper skin is in compression.

## 1.3 STRINGER PANEL
The weld joint in the stringer should be in the web close to the skin panel and the thickness of all weld samples are 7mm after post-weld machining. The final design configuration was shown in Fig. ,it is like "T".
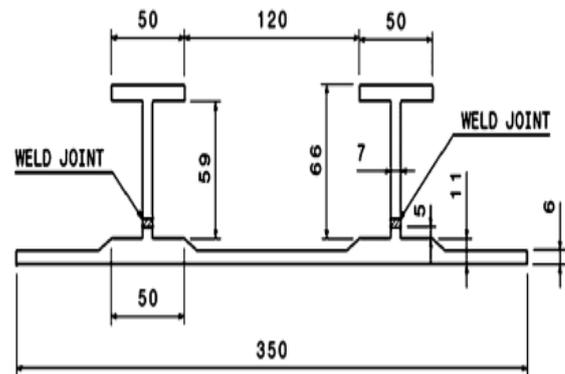


## II.     FRICTION STIR WELDING:
Friction stir welding (FSW) is a relatively new (1991) solid-state welding technique. In FSW, a rotating tool traverses along the joint seam of the material to be joined and accomplishes welding via mechanical stirring. It was First patented in Great Britain by Wayne Thomas et al from the Welding Institute in 1991 [Thomas et al., 1991a].The United States Patent is dated 1995 [Thomas et al., 1995].
The FSW tool rotates about its axis and the probe (or pin) plunges into the material. The shoulder of the tool applies force to the top of the material. Heat is generated through the downward force on the shoulder which softens the material along the joint line. The tool then traverses along the weld line, and the rotating tool probe drags the plasticized material to the back of the probe. This causes the solid-state joining of the material [Khaled, 2005]
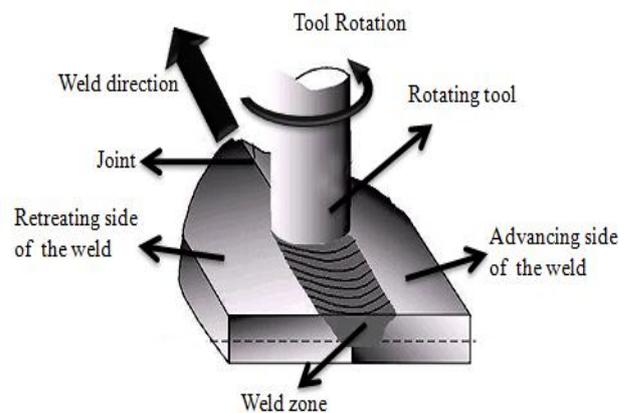


Stir welding (Thomas et al. 1991)

The emergence of the FSW alters the traditional approach for producing lightweight assemblies.

Boeing has reduced cost and production time with the FSW on pressure vessels (Johnsen 1999). Likewise, Eclipse aviation began using FSW to join skin structures and Hitachi has applied this technology to the welding of aluminum skin structures in their trains in anticipation of large cost and time savings (Ohba et al. 2001). Complex material movement and plastic deformation contribute significantly to the physical mechanism of FSW. Tool geometry, welding parameters, and joint design significantly influence the material flow. Figure 2.2 shows the FSW tool which consists of a shoulder and a pin. The shape and relative size of the pin and the shoulder are important for maximizing the heat generation, which aids the material flow and reduces welding force.
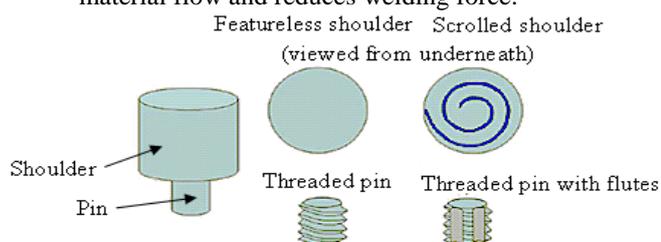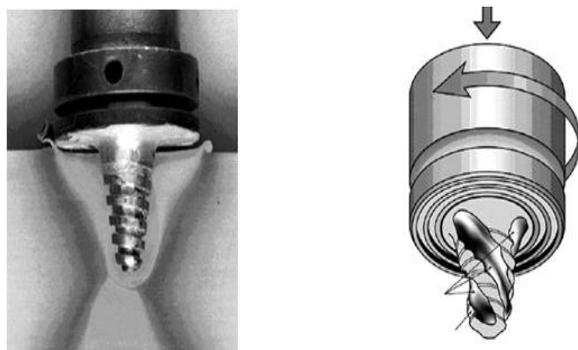


Fig. 2.2: Schematic drawing of the FSW tool (Mishra and Ma 2005)



(a)  Three flutes          (b) left hand helix on
                               Outer diameter land
Fig. 2.3: (a) Work tool
(b) MX triflute tool  (Thomas et al. 2003)

TWI (Thomas et al. 2003) has developed several types of tools like the worl and MX triflute tools as shown in Figure 2.3. It has been suggested that these design features reduce required welding forces, enable easier flow of plasticized material, facilitate a downward auguring effect, and increase the interface surface area between the pin and material. Zhao et al. (Zhao et al. 2005) investigated the influence of the pin geometry on bonding and mechanical properties in friction stir welded Al alloys. He claimed that pin design affects the flow of the plastic material strongly. The best quality weld was acquired using a tapered screw threaded pin.

Figure 2.4 shows the four visually distinct micro structural zones in which welds in aluminum are typically divided into:
(a) Unaffected parent material,
(b) Heat affected zone,
(c) Thermo-mechanically affected zone, and
(d) Weld nugget.

In the heat affected zone, properties and microstructure are affected by the heat from the weld, although there is no mechanical deformation. This zone retains the same grain structure as the parent materials.  The thermo-mechanically affected zone shows characteristics that suggest that it underwent plastic deformation but recrystallization did not occur in this zone due to insufficient deformation strain. In weld nugget zone, intense plastic deformation and frictional heating during FSW result in recrystallized fine-grained microstructure (Threadgill 1999).
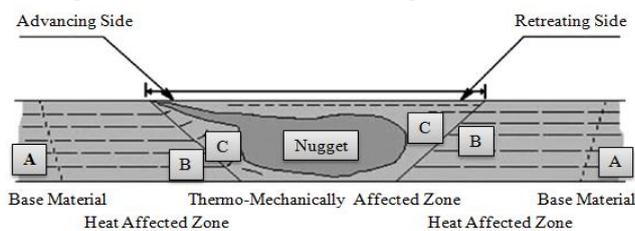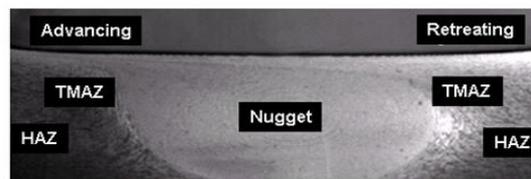


Fig 2.4  : (a) Schematic diagram of micro structural zones in friction stir welds in  aluminum
(b) micrograph showing various micro-structural zones (Threadgill 1999)

## III.     INTRODUCTION TO EXPERIMENT

The objective of this paper is to investigate optimum process parameters in friction stir welding to determine the induced stresses and the fatigue life in the Stringer Panel. More specifically , the choice of tool rotational speed  have been sought with a steady, 2 dimensional sequentially  coupled thermo mechanical model implemented in FE-Code, ANSYS. The thermal model is based on a heat source description which in essence is governed by the rotational speed and the temperature dependent yield stress of the work piece material. This model in turn delivers the temperature field, in order to compute thermal strain field which is the main driver for mechanical model predicting both transient and finally residual stresses in the work piece.

Most pure thermal models apply a surface flux as representing the entire heat generation, thereby avoiding the source term in the heat conduction equation, which is governed by the plastic dissipation and therefore in essence calls for knowledge about the material flow and hence the formation of the shear layer.

In this model the heat generation is expressed as a surface heat flux from the tool shoulder (without the tool probe) into work piece, however it is the function of the tool radius and the temperature dependent yield stress as follows.

$$\frac{Q_{Surf}}{A}(r, T) = \frac{2\pi n}{60} \times \frac{r}{1000} \times \frac{\sigma_{yield(T)}}{\sqrt{3}} \quad \dots [1]$$

$$\text{For } 0 \le r \le R$$

Where n is the tool revolution per minute, r is the pin radius originating in the tool center, R is the tool shoulder radius and the temperature dependent yield stress, $\sigma_{yield(T)}$ is defined as

$$\sigma_{yield(T)} = (\sigma_{yield})ref \times \left[1 - \frac{T - T_{ref}}{T_{melt} - T_{ref}}\right] \dots [2]$$

where, $(\sigma_{yield})ref$ is the yield stress at room temperature. $T_{ref}$ is 20°C and $T_{melt}$ is solidus temperature which is 1000°C.

Once the temperature reaches the solidus temperature, i.e. T is equal to $T_{melt}$ as in Eq.[2], the self stabilizing effect causes the heat generation decreases automatically due to thermal softening. The model is often denoted "Thermal-Pseudo-Mechanical" since the heat generation is expressed via the temperature dependent yield stress, thus taking some mechanical effects into.

### 3.1 CHOICE OF MATERIAL:

For the present problem of analyzing the Stringer Panel we take the material of ALUMINIUM 7075.the following are some of the properties tabulated.

| Structural | |
|---|---|
| Young's Modulus | 16000 MPa |
| Poisson's Ratio | 0.33 |
| Density | 2.77e-006 kg/mm³ |
| Thermal Expansion | 2.3e-005 1/°C |
| Tensile Yield Strength | 280. MPa |
| Compressive Yield Strength | 280. MPa |
| Tensile Ultimate Strength | 310. MPa |
| | |

| Thermal | |
|---|---|
| Specific Heat | 875. J/kg·°C |
| | |
| Resistivity | 5.7e-005 Ohm-mm |
| Melting point | 482.22 °C |
| | |
| Lower Forging Temperature | 260 °C |
| Upper Forging Temperature | 371.11 °C |

### 3.2 STRESS CALCULATIONS AT FOLLOWING TEMPERATURES

Theoretical stress values can be calculated by using following formula

$$\sigma_{yield(T)} = (\sigma_{yield})ref \times \left[1 - \frac{T - T_{ref}}{T_{melt} - T_{ref}}\right]$$

At 150°C the theoretical yield stress is:

$$\sigma_{yield(T)} = 420 \times \left\{1 - \frac{150 - 22}{482 - 22}\right\} = 308.49 \text{ MPa}.$$

At 200°C the theoretical yield stress is:

$$\sigma_{yield(T)} = 420 \times \left\{1 - \frac{200 - 22}{482 - 22}\right\} = 262 \text{ MPa}.$$

At 260°C the theoretical yield stress is:

$$\sigma_{yield(T)} = 420 \times \left\{1 - \frac{260 - 22}{482 - 22}\right\} = 202.7 \text{ MPa}.$$

At 371°C the theoretical yield stress is:

$$\sigma_{yield(T)} = 420 \times \left\{1 - \frac{371 - 22}{482 - 22}\right\} = 101.34 \text{ MPa}.$$

### 3.3 CALCULATIONS FOR HEAT FLUX

Heat flux can be calculated by using the formula:
Heat flux (ø): $(Q_{sur}/\text{Area}) = \omega r \sigma_{yield(T)} =$

$$\frac{2\pi r N}{60 * 1000} \times \frac{\sigma(T)}{\sqrt{3}}$$

At radius 4 mm and at σ(T) = 308.49MPa, the heat flux observed is:

$$\text{Ø} = \frac{2 * \pi * 100}{60} \times \frac{4}{1000} \times \frac{308.49 * (10^6)}{\sqrt{3}}$$

$$= 74.60 \times 10^5 \text{ W/m}^2.$$

Similarly at radius 4 mm and at σ(T) = 262MPa, the heat flux observed is:

$$\emptyset = \frac{2*\pi*100}{60} \times \frac{4}{1000} \times \frac{2.62*(10^6)}{\sqrt{3}} = 63.36 \times 10^5 \ W/m^2.$$

Similarly at radius 4 mm and at σ (T) = 202.7 MPa, the heat flux observed is:

$$\emptyset = \frac{2*\pi*100}{60} \times \frac{4}{1000} \times \frac{202.7*(10^6)}{\sqrt{3}}$$

= 49.02 x $10^5$ W/m$^2$.

Similarly at radius 4 mm and at σ (T) = 371 MPa, the heat flux observed is:

$$\emptyset = \frac{2*\pi*100}{60} \times \frac{4}{1000} \times \frac{371*(10^6)}{\sqrt{3}}$$

= 89 x $10^5$ W/m$^2$.

Therefore heat flux and stress calculations are calculated.

### 3.4 INPUTS GIVEN IN CATIA

| Specification of Stringer Panel | Dimension (mm) |
|---|---|
| Thickness of the structure along web and top flange region | 7 |
| Thickness of the structure along bottom flange | 6 |
| Width of the top flange | 50 |
| Height of the web | 59 |
| Total height of the structure | 77 |
| Total bottom length of the two Flanges | 350 |
| In between space provided for the weld between top and the bottom joint | 3 |
| Distance in between the two flange heads | 120 |
| Total length of the Stringer Panel | 1240 |

### 3.5 STEPS TO SOLVE PROBLEM IN ANSYS Work bench

The following are the steps required to solve the problem in ANSYS Work bench:

STEP 1: Launch ANSYS Workbench
STEP 2: Select GEOMETRY> FILE > IMPORT EXTERNAL GEOMETRY
        After importing the stp file (MODEL) return to the project.

STEP 3: Select NEW SIMULATION > MESH >GENERATE MESH

STEP 4: Select NEW ANALYSIS > STEADY STATE THERMAL ANALYSIS
        After selecting steady state thermal analysis the ambient and melting temperatures are given as inputs by selecting the corresponding surfaces. In

addition to that heat flux or the heat flow is given followed by selecting the required lines at the interface in the model.
        STEADY STATE THERMAL ANALYSIS > ANALYSIS> INSERT> TEMPERATURE (AMBIENT)
        STEADY STATE THERMAL ANALYSIS > ANALYSIS> INSERT> TEMPERATURE (MELTING)
        STEADY STATE THERMAL ANALYSIS > ANALYSIS> INSERT> HEAT FLOW/HEAT FLUX.

STEP 5: Select SOLUTION>TOTAL HEAT FLUX
        >DIRECTIONAL HEAT FLUX
        >TOTAL DEFORMATION
        >EQUIVALENT STRESS
        >NORMAL STRESS
        >SHEAR STRESS
        >DIRECTIONAL DEFORMATION

STEP 6: Select ANALYSIS > FATIGUE>LIFE
        >DAMAGE
        >SAFETY FACTOR
        >EQUIVALENT ALTERNATING STRESS

STEP 7: Right click on the SOLUTION > GENERATE > STEADYSTATE THERMAL

STEP 8: SAVE the FILE in the Word Document.
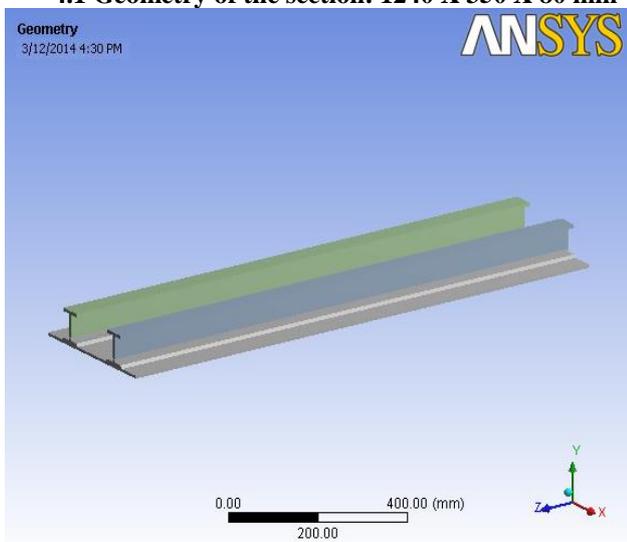
### 3.6 INPUTS IN TO ANSYS WORK BENCH

| Speed rpm | 100 | 200 | 400 |
|---|---|---|---|
| Angular Vel(w), rad/s | 10.472 | 20.944 | 41.888 |
| σ yield(260°C) M Pa | 202.7 | 202.7 | 202.7 |
| Heat flux (W/m$^2$) | 49.02e5 | 98.4e5 | 196.08e5 |
| σ yield(371°C) M Pa | 101.25 | 101.25 | 101.25 |
| Heat flux (W/m$^2$) | 24.49e5 | 48.97e5 | 97.95e5 |
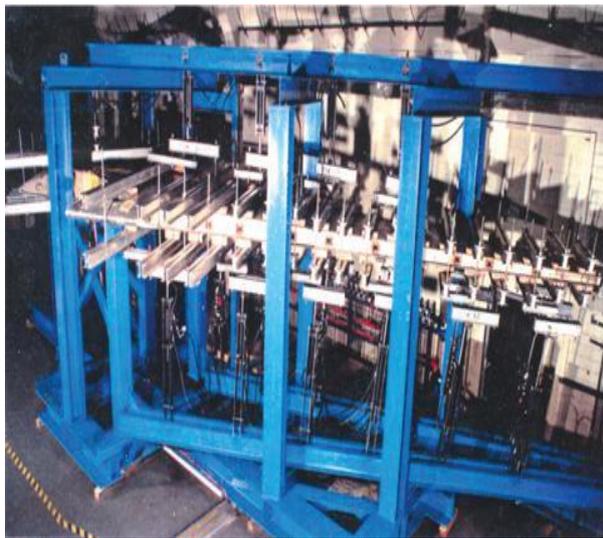
Wing section of T-39 trainer undergoing fatigue testing

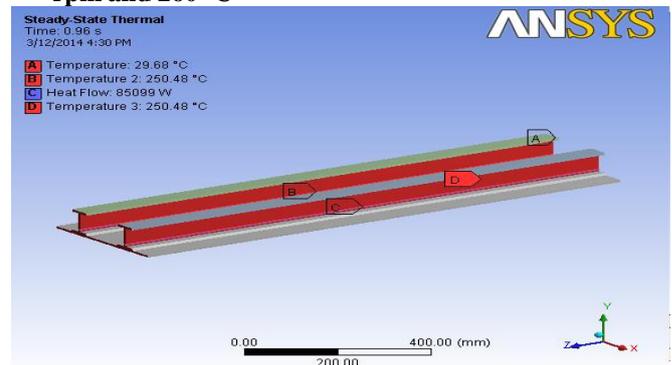## 4. RESULTANT PLOTTING AFTER ANALYSIS
### 4.1 Geometry of the section: 1240 X 350 X 80 mm
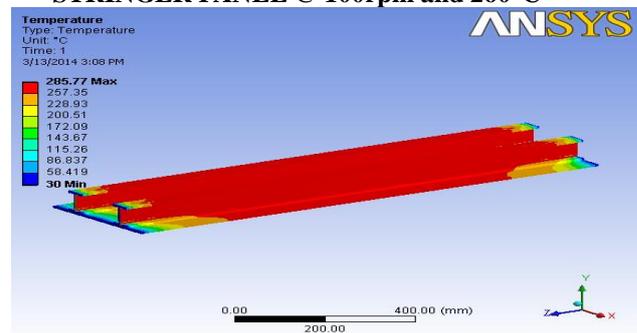


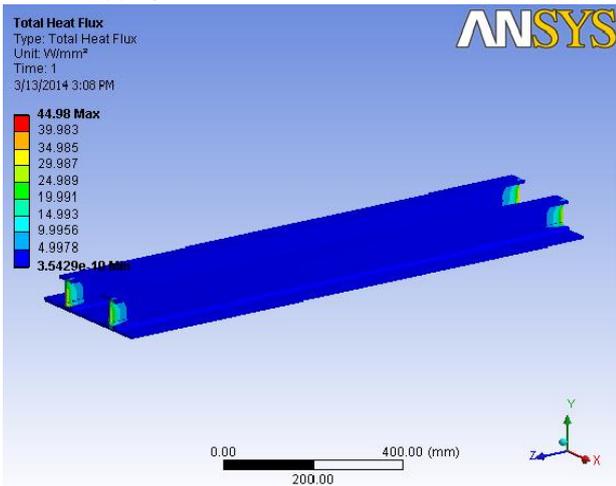### 4.2 MESH OF THE STRINGER PANEL STRUCTURE
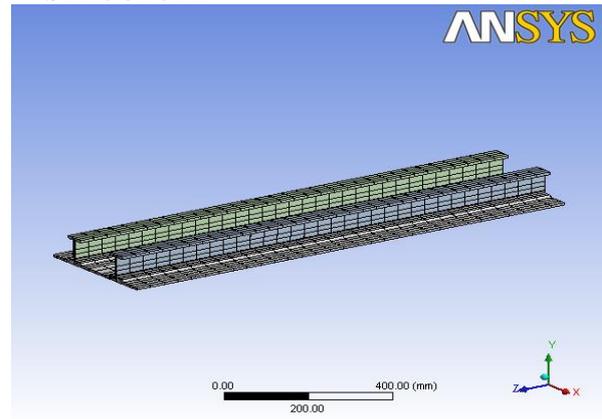


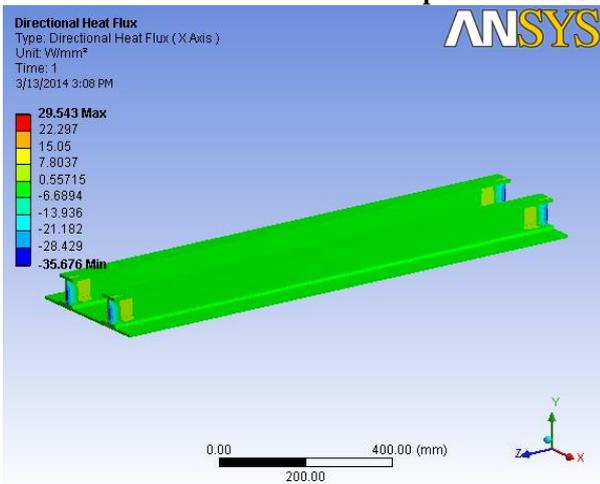### 4.3 Steady-State Thermal condition of 100 rpm and 260 °C



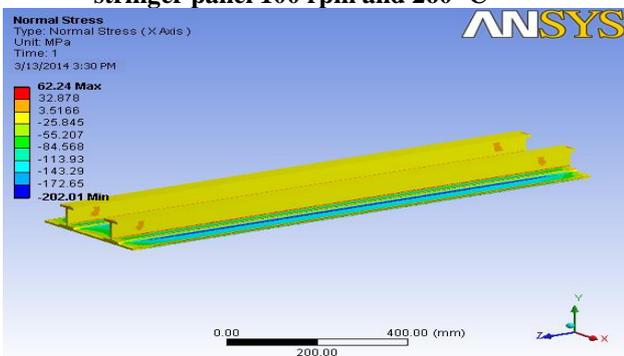### 4.4 Temperature distribution along the STRINGER PANEL @ 100rpm and 260°C

**4.5 Total Heat Flux distribution at 100 rpm and 260 $^o$C**



**4.6 Directional Heat Flux at 100 rpm and 260 $^o$C**



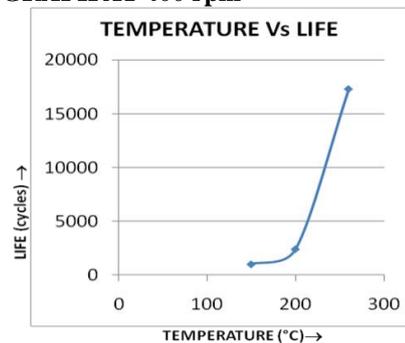**4.7 Normal Stress distribution over the stringer panel 100 rpm and 260 $^o$C**



**4.8 RESULTS**

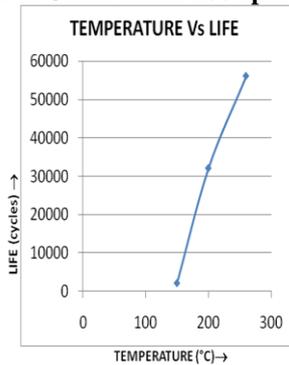|  | Stress (MPa) | Life(cycles) |
|---|---|---|
| @100 rpm |  |  |
| 150 $^o$C | 300 | 2100 |
| 200 $^o$C | 254.7 | 32087 |
| 260 $^o$C | 194.65 | 56148 |
| @200 rpm |  |  |
| 150 $^o$C | 305 | 1600 |
| 200 $^o$C | 261 | 26942 |
| 260 $^o$C | 203 | 39556 |
| @400 rpm |  |  |
| 150 $^o$C | 318 | 900 |
| 200 $^o$C | 264 | 2404 |
| 260 $^o$C | 218 | 17326 |

**5 GRAPHS**
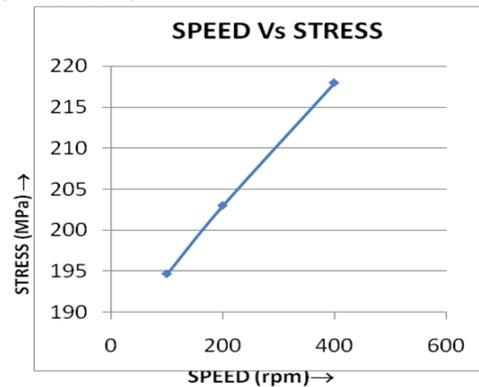**5.1 ANALYTICAL TEMPERATURE Vs LIFE GRAPH AT 400 rpm**



**ANALYTICAL TEMPERATURE Vs LIFE GRAPH AT 400 rpm**
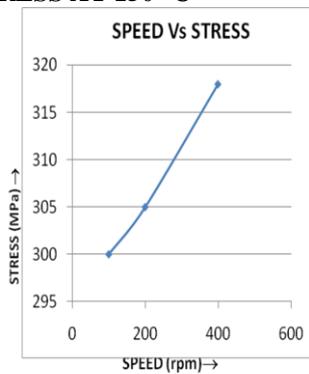
## 5.2 ANALYTICAL TEMPERATURE Vs LIFE GRAPH AT 100 rpm



ANALYTICAL TEMPERATURE Vs LIFE GRAPH AT 100 rpm

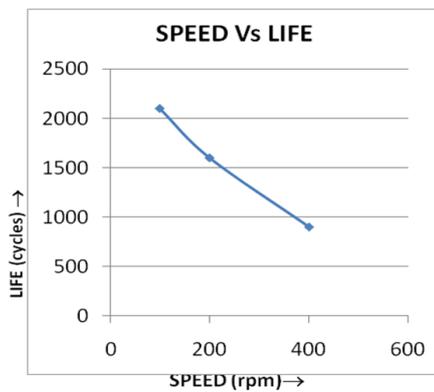## 5.3 ANALYTICAL TEMPERATURE Vs STRESS AT 150° C



ANALYTICAL SPEED Vs STRESS AT 150 °C

## 5.4 ANALYTICAL SPEED Vs LIFE AT 100 RPM



ANALYTICAL SPEED Vs LIFE AT 100 rpm

## 5.5 ANALYTICAL TEMPERATURE Vs STRESS AT 260° C



ANALYTICAL SPEED Vs STRESS AT 260 °C

## CONCLUSIONS

The Stress and Life Cycles of Stringer Panel in the FRICTION STIR WELDING was analyzed and studied. From the results the following points are concluded:

For a given speed at different temperatures the Life Cycles are Maximum at Higher Temperatures of the Stringer Panel i.e. 260$^{\circ}$C with 56148 Life Cycles.(Graph 5.2)

Stress component of the Stringer Panel in the Friction Stir Welding was minimum when the Speed of the Tool is minimum i.e. 100 rpm. (Graph 5.5)

For different speeds of the Tool in the Friction Stir Welding at Lower Speeds the Life Cycles are Maximum.(Graph 5.4)

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