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Tool Design and Analysis of Friction Stir Welding Process by Using FEA

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ABSTRACT : *Friction Stir Welding (FSW) process is a solid state welding process, that uses a non consumable tool for joining the plates. The tool, its pin profile, shape and dimensions plays a vital role in making the weld joint. In FSW, the stress distribution of tool pin is affected by the thermo mechanical characteristics of the work piece. In this present work, three tools with different pin shapes (Conical, Cylindrical and Frustum) were designed with and without threads in their profiles .Initially the tools dimensions are based on the base material plate thickness taken in to consideration, the induced structural stresses were checked with in the permissible stress limits. The tools were modeled in CATIA and analysis is performed in ANSYS software for exploring stress distributions and displacement vector sum in the pin, at different speeds and temperatures. The frictional force between the tool shoulder and work piece is considered for simulating the stress and displacement vector in the pin profiles. The tool pin profiles considered for structural and thermal analysis are used in this study are cylindrical, conical, and frustum. The vonmises stress distributions in pin profiles, displacement vector sum of the pin profiles, are obtained from ANSYS software and the pin with optimum strength is determined.*

Keywords: *Friction Stir Welding, thermo mechanical, CATIA, Tool pin profiles, thermal analysis.*

I. INTRODUCTION

There is an increasing need for low distortion aluminium alloys in sheet and plate form in the fabrication industry, such as ship panels, bridge decks and other transportation applications such as train and airplane components. Therefore, sound welding methods are necessary to fabricate large Al alloy sheet and plate.

In many industrial applications steels are readily replaced by non-ferrous alloys, in most cases by aluminium alloys. Some of these materials combine mechanical strength comparable with structural steels and low weight, allowing for a significant reduction of weight. While production of components of aluminium alloys is not very complex, joining of these materials can sometimes cause serious problems. Lack of structural transformations in solid state and excellent thermal and electrical conductivity cause problems in fusion and resistance welding of aluminium alloys. That led to the development of Friction Stir Welding a solid state joining technique in which the joined material is plasticized by heat generated by friction between the surface of the plates and the contact surface of a special tool, composed of two main parts: shoulder and pin. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, while pin mixes the material of the components to be welded, thus creating a joint. This allows for producing defect-free welds characterized by good mechanical properties.

Among aluminum alloys, aluminium-magnesium-silicon (Al-Mg-Si) heat treatable wrought alloys, although of only medium strength appears to have weldability advantage over high strength aluminium alloys. For this reason Al-Mg-Si alloys are widely used for structural components in welded assemblies. However, Al-Mg-Si alloys (6000 series) are crack sensitive when they are fusion welded without filler metal.

The major advantages of friction stir welding (FSW) in aluminium alloys, when compared to conventional fusion welds, are primarily the elimination of cracking and evaporative loss of alloying elements. This is due to the solid-state joining and a weld zone with fine worked or recrystallized grain structure generated by stirring and forging during FSW. During friction stir (FS) welding, temperatures remaining below the melting point result in a low shrinkage phenomenon and excellent mechanical properties, together with reduction of residual stress within the weld zone mechanical properties of the FSW joint are quite good and fatigue properties are practically the same as the parent metal.

To date, the major application fields of FSW are marine industries(ship sections, hulls, structures), aerospace industry (fuselages, wings, fuel tanks), railway industry (high speed trains, carriages), automotive industry (chassis, wheel rims, space frames, truck bodies) motor cycle frames and other sections, such as electrical and refrigeration. Due to the combined effect of tooling, FSW produces five different microstructure zones: The nugget in the centre of the weld where the pin has passed, A shoulder contact zone on the top surface, Thermo-mechanically affected zones (TMAZ) that are immediately on each side of the nugget, heat affected zones (HAZ) adjacent to the TMAZ that experiences a thermal cycle but not a mechanical shearing, and the unaffected parent material.

FSW produces an asymmetric micro structure in which the advancing and retreating sides experience different strain levels and thermal cycles. Material on the advancing side (rotation opposed to plate motion) experiences more shear than the retreating does. The closer the material to the tool, the higher is the deformation and temperature gradients to which it is subjected. This implies as effective deformation rate higher in the advancing side than in the retreating, resulting in different stress, flow and temperature cycles. Moreover, almost all the metal form in front of the tools is transformed to the retreating side creating a much broader flow band than that of the advancing. In addition to the grain and substructure evolution during the severe thermo-mechanical conditions imposed by FSW, the various thermal cycles in the different weld zones induce different precipitate distributions within each zone. In the present report for FSW tools with various pin profiles, stress distributions and displacement of the pin are analyzed.

II. TOOL DESIGN

The design of the tool is a critical factor as a good tool can improve the quality of the weld at the maximum possible welding speed. It is desirable that the tool material is sufficiently strong, tough and hard wearing, at the welding temperature. Further it should have good oxidation resistance and a low thermal conductivity to minimize heat loss and thermal damage to the machinery further up the drive train. Hot-worked tool steel such as AISI H13 has proven perfectly acceptable for welding aluminum alloys within the thickness range of 0.5 – 50 mm. But more advanced tool materials are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials such as steel or titanium. Improvements in tool design have been shown to cause substantial improvements in productivity and quality. TWI has developed tools specifically designed to increase the depth of penetration and so increase the plate thickness that can be successfully welded. An example is the ‘whorl’ design that uses a frustum pin with re-entrant features or a variable pitch thread in order to improve the downwards flow of material. The majority of tools have a concave shoulder profile which acts as an escape volume for the material displaced by the pin, prevents material from extruding out of the sides of the shoulder and maintains downwards pressure and hence good forging of the material behind the tool.

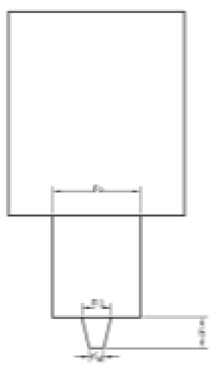

Fig1. Schematic diagram of FSW tool

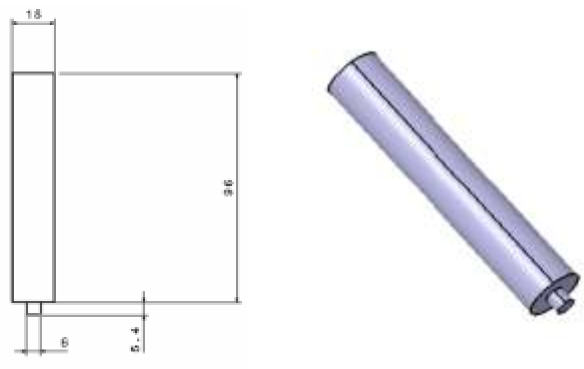

Fig2. 2D and 3D model of FSW tool with Cylindrical pin

Design Of Fsw Tool With Cylindrical Pin

Where r_o is the radius of the tool shoulder, r_{i1} is the radius of the pin at the tool shoulder, r_{i2} is the radius of the pin at the pin bottom and h is the pin height.

Pin diameter = 6 mm, Pin height = 5.4 mm, Downward force applied on the pin = 7000N, In the present work, as an initial study, the applied downward force is taken as 7000 N.

Maximum load carrying capacity of tool pin:

$$F_{ultimate} = \sigma_{allowable} \times A_C$$

The stresses are induced in tool due to reaction force from bottom.

Induced stress due to applied load ($\sigma_{induced}$) = F / A_C

$T_{total} = T_{shoulder} + T_{pinbottom} + T_{pinsurface}$

T_{total} = Total Torque produced in the in N-mm

$T_{shoulder}$= Torque produced at the shoulder of the pin in N-mm

$T_{pinbottom}$= Torque produced at the bottom of the pin in N-mm

$T_{pinsurface}$ = Torque produced on the surface of the pin in N-mm

Introducing τ as the uniform shear stress during welding, then the total torque becomes:

$$T_{Total} = \int_{r_{i1}}^{r_o} (\tau r)(2\Pi r)dr + \int_{0}^{r_{i2}} (\tau r)(2\Pi r)dr + 2\Pi \tau r_i^2 h$$

Where r_o is the radius of the tool shoulder, r_{i1} is the radius of the pin at the tool shoulder, r_{i2} is the radius of the pin at the pin bottom and h is the pin height. To simplify the evaluation of equation (4), the pin shape is assumed as straight cylindrical, i.e. $r_{i1}=r_{i2}$, thus

$$T_{Total} = \tau(\frac{2}{3}\Pi r_0^3 + 2\Pi r_i^2 h) = 2\mu F(\frac{r_o}{3} + \frac{r_i^2}{r_0^2} h)$$

Therefore Torque due to tool geometry:

$$T_{7000} = 2\times\mu\times F \left[\left(\frac{r_0}{3}\right) + \left(\frac{r_i^2}{r_0^2}\right)\times h\right]$$

Because of torsion Shear stress () is induced in the tool material.

Therefore shear stress (τ) = $\dfrac{16\times T}{\prod \times d^3}$

$$\tau_{7000} = \frac{16\times T}{\prod \times d^3}$$

$$= \frac{16\times 15{,}120}{\prod \times 6^3}$$

There are many cases in engineering practice, in which members are subjected to combined stresses due to simultaneous action of either tensile or compressive stresses combined with shear stresses. In such cases, the maximum principal stresses, due to the combination of tensile or compressive stresses with shear stresses may be obtained. Therefore, Maximum compressive stress ($\sigma_{c\ max}$) = $\frac{1}{2}\times\left[\sigma_{induced} + \sqrt{\sigma_{induced}^2 + 4\tau^2}\right]$

Maximum shear stress ($_{max}$) = $\frac{1}{2}\times\left[\sqrt{\sigma_{induced}^2 + 4\tau^2}\right]$

$$\sigma_{c\ max} = \frac{1}{2}\times\left[\sigma_{induced} + \sqrt{\sigma_{induced}^2 + 4\tau^2}\right]$$

Maximum shear stress (τ_{max}) = $\frac{1}{2}\times\left[\sqrt{\sigma_{induced}^2 + 4\tau^2}\right]$

$$\tau_{7000} = \frac{1}{2}\times\left[\sqrt{\sigma_{induced}^2 + 4\tau^2}\right]$$

$$(\tau_{\max}) \leq \frac{\sigma_{yc}}{2} \;, \quad \frac{\sigma_{yc}}{2} =$$

Design Of Fsw Tool With Conical Pin

Maximum load carrying capacity of tool pin:

$F_{ultimate} = \sigma_{allowable} \times A_C$

The stresses are induced in tool due to reaction force from bottom.

Induced stress due to applied load ($\sigma_{induced}$) = F / A_C

$T_{total} = T_{shoulder} + T_{pinbottom} + T_{pinsurface}$

Introducing as the uniform shear stress during welding, then the total torque becomes:

$$T_{Total} = \int_{r_{i1}}^{r_o} (\tau r)(2\Pi r)dr + \int_{0}^{r_{i1}} 2\Pi \tau r_i^2 h$$

Where r_o is the radius of the tool shoulder, r_{i1} is the radius of the pin at the tool shoulder, r_{i2} is the radius of the pin at the pin bottom and h is the pin height.

$$T_{Total} = 2\mu F\left(\frac{r_o}{3} - \frac{r_{i1}^{\;3}}{3r_0^{\;2}} + \frac{r_{i1}^3}{3r_0^2} h \right)$$

Therefore shear stress (τ) = $\frac{16 \times T}{\prod \times d^{\;3}}$

$$\sigma_{c\,max} = \frac{1}{2} \times \left[\sigma_{induced} + \sqrt{\sigma_{induced}^{\;2} + 4\tau^2}\right]$$

Maximum shear stress (τ_{max}) = $\frac{1}{2} \times \left[\sqrt{\sigma_{induced}^{\;2} + 4\tau^2}\right]$

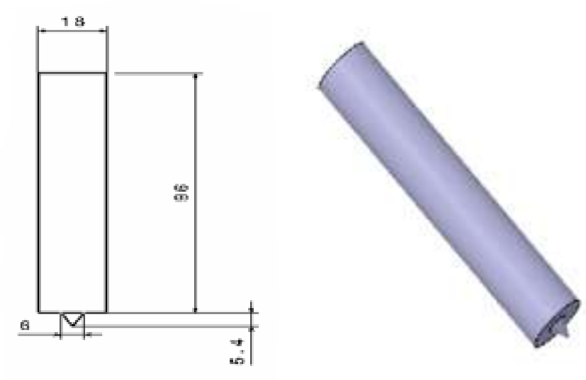

Fig4. 2D and 3D model of FSW tool with Conical Pin

Design Of Fsw Tool With Frustum Pin

$F_{ultimate} = \sigma_{allowable} \times A_C$

The stresses are induced in tool due to reaction force from bottom.

Induced stress due to applied load ($\sigma_{induced}$) = F / A_C

$T_{total} = T_{shoulder} + T_{pinbottom} + T_{pinsurface}$

Introducing as the uniform shear stress during welding, then the total torque becomes:

$$T_{Total} = \int_{r_{i1}}^{r_o} (\tau r)(2\Pi r)dr + \int_{r_{i2}}^{r_{i1}} (\tau r)(2\Pi r)dr + \int_{r_{i2}}^{r_{i1}} 2\Pi \tau r_i^2 h$$

Where r_o is the radius of the tool shoulder, r_{i1} is the radius of the pin at the tool shoulder, r_{i2} is the radius of the pin at the pin bottom and h is the pin height. To simplify the evaluation of equation (4), the pin shape is assumed as tapered cylindrical, thus

$$T_{Total} = 2\mu F\left(\frac{r_o}{3} - \frac{r_{i2}^{3}}{3r_0^{2}} + \frac{r_{i1}^{3}}{3r_0^{2}}h - \frac{r_{i2}^{3}}{3r_0^{2}}h\right)$$

Therefore Torque due to tool geometry:

Therefore shear stress (τ) = $\frac{16 \times T}{\prod \times d^{3}}$

$\sigma_{c\,max} = \frac{1}{2} \times \left[\sigma_{induced} + \sqrt{\sigma_{induced}^{2} + 4\tau^{2}}\right]$

Maximum shear stress (τ_{max}) = $\frac{1}{2} \times \left[\sqrt{\sigma_{induced}^{2} + 4\tau^{2}}\right]$

$\tau_{max} = \frac{1}{2} \times \left[\sqrt{\sigma_{induced}^{2} + 4\tau^{2}}\right]$

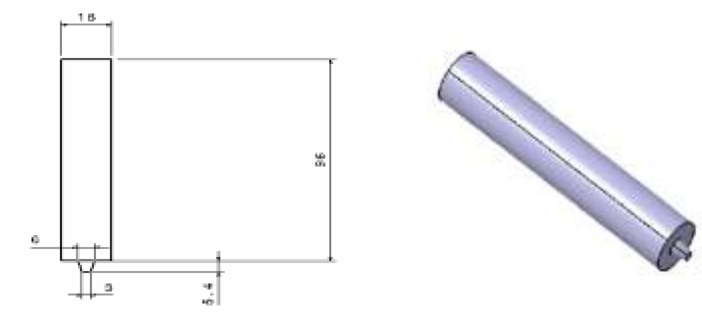

Fig.5 2D AND 3D model of FSW tool with Frustum Pin

Design Of Fsw Tool With Threaded Cylindrical Pin

Induced stress due to applied load ($\sigma_{induced}$) = F / A_C

$T_{total} = T_{shoulder} + T_{pinbottom} + T_{pinsurface}$

Introducing as the uniform shear stress during welding, then the total torque becomes:

$$T_{Total} = \tau\left(\frac{2}{3}\Pi r_0^{3} + 2\Pi r_i^{2} h\right) = 2\mu F\left(\frac{r_o}{3} + \frac{r_i^{2}}{r_0^{2}}h\right)$$

Therefore Torque due to tool geometry:

$$T_{7000} = 2\times\mu\times F\left[\left(\frac{r_0}{3}\right)+\left(\frac{r_i^{\,2}}{r_0^{\,2}}\right)\times h\right]$$

Because of torsion Shear stress (τ) is induced in the tool material.

Therefore shear stress (τ) = $\frac{16\times T}{\prod\times d^{3}}$

$$\sigma_{c\,max} = \frac{1}{2}\times\left[\sigma_{induced}+\sqrt{\sigma_{induced}^{\;2}+4\tau^2}\right]$$

Maximum shear stress (τ_{max}) = $\frac{1}{2}\times\left[\sqrt{\sigma_{induced}^{\;2}+4\tau^2}\right]$

Maximum shear stress theory, $\left(\tau_{\max}\right)\le\frac{\sigma_{yc}}{2}$,

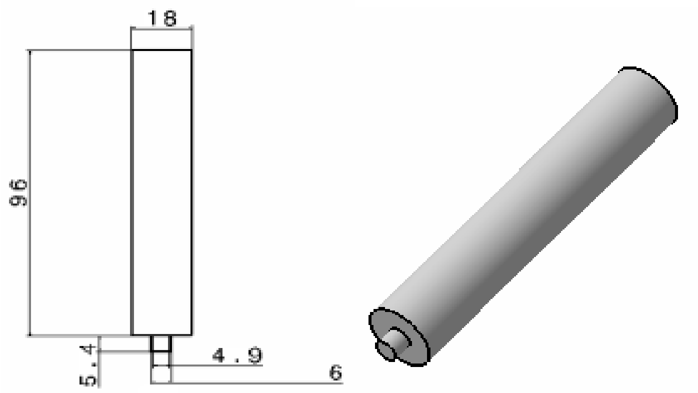

Fig.6.3D and 2D model of FSW tool with Threaded Cylindrical Tool Pin

Design Of Fsw Tool With Threaded Frustum Pin

The stresses are induced in tool due to reaction force from bottom.

Induced stress due to applied load ($\sigma_{induced}$) = F / A_C

$T_{total} = T_{shoulder} + T_{pinbottom} + T_{pinsurface}$

Introducing as the uniform shear stress during welding, then the total torque becomes:

$$T_{Total} = \int_{r_{i1}}^{r_o}(\tau r)(2\Pi r)dr + \int_{r_{i2}}^{r_{i1}}(\tau r)(2\Pi r)dr + \int_{r_{i2}}^{r_{i1}} 2\Pi\,\tau r_i^2 h$$

Where r_o is the radius of the tool shoulder, r_{i1} is the radius of the pin at the tool shoulder, r_{i2} is the radius of the pin at the pin bottom and h is the pin height. To simplify the evaluation of equation (4), the pin shape is assumed as tapered cylindrical, thus

$$T_{Total} = 2\mu F\left(\frac{r_o}{3}-\frac{r_{i2}^{\;3}}{3r_0^{\;2}}+\frac{r_{i1}^3}{3r_0^2}h-\frac{r_{i2}^3}{3r_0^2}h\right)$$

Therefore shear stress (τ) = $\frac{16\times T}{\prod\times d^{3}}$

$$\sigma_{c\,max} = \frac{1}{2}\times\left[\sigma_{induced}+\sqrt{\sigma_{induced}^{\;2}+4\tau^2}\right]$$

= Maximum shear stress (τ_{max}) = $\frac{1}{2} \times \left[\sqrt{\sigma_{induced}{}^2 + 4\tau^2} \right]$

τ_{max} = $\frac{1}{2} \times \left[\sqrt{\sigma_{induced}{}^2 + 4\tau^2} \right]$

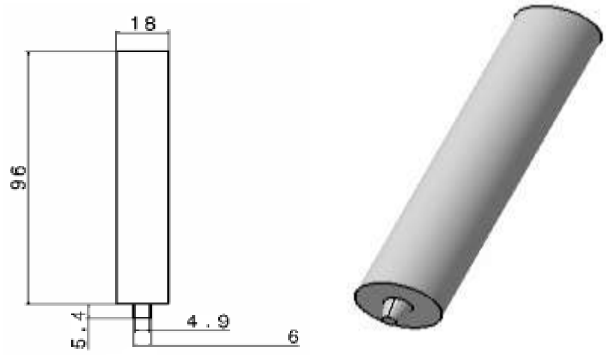

Fig 7.2D and 3D model of FSW tool with Threaded Frustum Pin

Design Of Fsw Tool With Threaded Conical Pin

Induced stress due to applied load ($\sigma_{induced}$) = F / A_C

$$T_{total} = T_{shoulder} + T_{pinbottom} + T_{pinsurface}$$

Introducing as the uniform shear stress during welding, then the total torque becomes:

$$T_{Total} = \int_{r_{i1}}^{r_o} (\tau r)(2\Pi r)dr + \int_{0}^{r_{i1}} 2\Pi \tau r_i^2 h$$

Where r_o is the radius of the tool shoulder, r_{i1} is the radius of the pin at the tool shoulder, r_{i2} is the radius of the pin at the pin bottom and h is the pin height.

$$T_{Total} = 2\mu F \left(\frac{r_o}{3} - \frac{r_{i1}{}^3}{3r_0{}^2} + \frac{r_{i1}^3}{3r_0^2} h \right)$$

Therefore Torque due to tool geometry:

Because of torsion Shear stress (τ) is induced in the tool material.

Therefore shear stress (τ) = $\frac{16 \times T}{\prod \times d^3}$

$\sigma_{c\,max}$ = $\frac{1}{2} \times \left[\sigma_{induced} + \sqrt{\sigma_{induced}{}^2 + 4\tau^2} \right]$

Maximum shear stress (τ_{max}) = $\frac{1}{2} \times \left[\sqrt{\sigma_{induced}{}^2 + 4\tau^2} \right]$

τ_{max} = $\frac{1}{2} \times \left[\sqrt{\sigma_{induced}{}^2 + 4\tau^2} \right]$ As per maximum shear stress theory, $(\tau_{max}) \leq \frac{\sigma_{yc}}{2}$

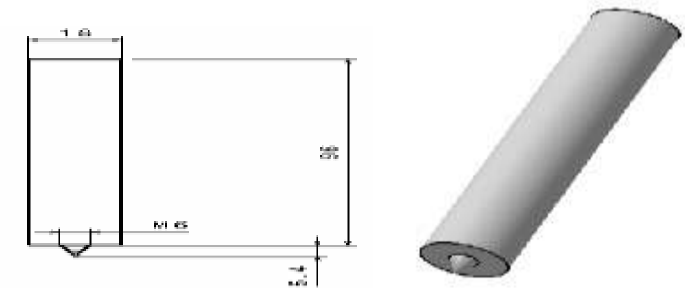

Fig.8 2D and 3D model of FSW tool with Threaded Conical Pin

III. RESULTS

The present analysis is a coupled field analysis. The structural and thermal analysis has to be performed simultaneously. Due to this, the structural properties and thermal properties of the material are given as input to the ANSYS software at a time. First structural loads were applied and on the obtained results, the thermal loads are applied. The data common to the shapes of the three pin profiles under consideration is given as input in ANSYS as follows.

Analysis Of Fsw Tool With Cylindrical Pin Using Ansys

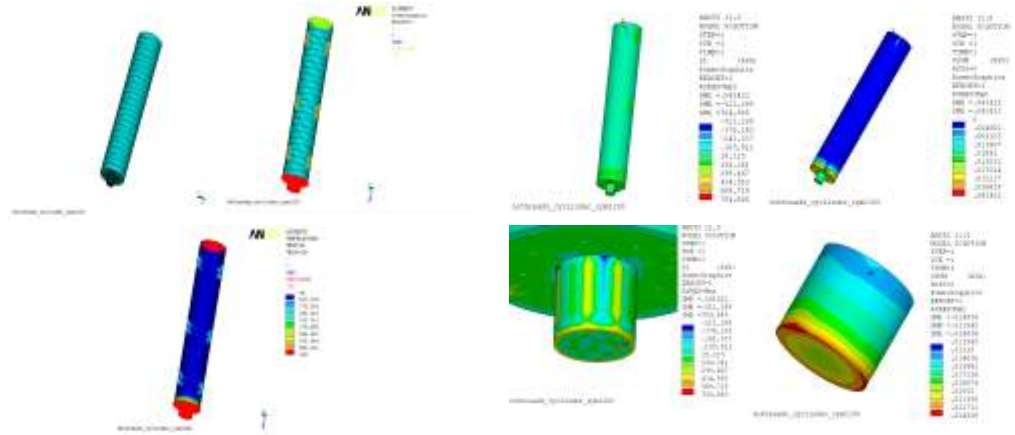

Fig.8.Schematic view of stress distribution and displacement vector sum at 1200rpm and meshed tool with loads and boundary conditions

Analysis Of Fsw Tool With Frustum Pin Using Ansys

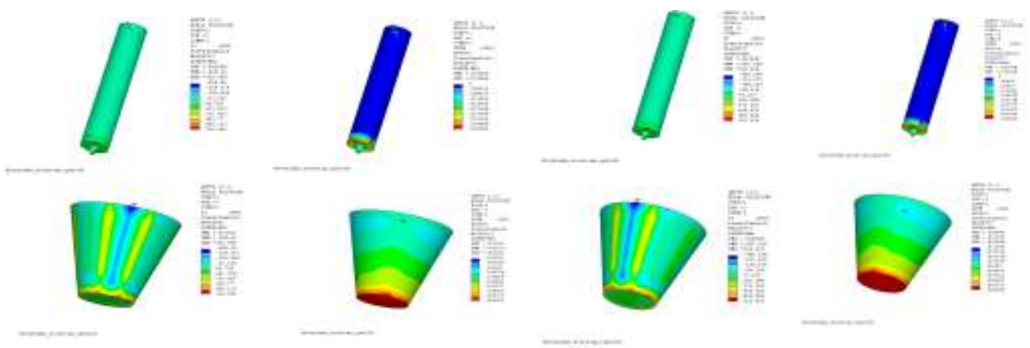

Fig**.9 Schematic view of stress distribution and displacement vector sum at 1300rpm**

Analysis Of Fsw Tool With Conical Pin Using Ansys

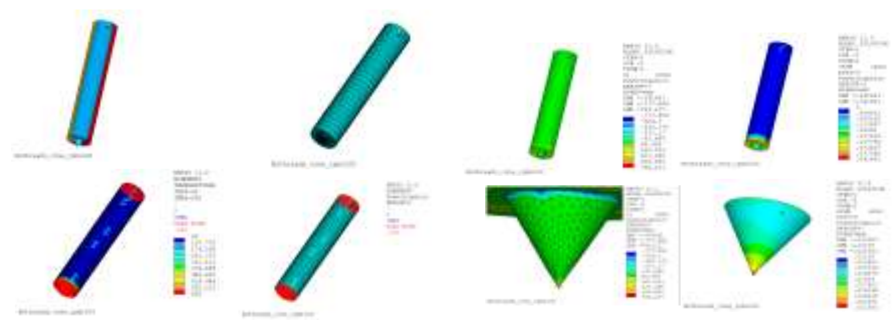

Fig 10 Schematic view of stress distribution and displacement vector sum at 1200rpm and meshed tool with applied loads&boundary conditions

Analysis Of Fsw Tool With Threaded Cylindrical Pin

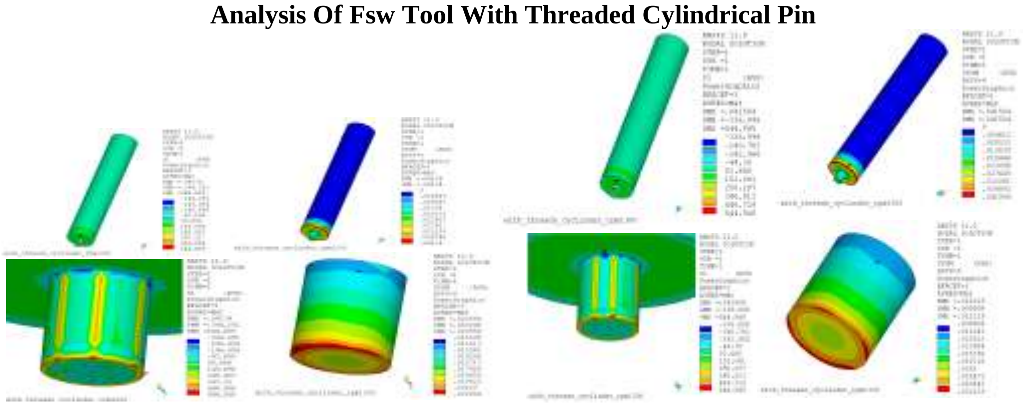

Fig.11 Schematic view of stress distribution and displacement vector sum at 1300rpm

Analysis Of Fsw Tool With Threaded Frustum Pin Using Ansys

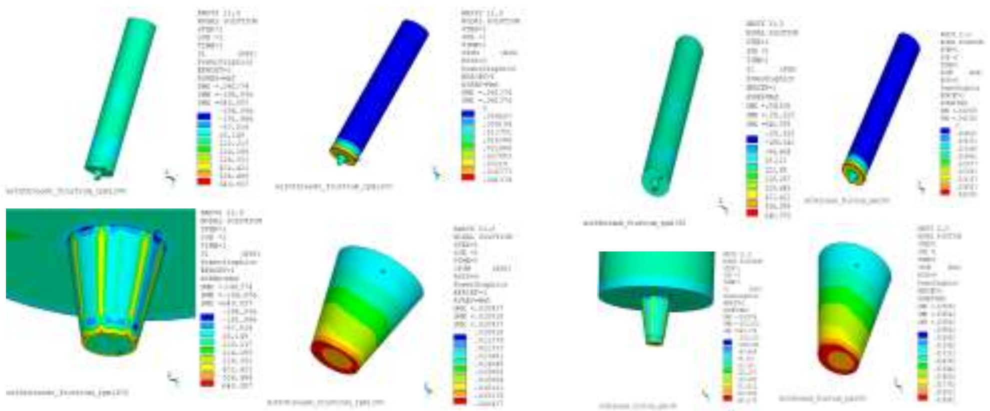

Fig.12 Schematic view of stress distribution and displacement vector sum at 1300rpm and Schematic view of stress distribution and displacement vector sum at 1200rpm

Analysis Of Fsw Tool With Threaded Conical Pin

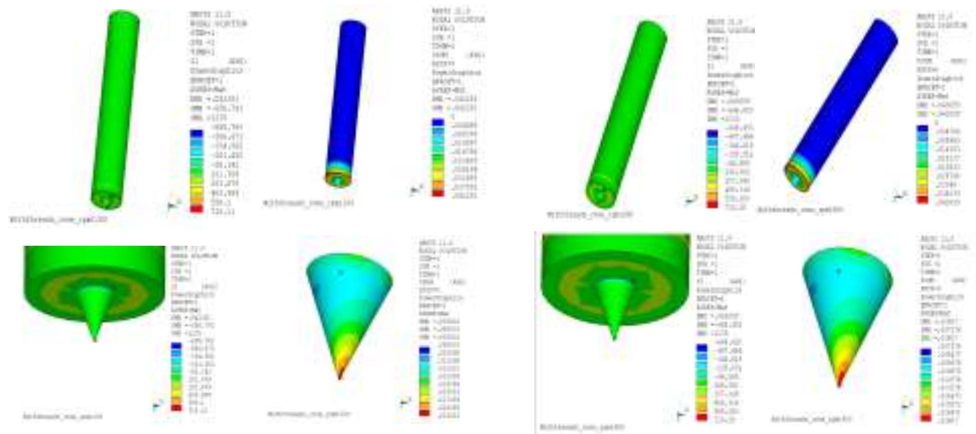

Fig.4.30 Schematic view of stress distribution and displacement vector sum at 1600rpm and stress distribution and displacement vector sum at 1200rpm

IV. CONCLUSIONS

- From the results it can be concluded that, among all tool pin profiles, the tool with cylindrical profile with threads is preferable because the maximum stress distribution and displacement vector sum are very less.
- As the temperature in the welding zone increases in the profiles with and without threads, the stress distribution and displacement vector sum are observed to be increased. It is also maximum in the tool with conical profile.
- The results of profiles with and without threads are compared, the stress distribution and displacement vector sum are observed to be maximum in the tool profiles without threads.
- Among all the profiles, the maximum stress distribution and displacement vector sum are maximum in the FSW tool with conical profile and is observed that by increasing the rotational speed there is not much change in the maximum stress distribution and displacement vector sum.

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