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Structural And Thermal Analysis for Friction Stir Welding of Aluminum Alloy and Copper

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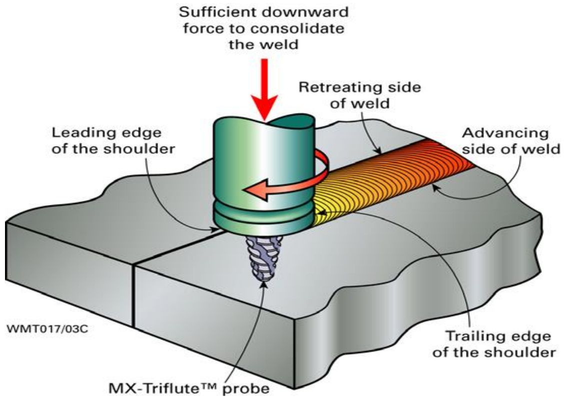
ABSTRACT:

Friction Stir Welding (FSW), invented by Wayne Thomas at TWI Ltd in 1991 overcomes many of the problems associated with traditional joining techniques. FSW is a solid-state process which produces welds of high quality in difficult-to-weld materials such as aluminium, and is fast becoming the process of choice for manufacturing lightweight transport structures such as boats, trains and aeroplanes.FEA analysis will be performed for friction stir welding of aluminium and copper at different speeds using Ansys. Coupled field analysis, thermal and structural will be performed. A parametric model with the weld plates and cutting tool will be done in Pro/Engineer. The speeds are 750rpm, 560 rpm and 410rpm. The temperatures taken for thermal analysis, at 410rpm 420^{0}C, at 560rpm 530^{0}C, at 750rpm 627^{0}C respectively.The effects of different tool pin profiles on the friction stir welding will also be considered for analysis. Different tool pin profiles are circular, tapered circular.

INTRODUCTION

Friction Stir Welding is the most recent upgrade to the Space Shuttle's gigantic External Tank, the largest element of the Space Shuttle and the only element not reusable. The new welding technique—being marketed to industry—utilizes frictional heating combined with forging pressure to produce high-strength bonds virtually free of defects. Friction Stir Welding transforms the metals from a solid state into a "plastic-like" state, and then mechanically stirs the materials together under pressure to form a welded joint. Invented and patented by The Welding Institute, a British research and technology organization, the process is applicable to aerospace, shipbuilding, aircraft and automotive industries. One of the key benefits of this new technology is that it allows welds to be made on aluminum alloys that cannot be readily fusion arc welded, the traditional method of welding. In 1993, NASA challenged Lockheed Martin Laboratories in Baltimore, Md., to develop a high-strength, low-density, lighter-weight replacement for aluminum alloy Al 2219–used on the original Space Shuttle External Tank. Lockheed Martin, Reynolds Aluminum and the labs at Marshall Space Flight Center in Huntsville, Ala., were successful in developing a new alloy known as Aluminum Lithium Al-Li 2195, which reduced the weight of the External Tank by 7,500 pounds (3,402 kilograms). Today, the External Tank project uses the new alloy to build the Shuttle's Super Lightweight Tanks. The lithium in the new lighter-weight material—aluminum lithium alloy Al-Li 2195—made the initial welds of the External Tank far more complex. The repair welds were difficult to make and the joint strength of the External Tank had much lower mechanical properties. This drove up production cost on the tank. In an effort to mitigate the increased production cost and regain the mechanical properties of the earlier Al 2219 External Tank the project began researching alternative welding techniques. Because Friction Stir Welding produces stronger welds—that are easier to make—the External Tank Project Managers chose to use the process on its Super Light Weight Tank, which is made from Al-Li 2195. The Friction Stir Welding process produces a joint stronger than the fusion arc welded joint, obtained in the earlier Light Weight Tank program. A significant benefit of Friction Stir Welding is that it has significantly fewer process elements to control. In a Fusion weld, there are many process factors that must be controlled–such as purge gas, voltage and amperage, wire feed, travel speed, shield gas, arc gap. However, in Friction Stir Weld there are only three process variables to control: rotation speed, travel speed and pressure, all of which are easily controlled. The increase in joint strength combined with the reduction in process variability provides for an increased safety margin and high degree of reliability for the External Tank. How does Friction Stir Welding work? First, a dowel is rotated between 180 to 300 revolutions per minute, depending on the thickness of the material. The pin tip of the dowel is forced into the material under 5,000 to 10,000 pounds per square inch (775 to1550 pounds per square centimeter) of force. The pin continues rotating and moves forward at a rate of 3.5 to 5 inches per minute (8.89 to 12.7 centimeters per minute). As the pin rotates, friction heats the surrounding material and rapidly produces a softened "plasticized" area around the pin. As the pin travels forward, the material behind the pin is forged under pressure from the dowel and consolidates to form a bond. Unlike fusion welding, no actual melting occurs in this process and the weld is left in the same fine-grained condition as the parent metal. One of the early drawbacks to the friction stir process was the fixed pin, because it limited welding to materials with a constant thickness. The Shuttle's External Tank project developed a through-spindle retractable pin tool that can retract or expand its pin tip within the material. This allows for changes in thickness such as on the tank's longitudinal barrel. The viability of the technology was demonstrated when NASA's Marshall Center used the retractable pin tool to weld a full-scale External Tank hydrogen barrel. The External Tank project will implement Friction Stir Welding on the longitudinal barrel welds on both the liquid oxygen and hydrogen tanks. External Tank 134—scheduled to fly in January 2005—will be the first tank to incorporate the process. The Marshall Center is NASA's lead center for development of space transportation and propulsion systems, including the development of the Space Shuttle's External Tank, Solid Rocket Boosters, Reusable Solid Rocket Motors and Main Engines.

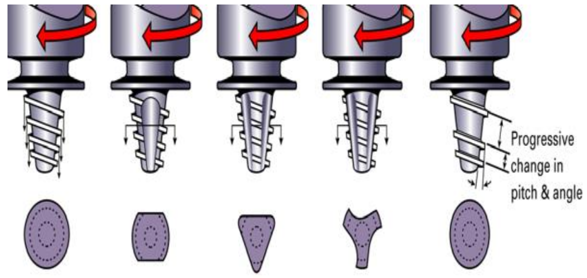


The principle of Friction Stir Welding

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 aluminium, 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 aluminium alloys.

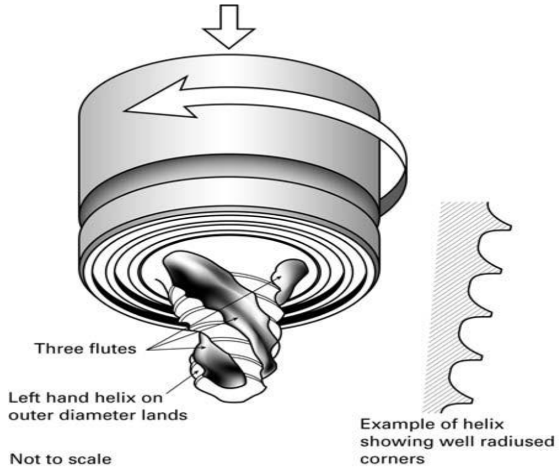
TOOL DESIGN

Tools consist of a shoulder and a probe which can be integral with theshoulder or as a separate insert possibly of a different material. The design ofthe shoulder and of the probe is very important for the quality of the weld. Theprobe of the tool generates the heat and stirs the material being welded butthe shoulder also plays an important part by providing additional frictionaltreatment as well as preventing the plasticised material from escaping fromthe weld region. The plasticised material is extruded from the leading to thetrailing side of the tool but is trapped by the shoulder which moves along theweld to produce a smooth surface finish. Clearly, different materials anddifferent thicknesses will require different profile probes and welds can beproduced from just one side or by welding half the thickness then turning overto complete the other side. Some typical Whorl™ type probes are shown inFig which can be designed to weld in excess of 60mm thick plate at higherspeeds than conventional pin type probes.

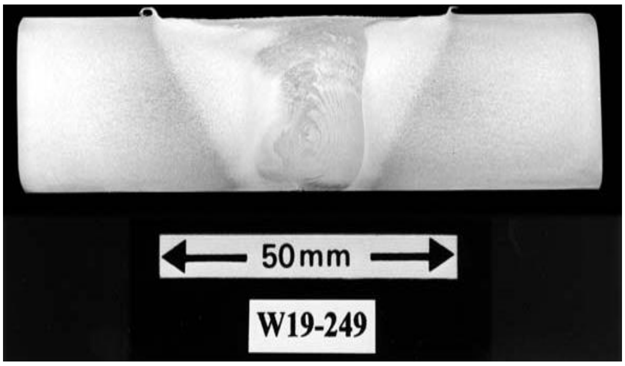


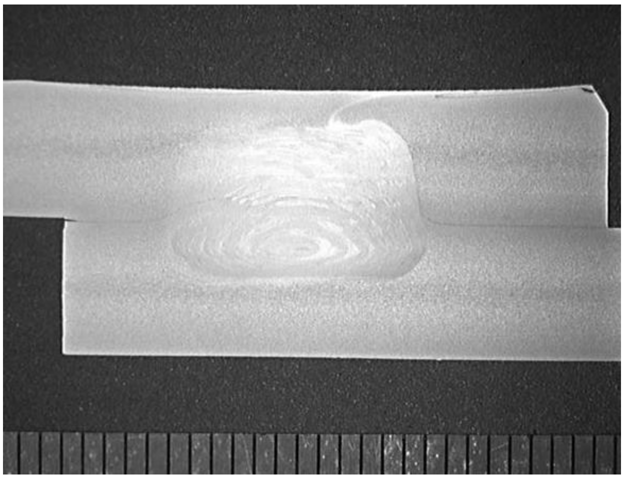
(a) Oval shape probe (b) Paddle shape probe (c) Three flat sided probe (d) Three sided re-entrant probe (d) Changing spiral form & flared probe

A variation on the Whorl™ probe is the MX-Triflute™ which canproduce a better weld than the Whorl™ tool with a narrower, more parallel side weld region.The improvement can clearly be seen in the shownfig of welds in 25mm thick6082-T6 aluminium alloy welded at 4mm/second. The Whorl™ tool, tending to produce an ‘union ring’ effect whereas the MX-Triflute™ weldis narrow and more uniform.



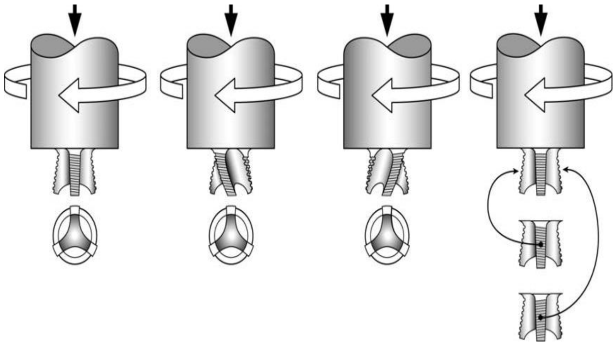
Advancing side treating Side



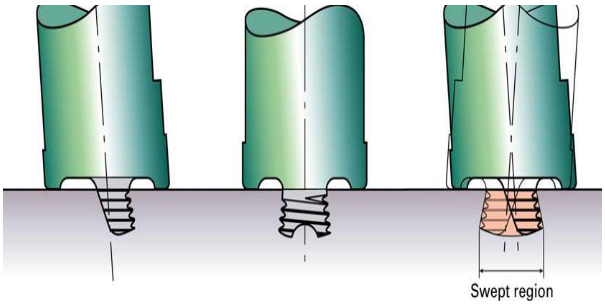


Friction stir welding is also used to carry out lap welds where the plates to be joined are overlapped and the probe run through the top sheet and into the bottom as illustrated

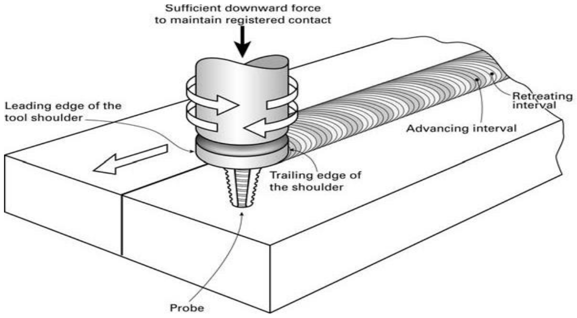
With the lap welds it is desirable to increase the width of the weld region to achieve a better bond. This is achieved by re-design of the tools as in Flared-Triflute™ as illustrated

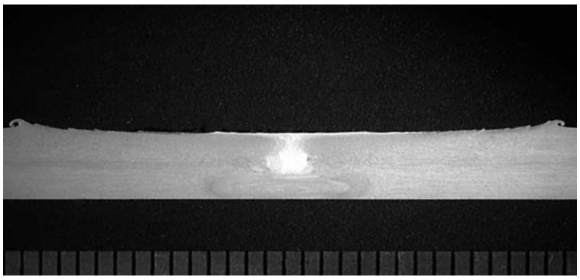


The fluted tool can have flutes neutral (a), left (b) right (c) handed as illustrated or a combination of all three at 120º intervals one neutral, one left and one right on an individual probe (d). The pitch of the ridges is also important in determining the properties of the tool. The ridges enable plasticised material to be deflected in the direction required especially to deflect oxide from the centre of the weld to the surface. To increase the spread in lap welds still further the probe was angled with respect to the tool axis in a variant of FSW known as Skew-Stir™ and illustrated in. It will be seen that the swept region is much larger than with conventional

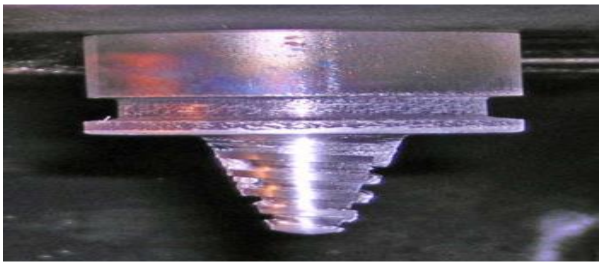


Another variation is known as Re-Stir™ which is similar to the conventional stir welding process but the tool continually reversed throughout the welding process either within one revolution or





Further variations being investigated involve a separate shoulder and probe both being rotated in the same direction but at different speeds. Clearly, the variations in tool design are infinite and combinations of shoulder diameter, shoulder profile, probe length, diameter and profile, are all important parameters in determining the speed of welding and the quality of the finished weld. Another important parameter in the determination of the suitability of a tool for a particular application is the tool material itself. Welding is carried out around 70 – 90% of the material melting point so it is important that the tool material has sufficient strength at this temperature otherwise the tool can twist and break. With conventional aluminium alloys tools made of tool steel give good results but with the harder alloys something stronger is required. Such as super alloys, oxide dispersion strengthened alloys (ODS) and refractory metals such as molybdenum alloys. However, although these materials have superior melting properties they are more difficult to fabricate especially into some of the complex shapes described above. Difficulties in fabrication lead to increased tool cost and it is often desirable to sacrifice some durability for a reasonably priced tool. In an ideal world the user requires to produce very long welds without tool wear or degradation occurring so some of the more exotic materials and designs could see increased usage.



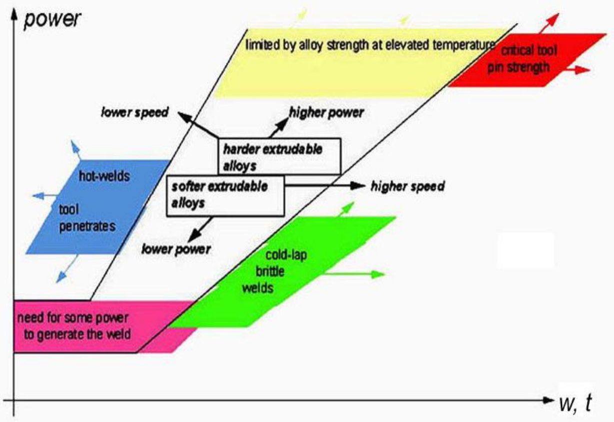
Because molybdenum has a fibrous structure with the fibres running parallel to the tool axis, the design of the tool must be simplified to avoid thin sections and sharp angles. However, the material shows promise and an excellent weld was produced with no tool wear being observed.

On removal of any FSW probe from the weld, a hole is left. There are several ways of dealing with this. It can be filled in with conventional TIG filler, the part of the weld with the hole can be cut off and discarded, or the weld can be run off into a scrap piece of material which is then discarded. Another method is to gradually remove the probe at the end of the weld but this is not recommended as a full penetration weld is not then produced in this region.

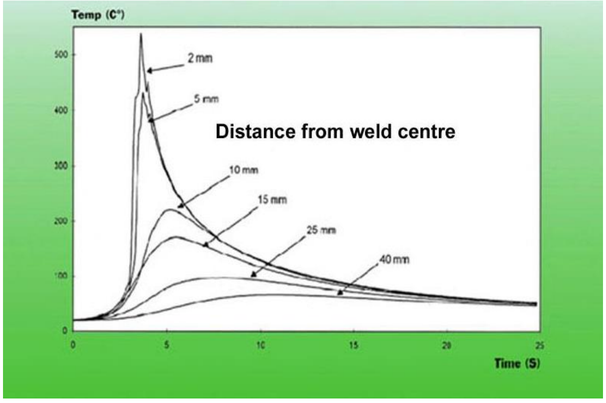
FSW process window

The figure shows a general process window which illustrates the applied FSW process power versus actual weld speed and profile/sheet thickness for softer and harder aluminium alloys. Along the y-axis the process power is a function of the friction coefficient between the steel tool and aluminium, the downward tool force (N) and the tool shoulder peripheral velocity (m/s). Along the x-axis is the selected weld speed and actual thickness of the welded component. The diagram shows that harder alloys need relative higher power, welded at relative lower speeds to generate sound welds, compared to softer alloys at the same thickness. If an alloy is welded at too low power, or at too high speed, then a brittle cold lap weld will be the result. On the other hand, if an alloy is welded by too high power at a too low speed, the material will soften too much and tool shoulder will penetrate the profile surface.

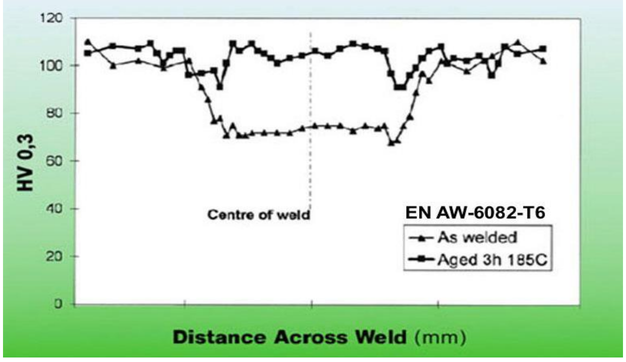
Process window shows power as f(friction coef., tool force [N], tool shoulder velocity [m/s]) *vs* weld speed, w, [mm/s] and thickness, t,[mm] for chemical composition/hot strength.



Properties of joints



Heat input Even though the temperature history of FSW welds shows that the heat input is more favorable than in case of fusion welding, there will be a heat affected zone (HAZ). Materials in age-hardened or cold worked tempers have a softer weld zone.



Post-weld heat treatment Hardness profiles for EN AW-6082-T6 (above) and T4 (below), as-welded and after post-weld heat treatment, show that the base

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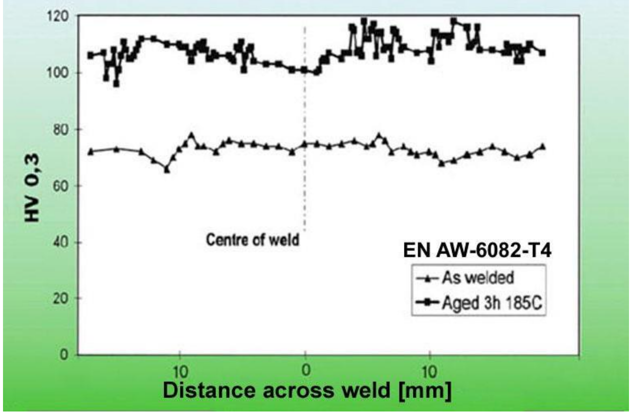
metal hardness can be almost fully restored (s. table below).

FSW involves **no use of filler** material.

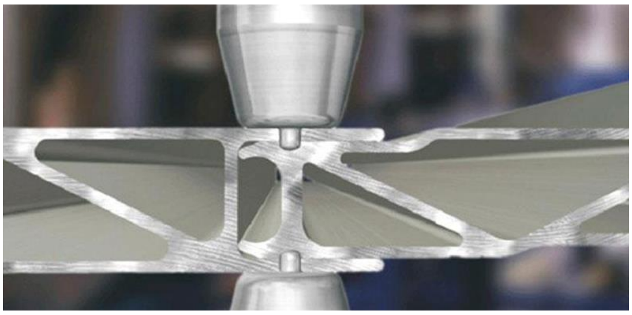


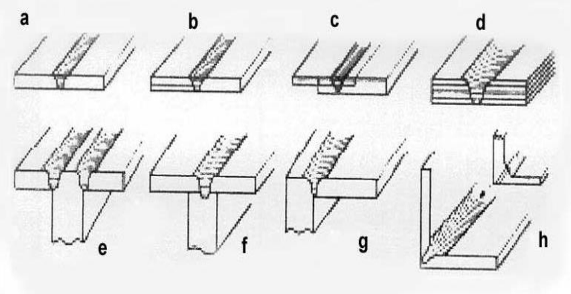
Good corrosion resistance Consequently, the base metal composition is unchanged in the joint and there is no segregation of alloying elements. Together with low residual stresses and absence of melting FSW joints have good corrosion resistance.

Joint types and tolerances

Product tolerances For extrusions +0.3, -0.1 mm thickness tolerances are specified within 20 mm from the joint line. Profile straightness tolerance is 1 mm/m. Process can tolerate max gap of 10% of thickness.

Joint types Butt welds and overlap welds are most applied. Sufficient backing must be ensured prior to welding.





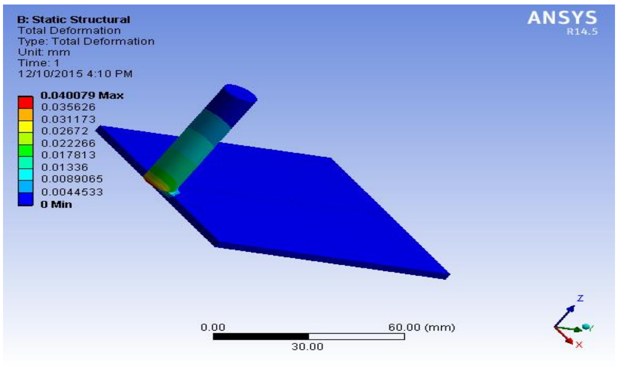
Geometries: a) square butt welds, b) combined butt/lap welds, c) single lap weld, d) multiple lap weld, e) 3 piece T-butt weld, f) 2 piece T-butt weld, g) edge butt weld, h) corner fillet weld.

Welding equipment – Standard and special FSW machines

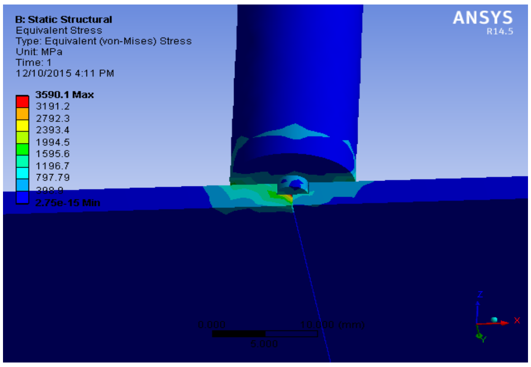
Even if Friction Stir welds of proper quality can be successfully produced in a rigid milling machine the special machine offers many advantages regarding handling, positioning, clamping and operation control equipment to assure a correct weld quality. At present there are only a few manufacturers of welding equipment specially designed for FSW on the market. FSW by robots has been reported but is still limited to small welds due to stability challenges.

SPEED 410rpm &TEMPERATURE 4200C

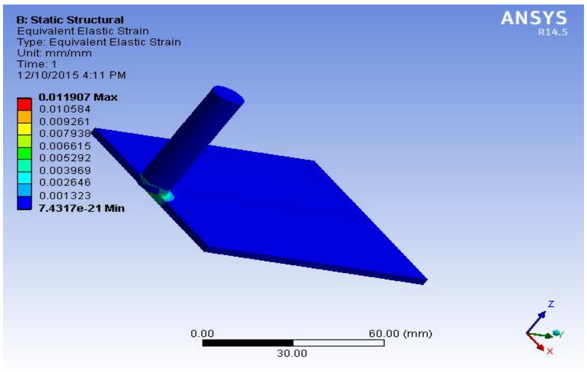
Total deformation



Stress

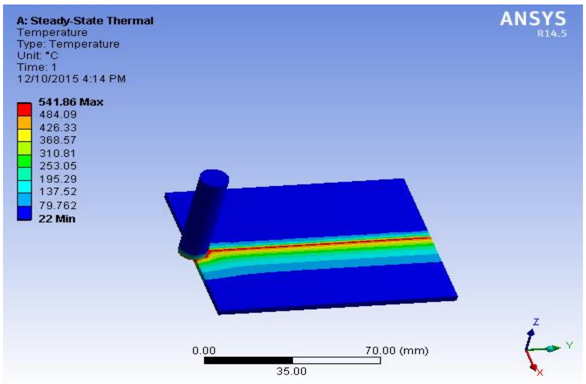


Strain

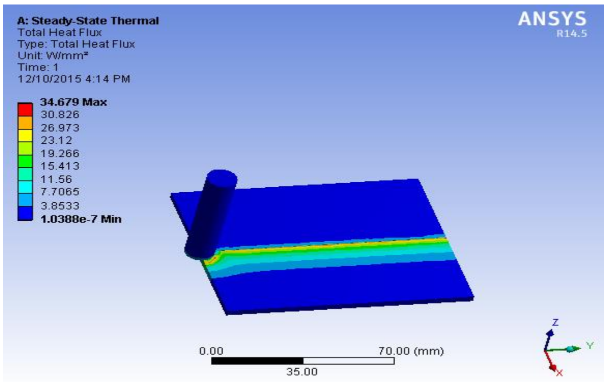


TEMPERATURE AT 5300C

Temperature

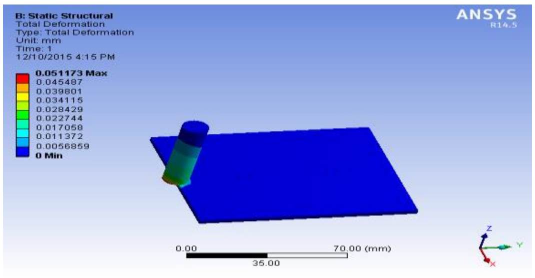


Heat flux



SPEED AT 560rpm & TEMPERATURE 5300C

Deformation



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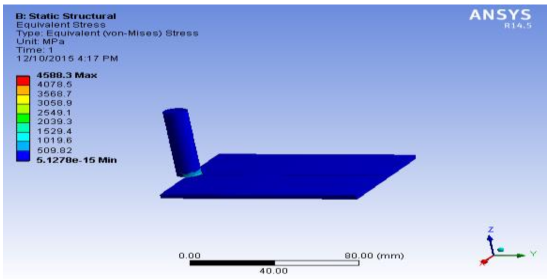

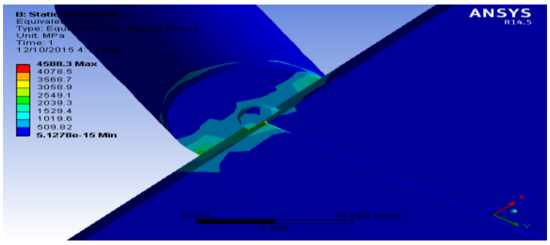

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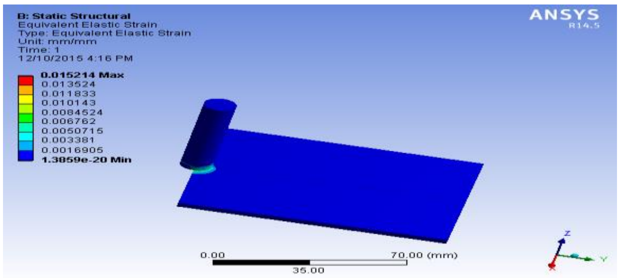
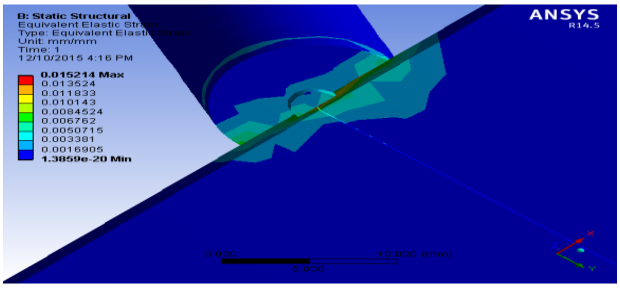
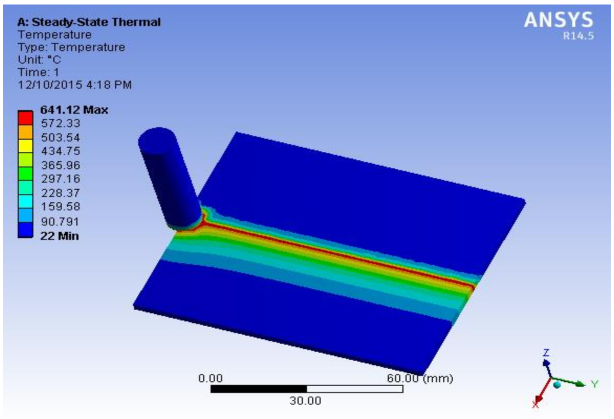




TEMPERATURE AT 6270C

Temperature



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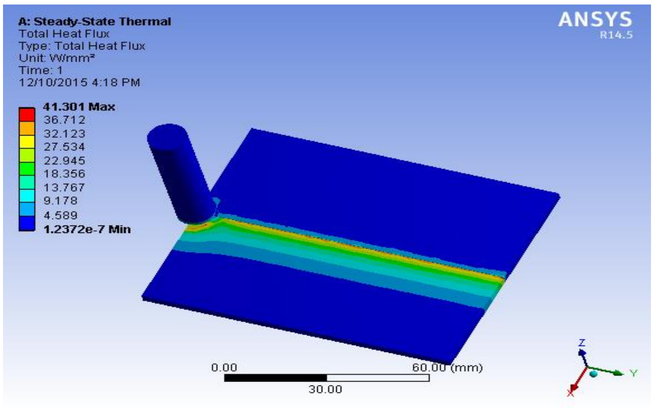
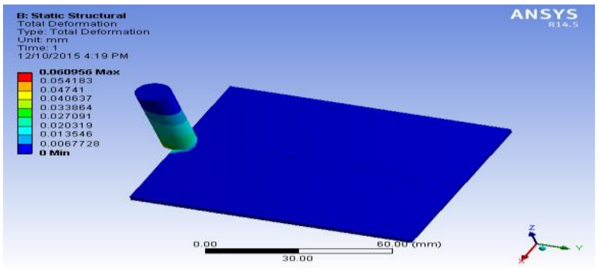
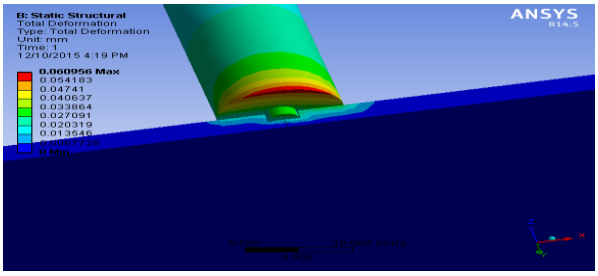
Heat flux



SPEED 750rpm& TEMPERATURE 6270C

Deformation





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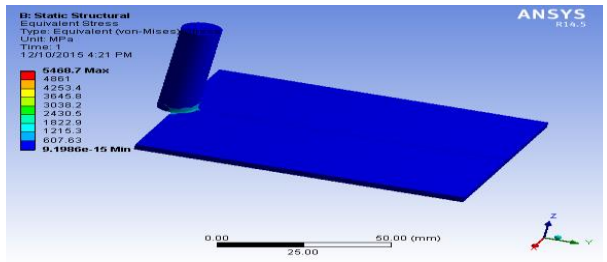

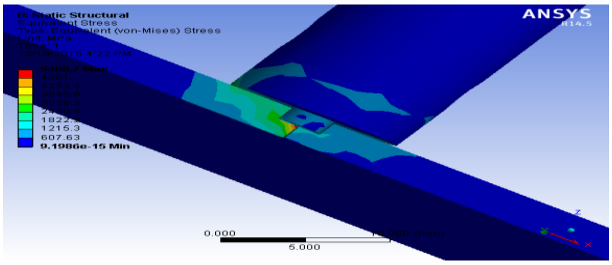

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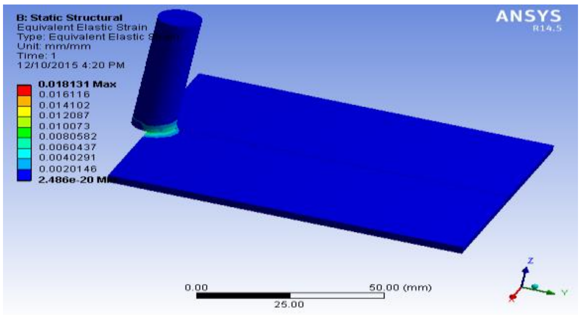
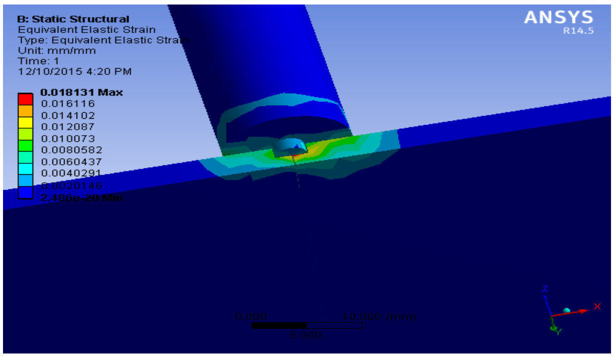
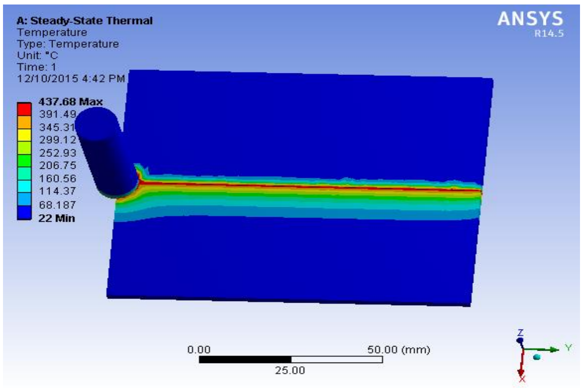


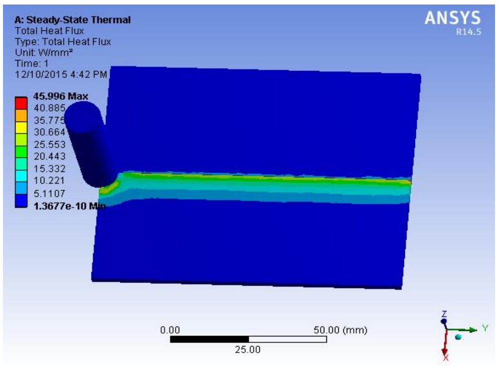


TAPER PIN PROFILE THERMAL - TEMPERATURE 4200C

Temperature

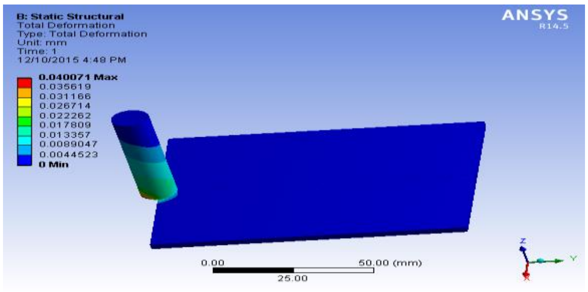


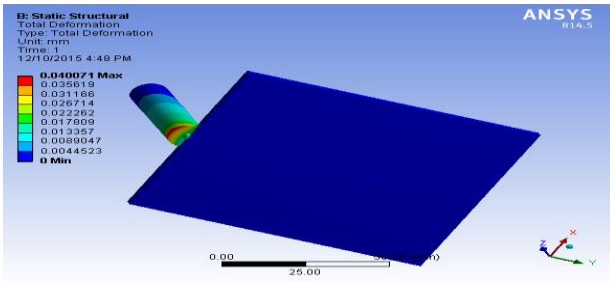
Heat flux



STRUCTURAL - SPEED AT 410rpm & TEMPERATURE 4200C

Deformation





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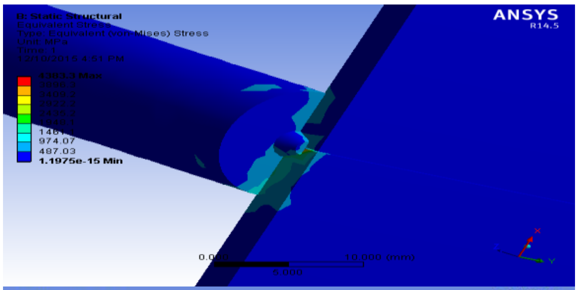

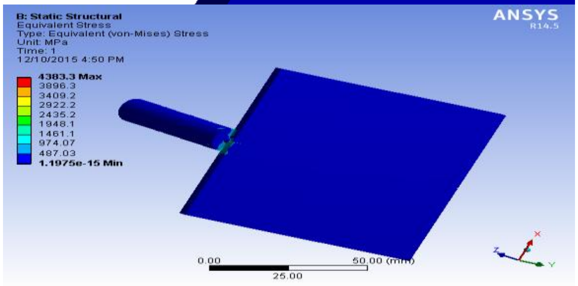

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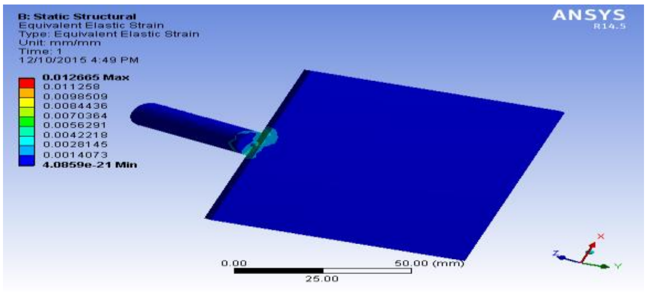
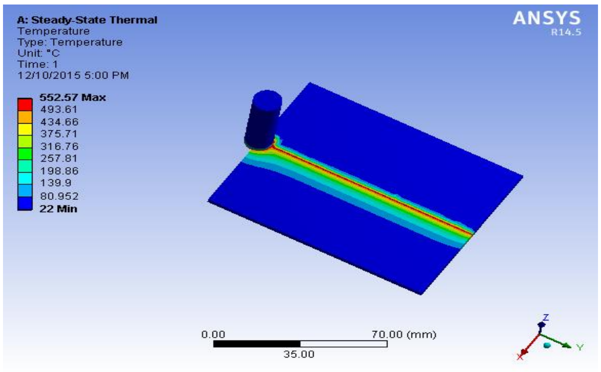
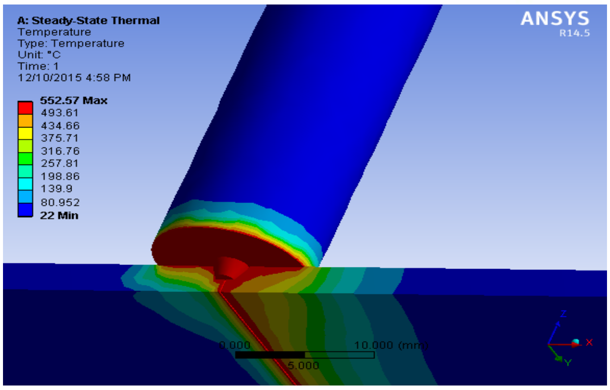


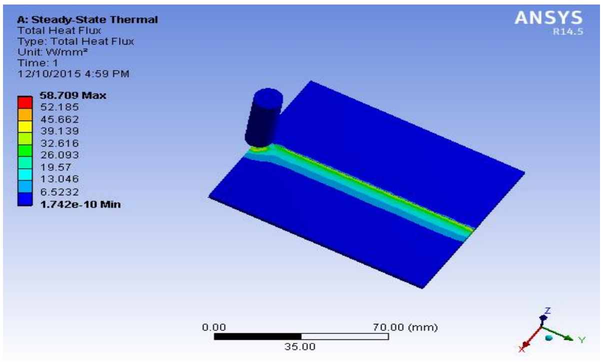
Thermal - TEMPERATURE AT 5300C

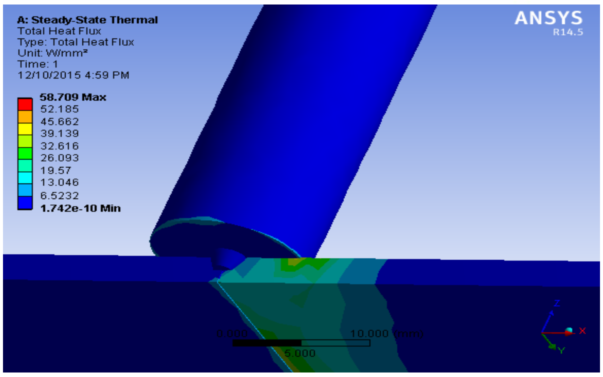
Temperature





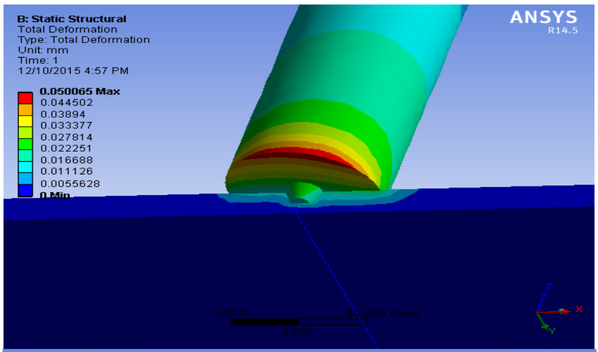
Heat flux

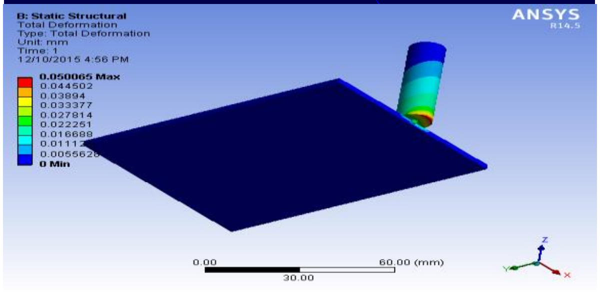




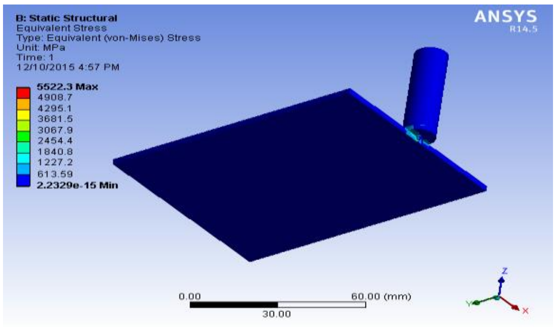
STRUCTURAL - SPEED AT 560rpm &TEMPERATURE 5300C

Deformation

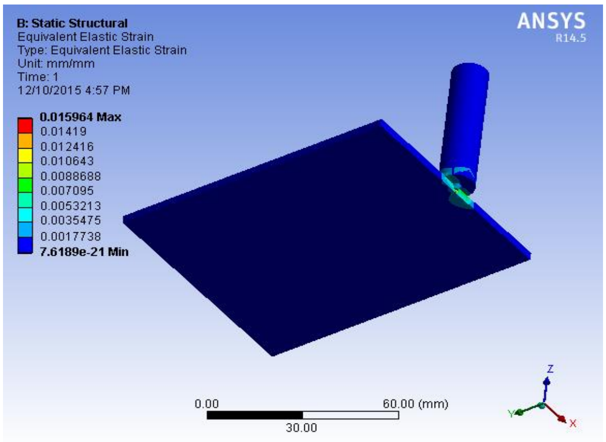




Stress

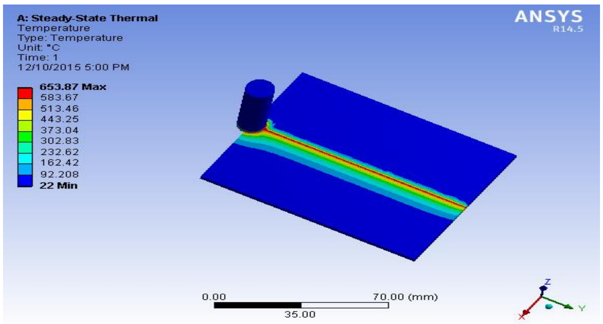


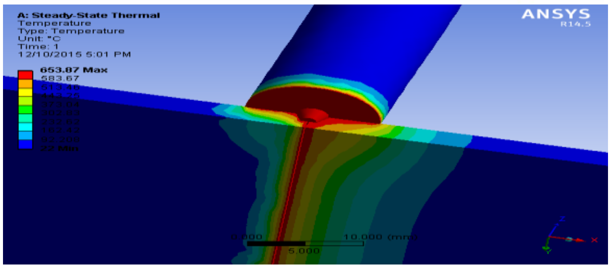
Strain



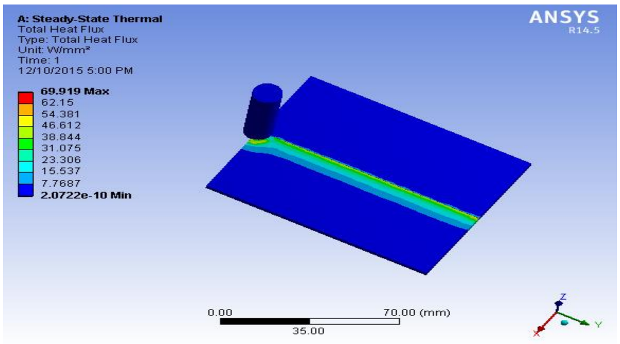
THERMAL - TEMPERATURE AT 6270C

Temperature



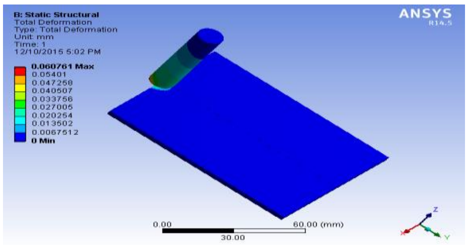


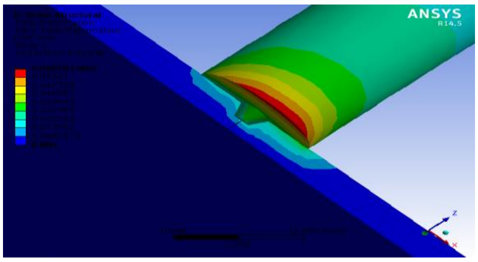
Heat flux



STRUCTURAL - SPEED AT 750rpm &TEMPERATURE 6270C

Deformation





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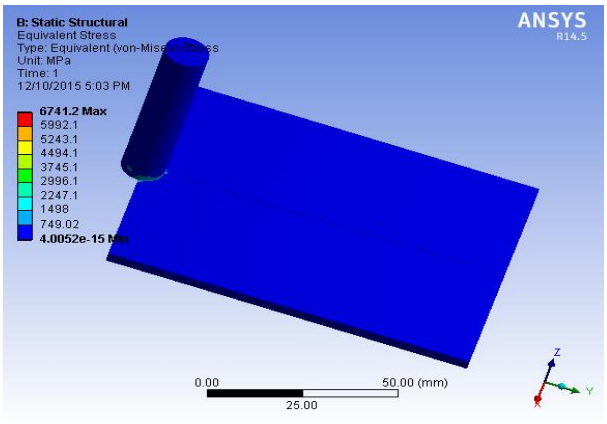
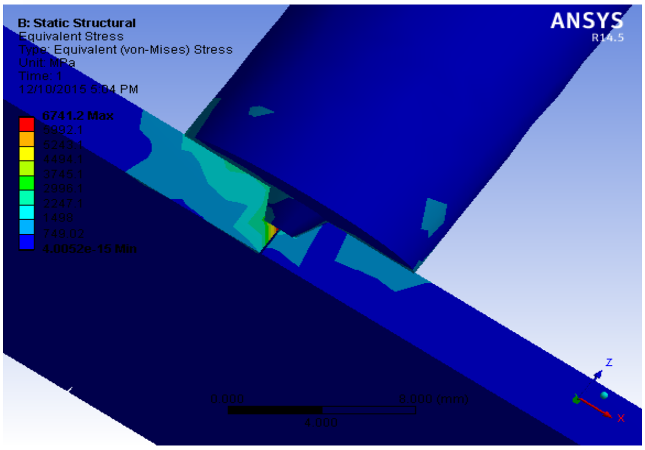
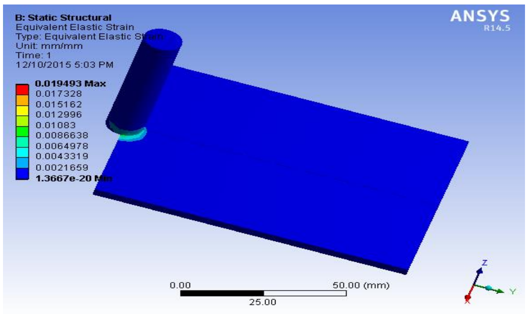
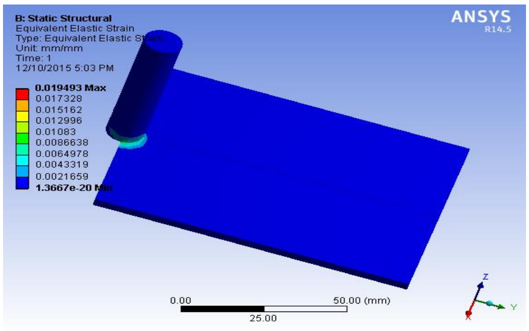
Stress





Strain





RESULTS TABLE

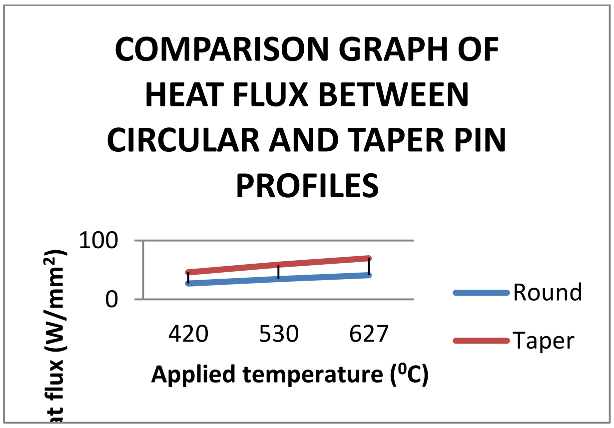
THERMAL

CIRCULAR PIN PROFILE

Temperature (ºC)	420	530	627
Nodal temperature (ºC)	429.29	541.86	641.12
Heat flux (W/mm²)	27.17	34.679	41.301

TAPER PIN PROFILE

Temperature (ºC)	420	530	627
Nodal temperature (ºC)	437.68	552.57	653.87
Heat flux (W/mm²)	45.996	58.709	69.919



STRUCTURAL

CIRCULAR PIN PROFILE

CASES	1 - Temp 420 (ºC) & Speed 410rpm	2 - Temp 530(ºC) & Speed 560rpm	3 - Temp 627(ºC) & Speed750rpm
Total deformation (mm)	0.040079	0.051173	0.060956
Stress (Mpa)	3590.1	4588.3	5468.7
Strain	0.011907	0.015214	0.018131

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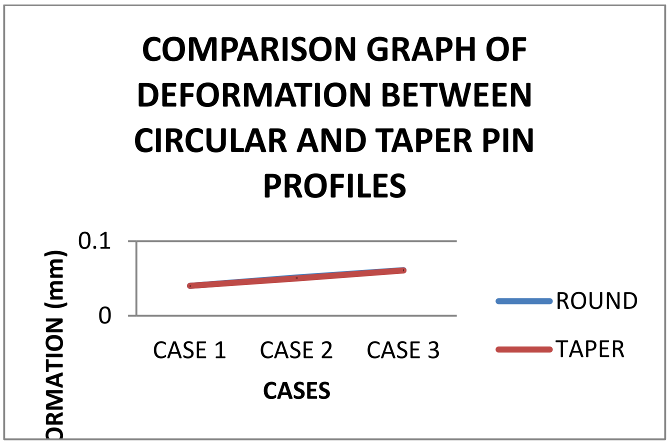
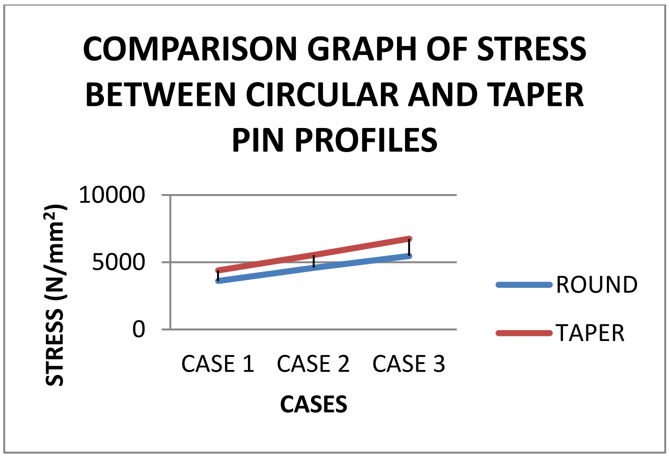
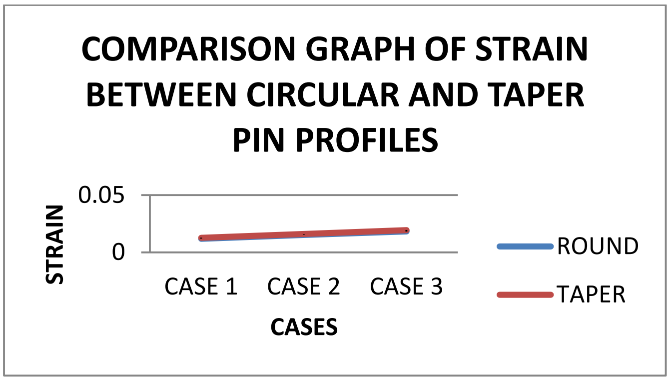
TAPER PIN PROFILE

CASES	1 - Temp 420 (°C) & Speed 410rpm	2 - Temp 530(°C) & Speed 560rpm	3 - Temp 627(°C) & Speed750rpm
Total deformation (mm)	0.040071	0.050065	0.060761
Stress (Mpa)	4383.3	5522.3	6741.2
Strain	0.012665	0.015964	0.019493







CONCLUSION

In this project 2 types of cutting tools Round and taper are designed for doing Friction Stir Welding of two dissimilar materials Aluminum alloy 5083 and Copper running at speeds of 750rpm, 560 rpm and 410rpm. The temperatures taken for thermal analysis, at 410rpm 420^{0}C, at 560rpm 530^{0}C, at 750rpm 627^{0}C respectively. Modeling is done in Pro/Engineer.

Coupled field analysis is performed on the tools Round, taper tool to verify the temperature distribution, thermal flux, gradient and stresses.

By observing the thermal results, thermal flux and thermal gradient are more for taper tool but the stresses produced are more than round tool. Temperature is also produced for required melting point of plates.So it can be concluded that using taper tool is better in terms of heat transfer rates but as per structural, round tool is better.

FUTURE SCOPE

From this thesis, it is found that using round tool is better from analysis, this can further be extended to the experimental tests to determine the hardness, tensile tests, microstructure analysis. The material used for the tool also can be changed.

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