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Thermo-mechanical analysis of friction stir welding Tool (W-alloy and Ti – alloy)

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Abstract
The Friction Stir Welding (FSW) is a newly developed among different types of welding process in which the relative motion between the tool & work-piece produces heat in the interface area, which makes two metal sheets joined by plastic diffusion utilizing the frictional heat during the process. The quality of weld produced in between workpiece is determined by the amount of heat present in weld zones (heat affected zone) during friction stir welding. Thus, the heat distribution characteristics and its magnitude in weld zones with respect to process variables such as applied force, temperature of tool & workpiece, rotational and travelling speed during welding is analyzed using thermal finite element analyses method. ANSYS 15.0 is used to model three-dimensional tool pin-shoulder and to simulate the friction stir process. The analysis has been shown in the present paper.
Keywords: *Friction stir welding, thermo-mechanical analysis, finite element analysis, process variables.*

Introduction

FRICTION Stir Welding (FSW) is a newly developed and highly effective technique which was invented by The Welding Institute in the UK in 1991. The FSW is a solid state joining process (tool-workpiece interface) that allows tool with pin& shoulder is rotated with certain rpm and to thrust (immerse) into the two parts of workpieces kept near or overlapped to each other. The fundamental of FSW is depicted in fig.1.During rotatory motion, tool is allowed to advance forward (traverses) (mm/min.) to produce friction heat and join the metal i.e. weldment area [1]. Heat generated by friction cause the material to get soften (workpiece) which easily allows joining/welding of materials. FSW is an effective welding technique because of no use of filler rods/ materials. There are two sides in the FSW:If the movement of rotating tool in the same direction of the traversing direction of weld, is known as the advancing side and the side, where tool rotation is opposite of the traversing direction, is known as the retreating side[2]. FSW has been used in a variety of applications such as automotive, aerospace, railway, ship building/marine etc.

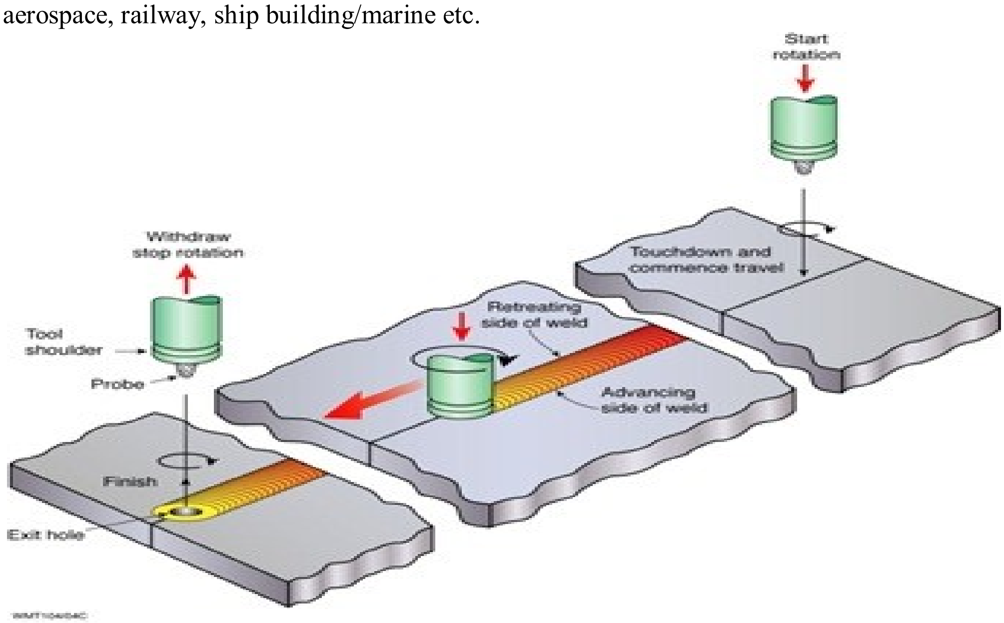


Fig. 1: Schematic diagram of Friction stir Welding

Friction stir welding (FSW) has been developed and innovated in years due to wide increased of its usage. It allows different metals including aluminum, lead, magnesium, steel, titanium, zinc, copper and metal matrix composites to be welded continuously. Many alloys, which are regarded as difficult to weld by (fusion processes) other welding process/techniques, now easily welded by Friction stir welding. A non-consumable rotating tool is available in various designs (tapered, cylindrical, triangular etc.), which is manufactured from materials with high mechanical (elastic behavior) and high temperature properties. Essentially, the probe of the tool is applied to the abutting faces of the workpieces and rotated, thereby generating frictional heat, which creates a softened plasticized region (a third-body) around the immersed probe and at the interface between the shoulder of the tool and the workpiece [1]. The shoulder provides additional frictional treatment to the workpiece, as well as preventing plasticized material from being expelled from the weld. The strength of the metal at the interface between the rotating tool and the workpiece falls to below the applied shear stress as the temperature rises, so that plasticized material is extruded from the leading side to the trailing side of the tool [2]. The tool is then steadily moved along the joint line giving a continuous weld. The process has already made a significant impact on the aluminum-producing [13] and user industries worldwide and FSW is now a practical technique for welding aluminum rolled and extruded products, of thickness ranging from 0.5 to 75mm. The presented paper describes recent developments in FSW tool design, as this is the key to the successful application of the process.

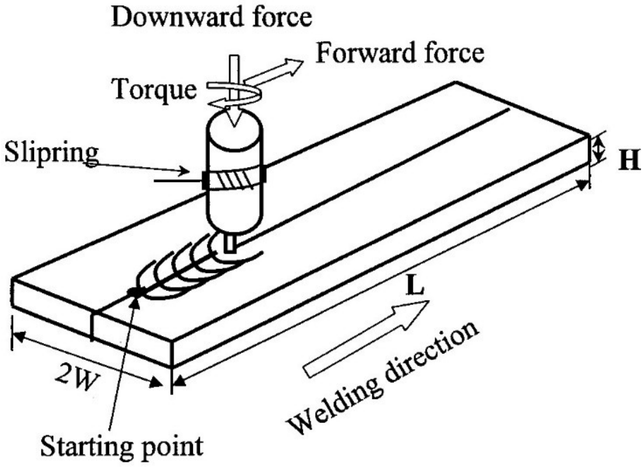


Fig.2: Force representation in FSW

Tool design

The design of the tool is a crucial factor, in deciding strength of joint and quality of weld. Therefore tool material be sufficiently strong, tough, and hard wearing at the welding temperature. Further it should have a good oxidation resistance and a low thermal conductivity to minimize heat loss .Hot-worked tool steel such as AISI H13, Titanium alloy, Tungsten alloy, Magnesium alloy etc. [12]. Has proven perfectly acceptable for welding aluminum alloys, copper alloys etc. Within thickness ranges of 0.5 – 50 mm ,but more advanced tool materials are necessary for more demanding applications such as highly abrasive composites or higher melting point materials such as steel or titanium[12][1]. Improvements in tool design have been shown to cause substantial improvements in productivity and quality. The tools can have flutes that allows symmetrical flow of molten solid during tool rotation [11]. The Titanium alloy tool allows wide range of application of welding from aluminum sheets to micro composites structure welding due its high temperature resistance and high mechanical strength. There are three types of FSW tools, i.e. fixed, adjustable and self-reacting.

Shoulder shape of Tool -shoulders of FSW tool are designed to frictionally heat the surface regions of the workpiece, produce the downward thrust action which is necessary for welding consolidation and constrain the heated metal beneath the bottom shoulder[11]. The shoulder surface usually has a cylindrical shape, a conical surface, convex, flat shape etc. According to usage. During tool thrusting, the material displaced by the probe is fed into tool shoulder cavity [12].

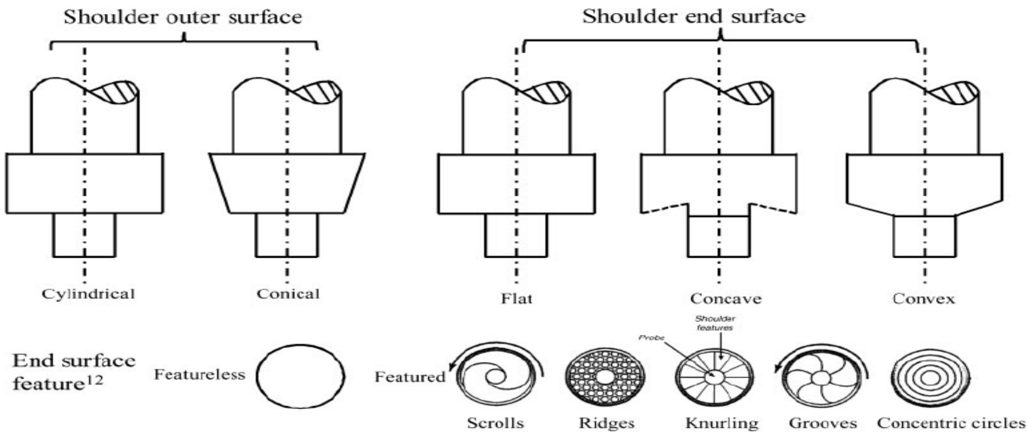


Fig.3 Probe types for various material thicknesses and joint types

FORMULATION OF BOUNDARY CONDITION:

Temperature distribution-

A non-linear three model is presented to analyze thermal distribution and mechanical strain in tool during its operation in Friction stir welding. The heat input of tool and weldment is a function of the shoulder radius to the third power but depends only linearly on the applied impressing force and the rotational speed. Therefore, the energy input in FSW is strongly dependent on the shoulder size. Furthermore, the Z- axis forge force is also a function of the shoulder radius.

$$Q = \frac{4}{3}\pi^2 * u * P * w * R^3$$

Where Q is the net power (Watt), u is the effective friction coefficient between the workpiece and the tool, P is the pressure (MPa), w is the rotation speed (rpm), and R is shoulder radius (mm). Friction on the shoulder butt surface occurs due to axial force from the rotated tool against workpiece surface in transverse plane. Contrastingly, friction on the pins side surface emerges as a result of travel force from the rotated tool against internal workpiece in coronal plane [14]. On the pin tip surface, friction comes up from the rotating tool against internal workpiece in transvers plane. The tools are designed intentionally by using simple cylindrical flat shoulder surface and tapered pin surface. Theoretically heat input relies on rotational speed and transverse speed of tool and both are the main process variables in friction stir process. The initial temperature of the tool before processing welding is assumed equal to the ambient temperature (30˚C). Convective heat (stagnant air) coefficient of 22 W/m˚C is applied at the top and side surfaces of the tool (Ti-alloy and W-alloy tool). The tool tip (Pin) experienced highest range of temperature while impressing welding to workpiece [19]. The temperature generated theoretically across tool pin and shoulder is range from 212^{0}C-372^{0}C during welding of Al-7020 [18].The cylindrical and tapered probe present in tool pin allows molten solid to symmetrically flow in all direction and produces smooth welding. Thus, pin experienced highest temperature due to constant contact with welding surface (heat affected zones) and generate heat flux density region.

HEAT INPUT-

The initial temperature of the Ti-alloy tool and W-alloy tool is assumed equal to the ambient temperature (30˚C). Convection's coefficient of 22W/m˚C (stagnant air) is applied at the top and side surfaces of the workpiece. Generally the significant temperatures of workpiece's material in weld zones during friction stir process in Aluminum based alloys (7020) [T6][18][13]can be reached around 305˚C - 404˚C whereby the material undergoes solid-state until melting (M.P- 605^{0}C). The highest temperature is observed in the area near to the pin side's surface[19], where the maximum heat flux exists. Temperature will continuously increase together with increasing the rotational speed, decreasing the feed rate, or precisely the pseudo-heat index, and an increasing in the plunge depth [5] [6].

The temperature calculation is based on Fourier's equation:

$$\rho CdT\ dt = div(k).grad(T) + qln\Omega$$

Where q is the amount of power generated by friction between the tool and the top of the workpiece via plasticdeformation work of the weld zone, T is the temperature (K), k is the conductivity, ρ is the material density, and c is the heat capacity. The significant amount of heat source in FSW is generally due to the friction between the rotating tool and the welded plates, and the processof cold workwelding in the plastic deformation of material in the vicinity of the tool pin and shoulder. Significant amount of load 4.5KN is constantly applied to workpiece through tool during friction stir welding. This pressure force per unit area at different minute section allows different part of material to move in plastic deformation, so that to they get properly diffused and weld together. Therefore thermo-mechanical method developed to know load variation in tool during temperature variation in it [6]. Applying reliable thermocouple measurements during welding of Aluminum alloy 7020 (workpiece) within the welding process foster the need for computer simulation models of tool, to analyze the temperatures variation and strain distribution in the tool profile[6][7]. In order to calculate the heat generation in tool, produced during the temperature of 305 ℃ and 404 ℃, the physical properties and thermal properties of AA7020 workpiece and (Titanium & W- alloy tool) material need to be considered. Generally, it is a cold welding process performed at a temperature lower than its melting point. . The weldment is produced due to severe plastic deformation of the material around the rotating tool. FSW of Tool and Aluminum workpiece can be successfully performed by prescribing a welding speed of 16-40mm/min. and rotational velocity in range of 500-1100 rpm of tool [18].

Elemental component of Titanium Alloy tool-

COMPONENTS	WEIGHT
Aluminum	6
Iron	0.25
Oxygen	0.20
Titanium	89.12
Vanadium	4

Elemental component of W- Alloy tool-

COMPONENTS	WEIGHT
Tungsten	95
Iron	0.7
Nickel	3.0
Copper	1.3

- **Process Parameter**

The quality of welding (butt joint, lap joint etc.) is purely depends upon the rotational speed, axial load and traverse speed of the tool over the workpiece [18].

The theoretical value opted for performance of tool are-

PROCESS	
Tool	**710**

Axial Load	4.5KN

Tool Geometry Design and Parameters

For the simulation, a 3-D model of tool designed in CATIA V5R17 and Ansys software was used for meshing. All the necessary boundary conditions were applied in Ansys thermal analysis. In the symmetrical model, the computation was made in less time as the total number of mesh decreased compared to the full model. Whenever possible, Ansys suggests applying symmetry. Tetrahedron meshing has been used to avoid complication and to have better relevance of nodes and sets of triangular element. Tools used for Al-7020[20][12][13] has been described in figure and similar model has been prepared to check Titanium tool strength during welding process.

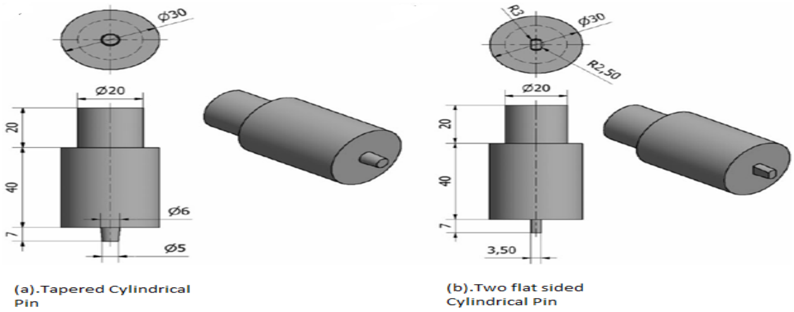


Fig. (a) Tapered Cylindrical Pin (b) Two flat sided cylindrical pin
Tool geometry and design used for welding AA7020-T6

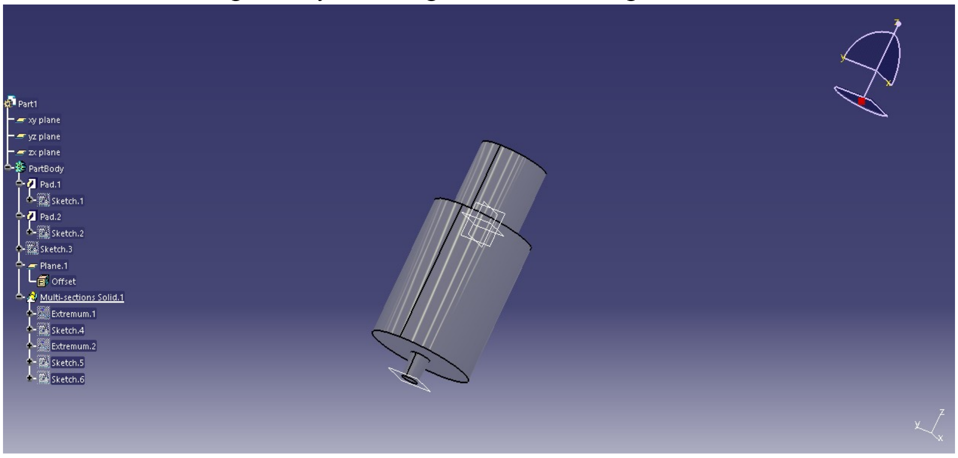


Fig. Tapered cylindrical pin(TCP)

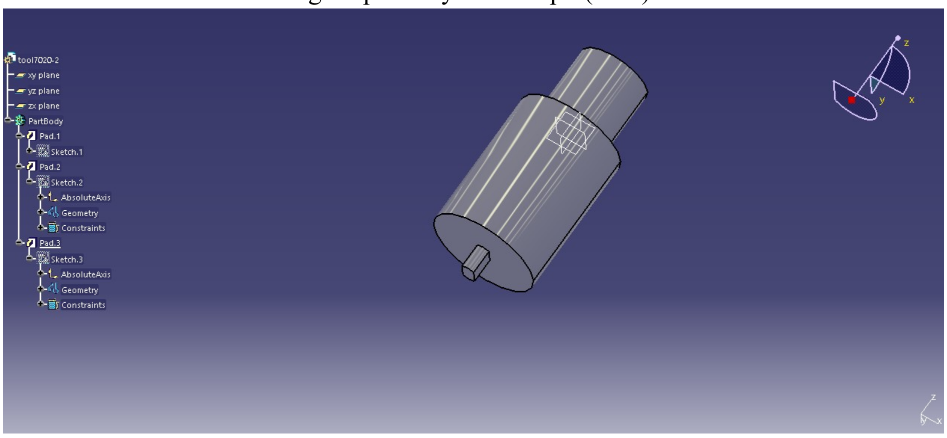


Fig. Two flat sides cylindrical pin (TFSCP)

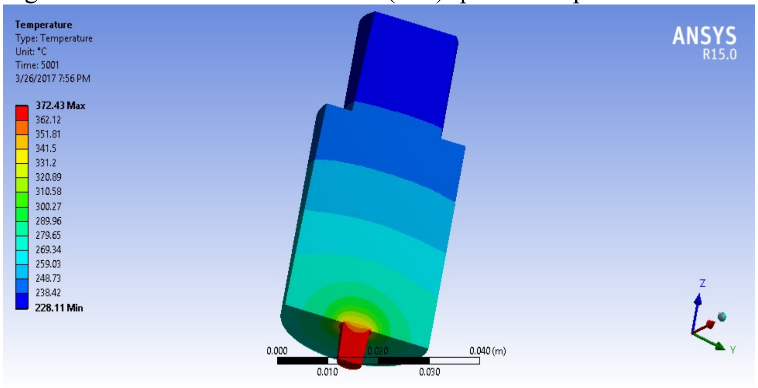
- **SIMULATION PROCEDURE**

CATIA V5 R17 Software is used to model the tool the whole process, a non-linear FE model (using ANSYS 15.0) was developed. A combination of Tetrahedron elements is used for tool. The mesh method that was adopted to simulate and solve the heat source model problem. An advanced meshing was used to mesh the whole system. The main aim is to develop a fine mesh near the tool curve surface in order to gain better accuracy in temperature profile.

STEADY STATE thermos-mechanical SIMULATION MODEL OF Titanium -Alloy & W- Alloy tool-

- **TEMPERATURE Gradient IN tool :**

A steady state temperature distribution is used to identify UNIFORM thermal distribution across tool in order to develop refinement .During rotation tool interface with specimenAluminum Alloy 7020-T6 regiondeveloped(theoretical) temperature range between 305^{0}C to 370^{0}C .The main heatsource is generated through friction, and the temperature pro file is along the radial direction[8]. Consequently, when the temperature at the friction interface becomes sufficiently high, the material completely transformsinto plastic, the stress field has likely become uniformed, and friction heat increases rapidly at the outer areas, such that the temperature profile is along the radial direction represents high heat flux generation around tool[9][10]. In this work we gave rotational force to the toolat (710) rpm with a pressure force of 4.5KN.



Fig, Temperature profile of Tapered cylindrical pin (Ti-alloy) tool

Significant amount of load 10KN is constantly applied to workpiece through tool during friction stir welding. This pressure force allows material to move in plastic deformation, so that to they get properly diffused and weld together. A **thermo-mechanical** (structural analysis) method is developed to know load variation in tool during temperature variation in it.

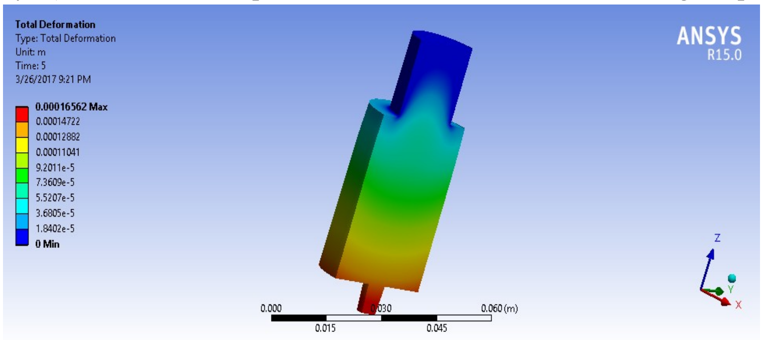


Fig.Thermo-mechanical deformation on Tapered cylindrical pin(Ti-alloy tool)

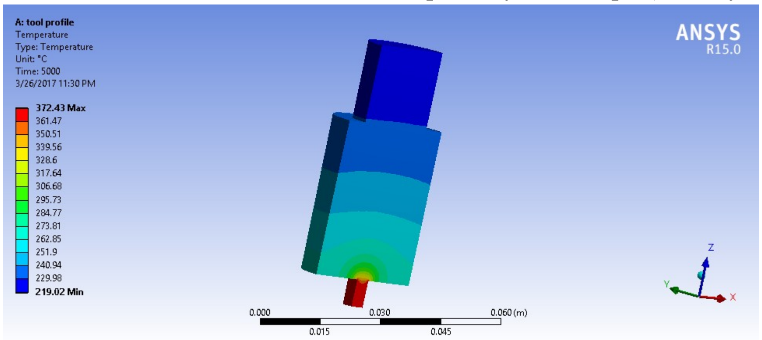


Fig. Temperature profile of two flat side cylindrical pin (Ti-alloy tool)

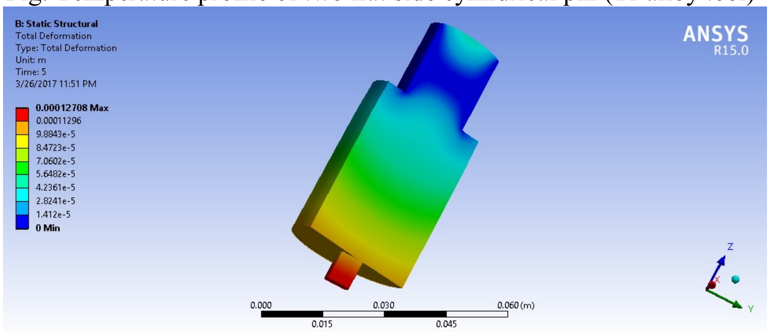


Fig.Thermo-mechanical Deformation on two flat side cylindrical pin (Ti-alloy)

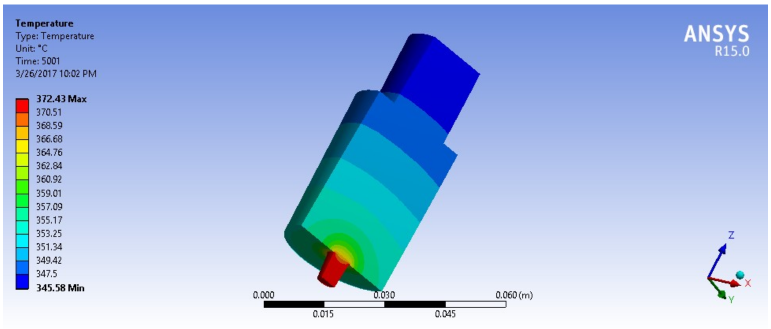


Fig. Temperature profile of Tapered cylindrical pin (W-alloy) tool

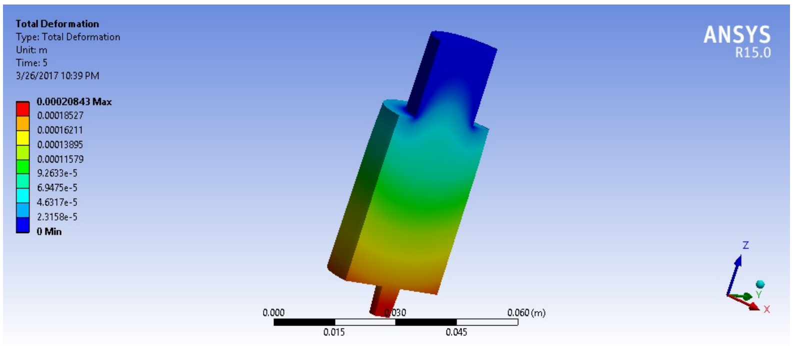


Fig.Thermo-mechanical deformation on Tapered cylindrical pin(W-alloy tool)

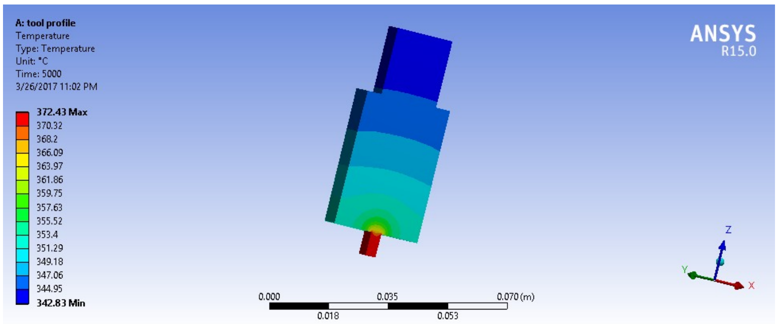


Fig. Temperature profile of two flat side cylindrical pin (W-alloy tool)

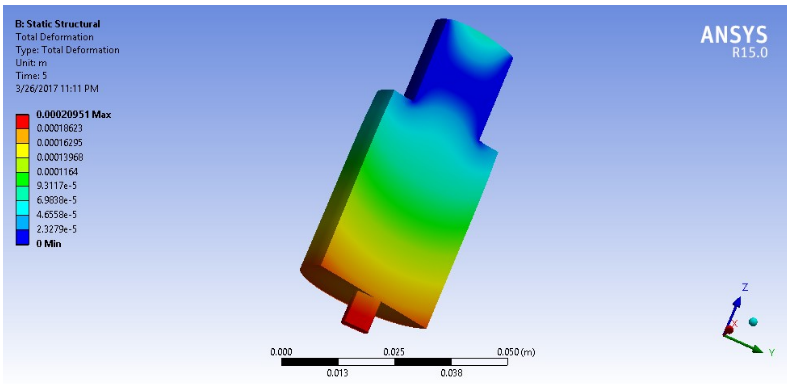


Fig. Thermo-mechanical Deformation on two flat side cylindrical pin (W-alloy)

Conclusion

In present paper, the thermal-mechanical model of tool with process parameters for given rotational speed and axial load in FSW is carried out on Ansys using FEM. Temperature variation on tool occurs due to heat affected zone during welding of Al-7020.The peak temperature in FSW of Al-7020 occurs in advancing side compared to retreating side. The steady state thermal analysis of Ti alloy and W-tool alloy tool allows us to know heat affected zone of tool material and high temperature tolerance capability of different section of tool. Further study such as observation through experimental works as well as comparing the results obtained via different numerical simulation tools are required to validate the results.

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