MODELING AND OPTIMIZATION OF FRICTION STIR WELDING EQUIPMENT FOR STRENGTH AND SURFACE FINISH IMPROVEMENT

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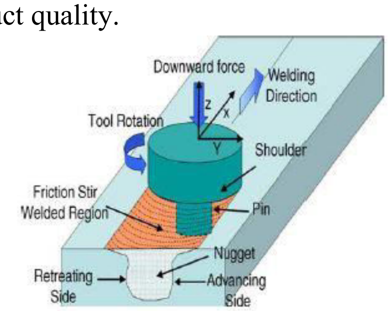
ABSTRACT
Friction Stir Welding (FSW) is an advanced solid-state joining technique widely used in aerospace, automotive, and manufacturing industries due to its ability to produce high-strength, defect-free joints. This study focuses on the modeling and optimization of FSW equipment parameters to enhance both the mechanical strength and surface finish of welded joints. Key process parameters such as tool rotational speed, traverse speed, axial force, and tool geometry are analyzed using design of experiments (DOE) and response surface methodology (RSM). A mathematical model is developed to predict the effects of these parameters on tensile strength and surface roughness. Optimization techniques are then applied to determine the optimal combination of parameters that maximize joint strength while minimizing surface irregularities. Experimental validation confirms that the optimized equipment settings significantly improve weld quality, demonstrating the potential for enhanced performance and durability in industrial applications.

I INTRODUCTION

Friction Stir Welding (FSW) has revolutionized the field of joining technology by enabling the welding of materials that are difficult to join using traditional fusion welding methods. Its solid-state nature leads to lower residual stresses, minimal distortion, and superior mechanical properties. However, the quality of FSW joints heavily depends on the precise control of equipment parameters such as tool rotation speed, traverse speed, axial force, and tool design. Optimizing these parameters is crucial for improving the mechanical strength and surface finish of the welds, which directly influence the structural integrity and service life of welded components. Various experimental and computational approaches have been employed to understand the relationship between process parameters and weld quality, but challenges remain in achieving a balance between high strength and smooth surface finish.

This study aims to develop a comprehensive modeling framework that predicts weld performance based on key equipment parameters and applies optimization algorithms to identify the best parameter set. By doing so, it seeks to enhance the practical application of FSW in critical industries, improving both efficiency and product quality.



Friction stir welding schematic diagram

Micro structural features

A highly distinctive microstructure is produced by the FSW process's solid-state nature, unusual tool, and asymmetric nature. Zones can be used to separate the microstructure:

1. A closely deformed area of fabric called the stir area, also referred to as the nugget or dynamically recrystallised zone, is kind of in which the pin is placed during welding. The stir quarter's grains are kind of equiaxed and frequently an order of importance smaller than the parent fabric's

grains. An "onion-ring" structure, the common occurrence of more than one concentric earrings, is a special feature of the stir zone. Although versions in particle number density, grain length, and texture have all been counseled, the perfect foundation of these rings has no longer been decided.

2. The cloth this is deposited on the advancing side of the weld is dragged with the aid of the shoulder from the chickening out side of the weld across the tool's rear and into the waft arm sector at the higher floor of the weld.
3. The stir area is flanked by using the thermo-automatically affected quarter (TMAZ). Welding has a smaller effect at the microstructure on this region because of decrease pressure and temperature. The microstructure is certainly that of the determine cloth, albeit considerably deformed and turned around, in contrast to the stir area.
4. The heat-affected sector (HAZ) is not unusual to all welding techniques. Although the term "TMAZ" technically refers back to the whole deformed vicinity, it's miles often used to describe any location that isn't already included by means of the phrases "stir zone" and "flow arm." This area undergoes a thermal cycle, as indicated by using its name, but is not deformed at some point of welding. Although the temperatures are decrease than the ones within the TMAZ, if the microstructure is thermally unstable, they'll still have a vast impact. In reality, this region typically well-knownshows the weakest mechanical houses in age-hardened aluminum alloys.

II. LITERATURE REVIEWS

Kumaran et al.(2011) In this research numerous advancements have been occurring in the field of materials processing. Friction welding is an important solid-state joining technique. In this research project, friction welding of tube-to-tube plate using an external tool (FWTPET) has been performed, and the process parameters have been prioritized using Taguchi's L27 orthogonal array. Genetic algorithm (GA) is used to optimize the welding process parameters. The practical significance of applying GA to FWTPET process has been validated by means of computing the deviation between predicted and experimentally obtained welding process parameters.

Elangovan et al.(2012) The researchers in this paper focuses on the development of an effective methodology to determine the optimum welding conditions that maximize the strength of joints produced by ultrasonic welding using response surface methodology (RSM) coupled with genetic algorithm (GA). RSM is utilized to create an efficient analytical model for welding strength in terms of welding parameters namely pressure, weld time, and amplitude. Experiments were conducted as per central composite design of experiments for spot and seam welding of 0.3- and 0.4- mm-thick Al specimens. An effective second-order response surface model is developed utilizing experimental measurements. Response surface model is further interfaced with GA to optimize the welding conditions for desired weld strength. Optimum welding conditions produced from GA areverified with experimental results and are found to be in good agreement.

Mariano et al. (2012) presents a literature review on friction stir welding (FSW) modelling with a special focus on the heat generation due to the contact conditions between the FSW tool and the work piece. The physical process is described and the main process parameters that are relevant to its modelling are highlighted. The contact conditions (sliding/sticking) are presented as well as an analytical model that allows estimating the associated heat generation. The modelling of the FSW process requires the knowledge of the heat loss mechanisms, which are discussed mainly considering the more commonly adopted formulations.

Ni (2014) observed that the Thin sheets of aluminium alloy 6061-T6 and one type of Advanced high strength steel, transformation induced plasticity (TRIP) steel have been successfully butt joined using friction stir welding (FSW) technique. The maximum ultimate tensile strength can reach 85% of the base aluminium alloy. Inter-metallic compound (IMC) layer of FeAl or Fe3Al with thickness of less than 1 lm was formed at the Al–Fe interface in the advancing side, which can actually contribute to the joint strength.

Simoes a, (2013) their work describes the thermomechanical conditions during Friction Stir Welding (FSW) of metals have already been subject of extensive analysis and thoroughly discussed in literature, in which concerns the FSW of polymers, the information regarding this subject is still very scarce. In this work, an analysis of the material flow and thermo-mechanical phenomena taking place during FSW of polymers is performed. The analysis is based on a literature review and on the examination of friction stir welds, produced under varied FSW conditions, on polymethyl methacrylate (PMMA).

III SOLID WORKS

SOLID WORKS is a group of packages that may be used to design, analyze, and convey genuinely any sort of product.

SOLID WORKS is a parametric, characteristic-based totally stable modeling gadget. By "feature based," we imply that in preference to specifying low-stage geometry like traces, arcs, and circles, you may define features like pads, ribs, slots, holes, and rounds to create components and assemblies. Features are targeted by placing values and attributes of factors like reference planes or surfaces, sample parameters, form, and dimensions, and others.

The time period "parametric" refers to an assembly or component whose bodily form is determined by means of the values assigned to its attributes (normally its dimensions). Any time, Parametric can define or change a characteristic's dimensions or other attributes.

For instance, in case your layout goal is to middle a hole on a block, you could use a numerical formula to attach the hole's dimensional place to the block's dimensions; The function of the centred hollow might be automatically calculated if the block's dimensions change.

The term "stable modeling" refers back to the capability of the pc version used to create it to incorporate all the facts that might be present on a genuine stable item. The fact that a pc version cannot be ambiguous or bodily non-realizable is the stable modeling's best gain.

There are six core SOLID WORKS concepts. Those are:

- Solid Modelling
- Feature Based
- Parametric
- Parent / Child Relationships
- Associative
- Model Centric

IV ANSYS

An all-cause suite of software for finite element analysis (FEA) is ANSYS. A numerical approach referred to as Finite Element Analysis is used to interrupt down a complicated system into very small pieces called factors that may be any length specified by using the consumer. Equations that manipulate these elements' behavior are positioned into movement and solved through the software program; developing a complete explanation of the machine's basic operation. The consequences can then be provided graphically or tabulated. Typically, this kind of analysis is used to design and improve a device that is too complicated to manually analyze. Due to their geometry, scale, or governing equations, systems that might fall into this class are too complicated.

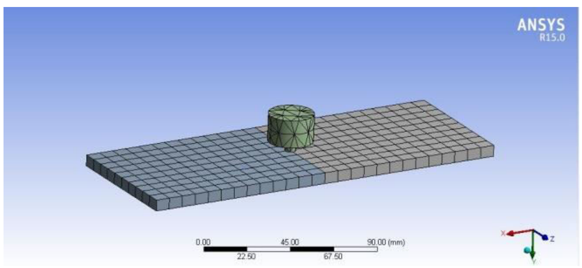
In many faculties' Mechanical Engineering departments, ANSYS is the standard FEA coaching tool. In addition, Civil and Electrical

Engineering, Physics, and Chemistry departments use ANSYS.

The virtual performance of products or approaches can be investigated at a low fee using ANSYS. Virtual prototyping is the call given to this approach of product development.

Users can iterate on a diffusion of situations the use of virtual prototyping techniques to enhance the product long earlier than manufacturing starts. Risk and the fee of useless designs can each be reduced due to this. Users may also be able to see how a layout affects the product's electromagnetic, thermal, mechanical, and other conduct way to ANSYS's multifaceted nature.

V MODELS

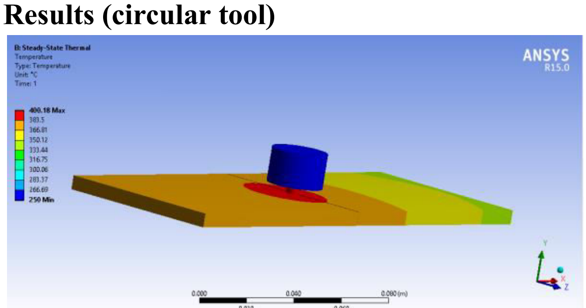


Model in Ansys

After finishing touch of meshing now we ought to practice boundary situations according to our requirement. Here we our plates will be restoration in 4 instructions to do this right here we must select constant supports to all four facets. And our device rotate with positive speed so right here we must observe inertial load situations and that inertial conditions is rotational pace with 1000 RPM. And observe pressure on device 2500N.

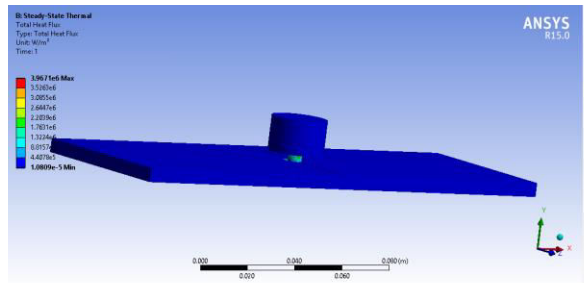
VI RESULTS AND ANALYSIS

Results (circular tool)



Total temperature for circular tool

The above figure shows the results of circular tool temperature distribution for above applied boundary conditions. And here we have maximum temperature value is 400.18*c which is shown in red colour and minimum value is 250*c which is shown in blue colour.

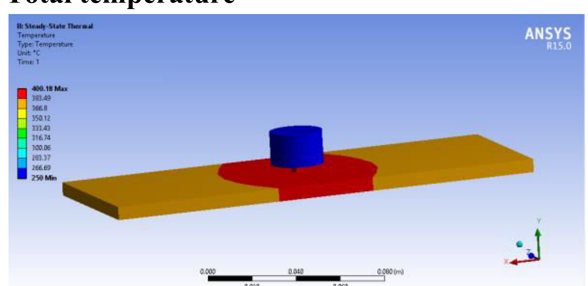


Total Heat Flux Values for Circular Tool

The above figure shows the results of circular tool heat flux distribution for above applied boundary conditions. And here we have maximum temperature value is 3.9671e6w/mm^2 which is shown in red colour and minimum value is 1.0809e-5w/mm^2 which is shown in blue colour.

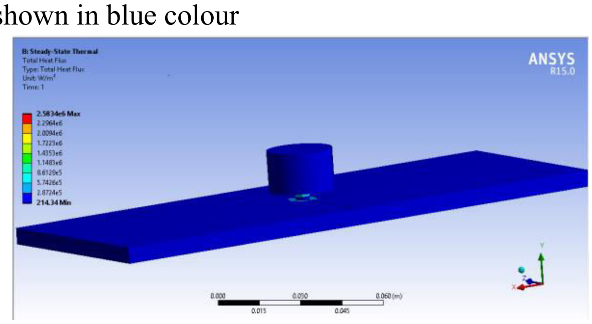
Results (pentagon tool)

Total temperature



Total temperature for pentagon tool

The above figure shows the results of pentagon tool temperature distribution for above applied boundary conditions. And here we have maximum temperature value is 400.18*c which is shown in red colour and minimum value is 250*c which is shown in blue colour

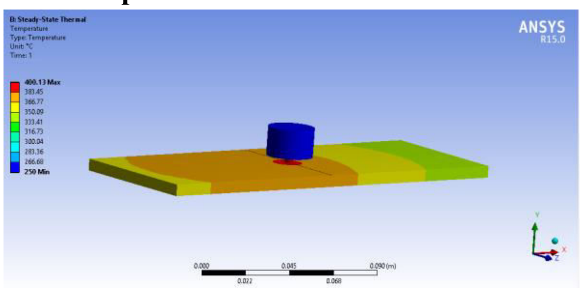


Total heat flux for pentagon tool

The above figure shows the results of pentagon tool heat flux distribution for above applied boundary conditions. And here we have maximum temperature value is 2.5834e6w/mm^2 which is shown in red colour and minimum value is 214.34w/mm^2 which is shown in blue colour

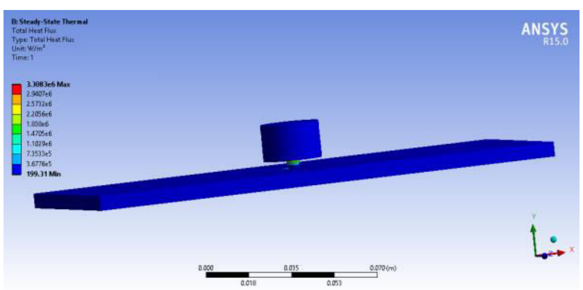
Results (tapered tool)

Total temperature



Total temperature for tapered tool

The above figure shows the results of tapered tool temperature distribution for above applied boundary conditions. And here we have maximum temperature value is 400.13*c which is shown in red colour and minimum value is 250*c which is shown in blue colour

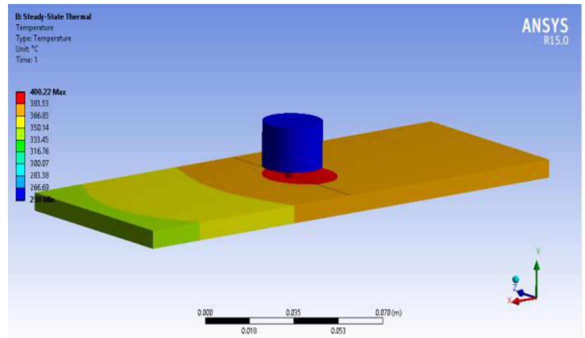


Total heat flux for tapered tool

The above figure shows the results of tapered toolheat flux distribution for above applied boundary conditions. And here we have maximum heat flux is 3.3083e6w/mm^2 which is shown in red colour and minimum value is 199.31w/mm^2 which is shown in blue colour

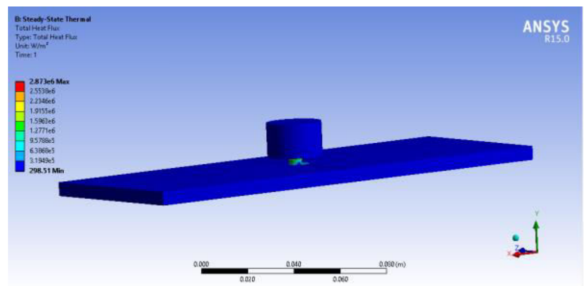
Results (truncated tool)

Total temperature



Total temperature for truncated tool

The above figure shows the results of truncated tool temperature distribution for above applied boundary conditions. And here we have maximum temperature value is 400.22*c which is shown in red colour and minimum value is 250*c which is shown in blue colour



Total heat flux for truncated tool

The above figure shows the results of truncated tool heat flux distribution for above applied boundary conditions. And here we have maximum heat flux is 2.873e6w/mm^2 which is shown in red colour and minimum value is 298.51w/mm^2 which is shown in blue colour

Table : Analysis results

	Circular tool	Pentagon tool	Tapered tool	Truncated tool
Total temperature(*C)	400.18	400.18	400.13	400.22
Total heat flux(w/m^2)	3.9671e6	2.5834e6	3.3083e6	2.873e6

VII CONCLUSIONS

The modeling and optimization of friction stir welding equipment parameters have demonstrated significant improvements in both tensile strength and surface finish of welded joints. The developed predictive model accurately captures the influence of tool rotational speed, traverse speed, axial force, and tool geometry on weld quality metrics. Optimization results reveal a set of process parameters that achieve a desirable balance between maximizing joint strength and minimizing surface roughness.

Experimental validation confirms that the optimized conditions lead to stronger, smoother welds compared to baseline settings, validating the effectiveness of the modeling approach. These findings highlight the importance of equipment parameter control in achieving high-quality FSW joints and suggest pathways for industrial adoption of optimized welding processes.

Future work could extend this research by incorporating real-time monitoring, adaptive control systems, and the use of artificial intelligence to further enhance the automation and precision of friction stir welding operations.

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