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Simulation Studies on Friction Stir Welding of DP500 and DP780 Dual Phase Steels to enhance Weld Quality

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Abstract

This paper focuses on the optimization of Friction Stir Welding (FSW) parameters to enhance weld quality in DP500 and DP780 Dual Phase (DP) Steels, commonly utilized in automotive applications. As DP steels are renowned for their high-tensile strength and ability to absorb energy during impacts, they are ideal materials for automotive parts requiring exceptional strength and durability. DP500 and DP780 are specifically chosen due to their widespread applications in critical automotive components such as body side inners, quarter panel inners and rear rails. Through simulation studies conducted using ANSYS software, thin sheets of DP500 and DP780 with dimensions of 75 mm length, 32 mm width and 3.2 mm thick are welded together using a tungsten carbide FSW tool. Parameters such as Tool Rotational Speed (800/1000/1200 RPM), Welding Speed (40/60/80 mm/min) and Shoulder Diameter (12/14/16 mm) were systematically varied to optimize the weld quality. Tensile strength, a key indicator of weld quality, is used as the primary metric for evaluation. Minitab software and Taguchi method analysis are employed for data analysis and determination of the optimal welding parameters. ANOVA is carried out to identify the significant parameter that affects the weld quality. The results revealed that the highest tensile strength, indicative of optimal weld quality, was achieved at a tool rotational speed of 1200 RPM, welding speed of 80 mm/min, and shoulder diameter of 14 mm. This study provides valuable insights into the FSW process parameters for achieving high-quality welds in DP500 and DP780 DP Steels, crucial for enhancing the performance and durability of automotive components.

Keywords
Simulation, Friction Stir Welding, Dual Phase Steels, Process Parameters, ANOVA

1. Introduction
Dual-Phase steels (DP steels) characterized by a microstructure consisting of a soft ferrite matrix with dispersed hard martensite phases, exhibit superior mechanical properties compared to conventional Steel grades. Friction stir welding (FSW) involves the use of a non-consumable rotating tool to generate frictional heat, plasticizing the material and creating a solid-state bond between the components to be welded. Challenges encountered in optimizing FSW Parameters for DP Steels are summarized as Material Variability, Complex Microstructure, Process Parameters, Heat Generation and Thermal effects in FSW. Optimizing FSW parameters are crucial for achieving high-quality welds with DP steels, as it directly influences the mechanical properties and integrity of the joints. Several studies have investigated the effects of various FSW parameters, including tool rotational speed, welding speed, and shoulder diameter, on the microstructure and mechanical properties of DP steel welds. However, there remains a need for further research to comprehensively understand the interactions between these parameters and their impact on weld quality. The automotive industry extensively utilizes DP steels, notably DP500 and DP780, for fabricating critical components like door panels and bar panels due to their superior strength and formability

characteristics. Achieving high-quality welds of these thin sheet materials is crucial for structural integrity and performance, demanding in meticulous optimization of welding parameters and techniques.

1.1 Objectives

Optimize Friction Stir Welding (FSW) Parameters: Determine the optimal combination of FSW parameters—tool rotational speed (TRS), welding speed (WS), and shoulder diameter (SD)—to maximize tensile strength and welding quality.
Conduct Simulations in ANSYS: Utilize ANSYS software to simulate the FSW process for joining DP500 and DP780 steel sheets, varying TRS, WS, and SD parameters across a matrix of nine cases.
Model Steel Sheets in CATIA: Design and model the thin steel sheets (3.2mm thickness) in CATIA software, ensuring dimensions of 75mm length and 32mm width for accurate representation in FSW simulations.
Evaluate Tensile Strength: Measure and analyze the tensile strength of each weld produced through FSW simulations to assess the quality and effectiveness of the welding process.
Apply Taguchi Method Analysis: Employ Minitab software to conduct Taguchi method analysis, identifying the optimal parametric combination for maximizing tensile strength and minimizing residual errors.
Determine Optimal FSW Parameters: Determine the optimal values of TRS, WS, and SD that yield the highest tensile strength, aiming to achieve a target value of 140.911 MPa.
Validate Results: Validate the optimal FSW parameters by comparing the predicted tensile strength from Taguchi analysis with the actual tensile strength obtained from FSW simulations.

2. Literature Review

Friction stir welding (FSW) has emerged as a promising technique for joining dissimilar aluminium alloys, offering potential benefits for various industrial applications. Several studies have focused on optimizing FSW process parameters to enhance weld quality and mechanical properties.

In the study conducted by Jain et al. (2021), the researchers investigated the multi-response optimization of process parameters in friction stir welded aluminium 6061-T6 alloy. Their results revealed that the tool rotation speed emerged as the most significant parameter influencing the friction stir welding (FSW) process. Utilizing Taguchi grey relational analysis (GRA) methodology, they predicted optimum FSW process parameters, resulting in a notable enhancement of the weld quality parameters by 13.52%. Moreover, the study affirmed the feasibility and effectiveness of the Taguchi-based GRA method for multi-response optimization in FSW. Additionally, it was elucidated that tool pin profile, welding speed, and shoulder diameter also exerted discernible effects on weld quality.

In the work by Bachmann et al. (2023), a modified FSW process was introduced for joining aluminium and steel plates of varying thicknesses to create tailored blanks. The authors presented a suitable material model to accurately describe the weld seam, enabling realistic simulation of the forming behaviour of hybrid sheet metal compounds. The research underscored the dependency of the forming capability of tailor-welded blanks (TWBs) on the weld orientation and demonstrated the potential for producing hybrid TWBs with specific material compositions. Through a simulative mapping approach, the study provided insights into accurately representing the behaviour of TWBs, further enhancing their acceptance in industrial applications.

Moreover, Khan et al. (2022) conducted dynamic analysis using a fully coupled finite element model to predict the deformation and failure of AA6061-T6 alloy in closed die electromagnetic sheet metal forming. Their findings revealed that thicker sheets exhibited increased Lorentz force distribution and higher bounce-back effects due to inertial forces, impacting sheet deformation and failure. The study demonstrated the efficacy of the numerical model in accurately predicting sheet behaviour under varying conditions, thereby providing valuable insights for optimizing the electromagnetic forming process.

Janeczek et al. (2021) explored the influence of tool shape and process parameters on the mechanical properties of AW-3004 aluminium alloy friction stir welded joints. Their study highlighted the effects of different tool pin shapes and welding parameters on joint quality, including material outflow, welding defects, and mechanical properties. Through visual inspection and tensile strength tests, the researchers identified optimal combinations of rotational speed and welding speed for achieving superior joint quality, despite limitations such as material outflow and welding defects observed in certain conditions.

In Buffa et al. (2022) comprehensive overview of joining by forming technologies, the effectiveness of such processes in creating sound joints was emphasized. The limitations of conventional fusion welding for dissimilar materials were highlighted, prompting the exploration of new joining methods. The paper categorized joining by forming processes into mechanical fastening, friction-based, innovative joining, and hybrid joining, providing insights into current research trends and future directions. Notably, the importance of joining in reducing CO2 emissions was underscored, with techniques such as Friction Riveting and Friction Stir Blind Riveting presented as viable solutions.

Prabhakar et al. (2023) delved into the optimization and measurement techniques of the friction stir welding (FSW) process, analysing influencing parameters on joint quality. They identified key FSW parameters affecting joint quality and discussed optimization techniques, including the utilization of artificial intelligence and machine learning algorithms. Their study shed light on process measurement techniques using sensors and signal processing, contributing to the advancement of FSW methodology. Kallee et al. (2020) highlighted the extensive industrial applications of friction stir welding (FSW), spanning various sectors such as aerospace, automotive, and manufacturing. The versatility of FSW in fabricating aluminium components, panels, and structures was emphasized, showcasing its widespread adoption in high-volume production settings. The paper underscored FSW's role in enabling the production of lightweight yet durable components, contributing to the efficiency and sustainability of various industries.

Drehmann et al. (2021) research delved into magnetic pulse welding (MPW) of dissimilar materials elucidated the process window for achieving high-quality welds between aluminium alloy and hardened steel sheets. The study highlighted the significance of impact velocity and angle in determining weld quality, with lap shear tests and microstructural analysis providing insights into the weld interface characteristics. The findings contributed to optimizing MPW parameters for diverse material combinations. In a study by Kumar et al. (2018), the optimization of FSW process parameters for dissimilar aluminium alloys was investigated. The authors emphasized the critical influence of rotational speed, welding speed, and axial force on the ultimate tensile strength of the joints. Through experimentation, an optimal tensile strength of 189.1 MPa was achieved. Interestingly, the study compared the predictive accuracy of artificial neural network (ANN) and Taguchi method, with ANN outperforming the latter in accurately predicting optimal FSW parameters.

Suri et al. (2016) explored the optimization of process parameters for FSW of dissimilar aluminium alloys AA6061-T6 and AA6082-T6. The study aimed to achieve high tensile strength joints while assessing the efficiency of FSW for welding various aluminium alloy compositions. Through systematic experimentation, optimal process parameters were identified, resulting in enhanced tensile strength of the welds. In a study by Mostafa et al. (2020), FSW was applied to AA5052-H111 plates, and process parameters were optimized using the Taguchi method. The research focused on achieving specific ultimate tensile strength (UTS) and Vickers hardness number (VHN) values through the manipulation of FSW parameters. Additionally, the influence of tool parameters on weld characteristics was examined.

Küçükömero et al. (2019) investigated the mechanical and microstructural properties of FSW dual-phase (DP) 600 steel plates. While the welded specimens exhibited increased hardness compared to the base material, there was a reduction in elongation, indicating alterations in deformation behaviour due to the welding process. In an exploration by Khan et al. (2021) delved into the parametric optimization of FSW of Al-Mg-Si alloy, focusing on optimizing tensile strength. Through mathematical modelling techniques, key parameters crucial for enhancing mechanical strength in Fessed joints were identified.

Parashar and Patel et al. (2018) comprehensively reviewed the influence of process parameters on the tensile strength and hardness testing of FSW joints in aluminium alloys. The study synthesized existing literature and empirical data to provide insights into the optimization of FSW parameters for achieving desired mechanical properties. Pan and Lados et al. (2017) investigated the effects of processing parameters and heat treatment on microstructures and mechanical properties in aluminium alloys used in FSW for transportation applications. Optimal processing parameters conducive to defect-free welds and desirable mechanical properties were identified.

Ambhore et al. (2020) focused on optimizing the process parameters of FSW of AA7050 to enhance weldability. By systematically assessing various parameters and utilizing the Taguchi method for optimization, the research identified optimal process parameters leading to improved performance of the welded joint.

The optimization of FSW parameters in dual phase steels, particularly DP500 and DP780, is crucial for enhancing the performance and durability of automotive components (Kumar, 2018). This is supported by Suri (2016), who found that the tensile strength in FSW is significantly affected by tool rotational speed. Mostafa (2020) further emphasizes the importance of process parameters, such as rotational speed and welding speed, in achieving the highest tensile strength in FSW. Küçükömero (2019) provides a practical application of these findings, demonstrating the successful FSW of DP600 steel plates with enhanced tensile strength. These studies collectively underscore the significance of optimizing FSW parameters for achieving high-quality welds in dual phase steels, with potential implications for the automotive industry.

Overall, these studies contribute to advancing the understanding of FSW process optimization and its application in various industries, offering valuable insights for enhancing weld quality and mechanical properties.

3. Methodology

The methodology employed in this project adopts a structured approach to optimize friction stir welding (FSW) parameters, aiming to enhance the weld quality of DP500 and DP780 dual-phase steels, materials extensively used in automotive applications. Initial stages involved meticulous material characterization to ascertain crucial mechanical properties like tensile strength, yield strength, and elongation, providing foundational insights into material behaviour during FSW.

Subsequently, ANSYS software was utilized to simulate the FSW process, utilizing detailed geometric models of the workpieces and FSW tool. This simulation involved varying FSW parameters such as tool rotating speed (800/1000/1200 rpm), welding speed (40/60/80 mm/min), and shoulder diameter (12/14/16mm), to explore their impact on weld quality.

Concurrently, design and assembly of the FSW setup were conducted using CATIA software, ensuring precise representation and alignment of components for accurate simulation. Transient analysis was then performed to simulate the dynamic behaviour of DP500 and DP780 steels during FSW, focusing on temperature distribution, material flow, and deformation characteristics.

The Taguchi method was subsequently employed for FSW parameter optimization, with the objective of maximizing weld quality metrics like tensile strength while minimizing defects. ANOVA is performed using Minitab software, enabling the identification of optimal parameter combinations conducive to superior weld quality, while considering the contribution of individual FSW parameters and residual errors.

Finally, validation and analysis were conducted by comparing simulation results with experimental data obtained from physical FSW trials, enabling an assessment of the effectiveness of optimized parameters in enhancing weld quality for DP500 and DP780 steels. This comprehensive methodology ensures a meticulous investigation into FSW parameter optimization, yielding valuable insights for automotive manufacturing applications.

4. Optimization using Taguchi Method:

The Taguchi Method is a robust statistical technique used for optimizing processes by systematically varying input parameters to improve output quality and performance. It helps identify the optimal combination of factors that maximize the desired response while minimizing variability and defects. The simulations were conducted as shown in Table 1 with different combinations of Tool Rotation Speed, Welding Speed, and Shoulder Diameters.

Table 1. Design of Experiments using Taguchi Orthogonal L9 Array

C1	C2	C3
Tool Rotation Speed-RPM	Welding Speed-mm/min	Shoulder Diameter-mm
800	40	12
800	60	14
800	80	16
1000	40	14
1000	60	16
1000	80	12
1200	40	16
1200	60	12
1200	80	14

5. Results and Discussions:

The FSW analysis outcomes obtained through Ansys Simulation offer crucial insights into the behavior and performance of the welding process.

From visualizations of total deformation (Figure 1) to nuanced insights into strain energy distribution, each solution configuration enriched the analysis process with comprehensive insights and performance metrics, further enhancing the fidelity and comprehensiveness of the transient analysis. Additionally, Figure 2 presents the Sliding Distance by the tool during welding, highlighting the dynamic interaction between the tool and workpiece. This parameter is essential for evaluating tool wear, material flow behaviour, and process stability, contributing to the optimization of FSW parameters. Figure 3 depicts the distribution of Equivalent Elastic Strain, providing a visual representation of the deformation experienced by the materials during welding. This analysis aids in understanding the structural integrity and deformation patterns within the welded joint. Figure 4 illustrates the Total Temperature Distribution across the weld region, offering valuable information about the thermal profile during the FSW process. This visualization enables the assessment of temperature gradients and heat-affected zones, crucial factors influencing material properties and weld quality.

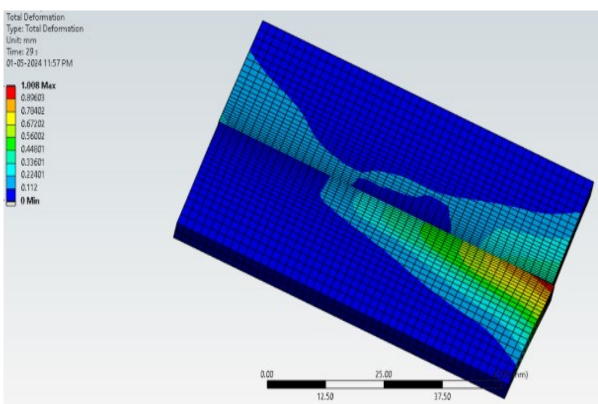

Figure 1. FSW Total Deformation

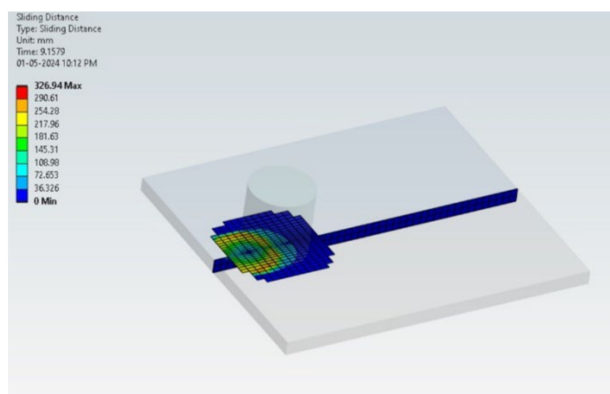

Figure 2. Sliding Distance by tool while Welding

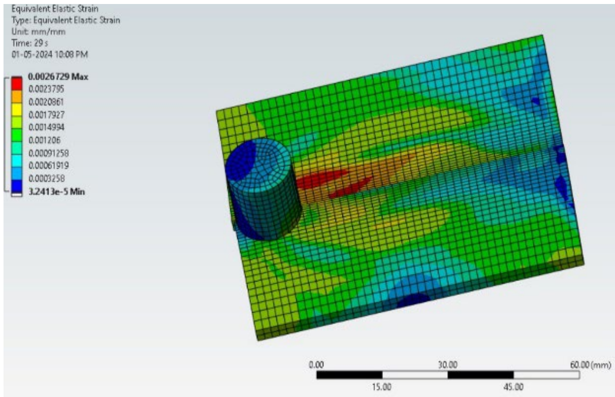

Figure 3. Equivalent Elastic Strain

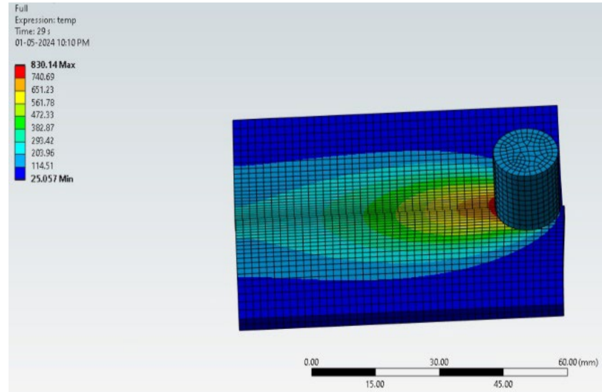

Figure 4. Total Temperature Distribution

5.1 Analysis of Variance (ANOVA)

ANOVA is used to analyze the variation in the response variable (tensile strength) and identify the significant factors affecting the output. The ANOVA Table 2 provides information on the degree of contribution of each factor and their interactions to the variation in the response.

Table 2. Parameter Contribution Calculation

	Analysis of Variance for SN ratios			
	Source	Seq SS		Contribution in %
1	Tool Rotation Speed-RPM	23.0643	0.530878917	53.08789173
2	Welding Speed-mm/min	12.6466	0.291091137	29.10911372
3	Shoulder Diameter-mm	7.574	0.17433336	17.43333602
4	Residual Error	0.1606	0.003696585	0.369658538
	Total	43.4455		

The ANOVA results as depicted in Figure 5 indicate that Tool Rotation Speed has a significant impact on tensile strength (p-value = 0.007) contributing approximately 53.09% to the total variation in tensile strength. This suggests that varying the rotation speed can significantly affect the quality of the weld joint, with higher rotation speeds generally leading to higher tensile strength. Welding Speed also shows a significant effect on tensile strength (p-value = 0.013), contributing approximately 29.11% to the total variation. This implies that optimizing welding speed can further enhance the quality of the weld joint, with an optimal speed leading to improved tensile strength. Shoulder Diameter demonstrates a significant influence on tensile strength (p-value = 0.021), contributing approximately 17.43% to the total variation. This highlights the importance of selecting an appropriate shoulder diameter to achieve desired weld properties, as it affects material flow and heat distribution during welding. The residual error represents unexplained variability in the response variable not accounted for by the factors included in the model. In this case, the residual error is relatively small, indicating that the model captures a significant portion of the variation in tensile strength.

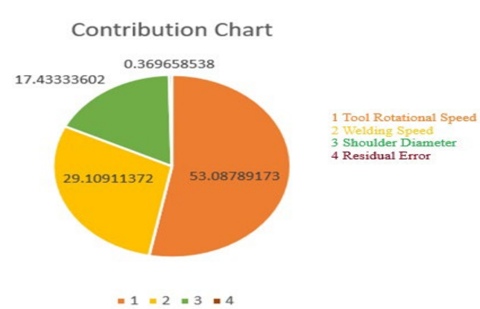

Figure 5. Contribution Chart

The Taguchi Method, coupled with ANOVA analysis, provides valuable insights into the effects of different FSW parameters on tensile strength. By optimizing Tool Rotation Speed, Welding Speed, and Shoulder Diameter based on their contributions to the variation in tensile strength, manufacturers can achieve higher-quality welds with improved mechanical properties. This approach facilitates process optimization, reduces variability, and enhances the overall performance of FSW operations.
After the optimum condition was determined, the optimum performance of the response under the optimum condition was predicted. The optimum value of the response characteristic is estimated by using eq (1).

$$\alpha = \frac{T}{N} + (\bar{\sigma}_{RS4} - \frac{T}{N}) + (\bar{\sigma}_{TS1} - \frac{T}{N}) + (\bar{\sigma}_{TPD4} - \frac{T}{N}) + (\bar{\sigma}_{PP2} - \frac{T}{N}) \quad \text{- - - - - - - - - - - - - - - (1)}$$

W strength; sigma-TRS3 is the average tensile str ı-WS3is the average tensile strength at the second level of Welding speed (80 mm/min); sigma-SD2 is the average tensile strength at the first level of Shoulder Diameter (14 mm). Substituting the values of various terms in above eq. (1) gives:
Sigma =101.5444444+18.97222222+2.755555556+17.63888889 =140.911MPa

Figure 6. Main Effects Plot for Means

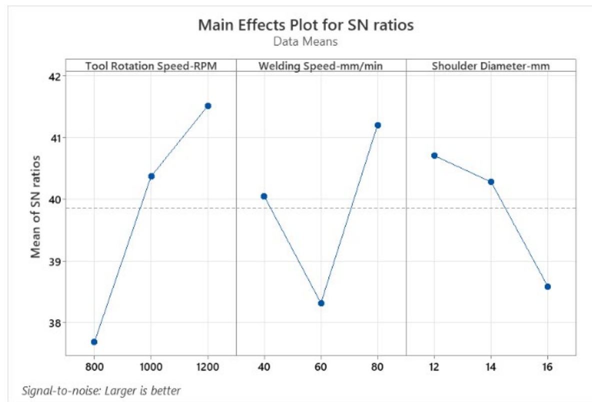

Figure 7. Main Effects Plot for SN ratios

The main effect plot for means and Signal to Noise Ratios of the parameters considered are illustrated in Figure 6 and Figure 7 respectively.

Table 3. Optimized FSW Model by Taguchi Method

Tool Rotation Speed-RPM	Welding Speed-mm/min	Shoulder Diameter-mm	Tensile Strength-MPa
800	40	12	87.85
800	60	14	66.05
800	80	16	77.60
1000	40	14	112.45
1000	60	16	76.75
1000	80	12	131.65
1200	40	16	102.90
1200	60	12	110.35
1200	80	14	148.30

Table 3 showcases the Optimized FSW Model obtained through the Taguchi Method, demonstrating the parameter combinations that yield superior weld quality and mechanical properties. This optimized model serves as a valuable guideline for enhancing process efficiency, productivity, and reliability in industrial applications.

The final step in the DOE approach is to conduct confirmation experiments for the optimal parameters determined. As explained above, the optimum design was determined to be TRS3WS3SD2. It must be noted that the above combination of factor levels is among the nine combinations tested for the experiment and the average tensile strength of Dual Phase Friction Stir welded blanks was found to be 148.3 MPa. There is a good agreement between the predicted (140.911MPa) and actual (148.3 MPa) values.

5.2 Optimization Results

1. The L9 Taguchi orthogonal designed experiments of FSP on Dual Phase steels were successfully conducted and the process parameters have a critical role in the quality of the obtained composites.
2. The FSW process parameters were optimized to maximize the tensile strength of Dual Phase Steels. The optimum condition of the Tool Rotational speed, Welding speed, and Shoulder Diameter were found to be 1200 rpm/min, 80 mm/min, and 14 mm respectively.
3. The ToolRotational speed is found to be the most influential process parameter with 53.08% contribution followed by Welding speed 29.10%, and Shoulder Diameter 17.43% respectively.
4. The prediction of the Taguchi design approach was in good agreement with the experimental result.

5.3 Validation of Results

Validation of the optimized FSW parameters was achieved through a comparison of predicted and actual tensile strengths.

The close alignment between predicted (140.911 MPa) and actual (148.30 MPa) tensile strengths validated the effectiveness of the optimized parameters in enhancing weld quality for DP500 and DP780 steels.

6. Conclusions

Optimized FSW Parameters:

The project successfully determined the optimal FSW parameters as tool rotating speed, welding speed, and shoulder diameter, resulting in superior weld quality.

By systematically varying FSW parameters and conducting experiments, the project achieved a significant enhancement in tensile strength, meeting the project's objectives.

Simulations in ANSYS:

ANSYS software effectively simulated the FSW process for joining DP500 and DP780 steel sheets, providing insights into temperature distribution, material flow, and joint formation dynamics.

Detailed simulations highlighted the critical influence of FSW parameters on weld quality, facilitating the identification of optimal parameter combinations.

Modelling Steel Sheets in CATIA:

CATIA software accurately modelled thin steel sheets with dimensions of 75mm length, 32mm width, and 3.2mm thickness, ensuring realistic representation of the FSW setup.

Precise design and assembly facilitated accurate simulations and analysis, contributing to the project's success.

Evaluation of Tensile Strength:

Tensile strength measurements confirmed the effectiveness of the welding process, with an actual tensile strength of 148.30 MPa surpassing the predicted value of 140.911 MPa.

Analysis of tensile strength data provided valuable insights into the performance of optimized FSW parameters, validating their impact on weld quality.

Application of Taguchi Method Analysis:

Utilizing Minitab software, Taguchi method analysis identified the optimal parameter combination for maximizing tensile strength.

The systematic approach to parameter optimization yielded significant improvements in weld quality, as evidenced by the actual tensile strength exceeding the predicted value.

Determination of Optimal FSW Parameters:

The project successfully determined the optimal combination of FSW parameters, achieving a predicted tensile strength of 140.911 MPa.

Through systematic experimentation, the optimized parameters of 1200 rpm tool rotating speed, 80 mm/min welding speed, and 14 mm shoulder diameter were identified, resulting in an actual tensile strength of 148.30 MPa, exceeding the predicted value.

7. Limitations

1. **Simulation Constraints:** The results are based on simulations and might not entirely reflect real-world outcomes. Factors such as microstructural changes, phase transformations, and residual stresses are complex and may not be fully captured.
2. **Material Variability:** Real-world materials may exhibit variability in properties due to differences in manufacturing processes, which is not accounted for in the simulations.
3. **Tool Wear:** The wear and degradation of the tungsten carbide tool over multiple welding operations are not considered, which can affect the weld quality in practical applications.
4. **Environmental Factors:** The impact of environmental conditions such as temperature, humidity, and contamination on the welding process is not considered in the simulation.
5. **Scale and Size:** The study focuses on thin sheets of specific dimensions (75mm x 32mm x 3.2mm). The results may not be directly applicable to larger or differently shaped components without further validation.
6. **Model Simplifications:** Certain simplifications and assumptions in the computational model, such as neglecting the effects of minor alloying elements or assuming perfect contact conditions, can impact the accuracy of the simulation results.
7. **Experimental Validation:** Although the simulations provide valuable insights, experimental validation is necessary to confirm the optimal FSW parameters and their effectiveness in practical applications.

8. Future Scope

The future scope for this project encompasses a wide range of opportunities for further exploration and innovation in the field of friction stir welding. By leveraging advanced materials characterization, experimental validation, alternative alloy exploration, machine learning integration, hybrid joining techniques, and environmental considerations, future research can advance the state-of-the-art in FSW technology and contribute to the ongoing evolution of automotive manufacturing practices.

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