# ENERGY ANALYSIS DURING ULTRASONIC WELDING OF PP: EDS-ABS POLYMER BLENDS - EXPERIMENTAL INVESTIGATION, STATISTICAL ASSESSMENT AND MATHEMATICAL MODELLING FOR ENERGY AND POWER SIGNAL DYNAMICS

T. Pragadeesan[1], K. Balaji[2], P. Maadeswaran[1], K. A. Ramesh Kumar[1*], G. Jacob[3]

[1]Department of Energy Science and Technology, Periyar University, Salem, India
[2]Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham (Deemed to be university), Coimbatore, India
[3]Centre for Nanotechnology Research, VIT University (Deemed to be university), Vellore, India
*Corresponding author: karameshkumar77@periyaruniversity.ac.in

## ABSTRACT

*This research provides an intensive experimental investigation of the energy issues with respect to tensile strength and energy consumption during ultrasonic welding of thermoplastic PP and Electrostatic Discharge ABS polymers. A scheduled set of 27 experiments were performed through varying amplitude, weld pressure, and weld time that led to the identification of the effect of process parameters on joint quality and energy usage. Quantitative data were gathered and analysed to recognize patterns to improve efficiency. The Pearson correlation coefficient was applied to confirm relations between the input variables and the response variables. The analysis indicated a strong positive correlation of weld time with energy consumed, and with the tensile strength and amplitude of the weld. The findings can help create energy-efficient welding methods for polymer materials used in energy systems. Power signals and harmonics analysis is performed using MATLAB to understand its variation when the process is ON and it provides an insight into signals and control mechanism to be fine-tuned for ultrasonic welding process.*

**KEYWORDS:** polymer welds, ultrasonic welding, energy analysis, Pearson's coefficient

## 1. INTRODUCTION

Ultrasonic welding has emerged as a swift, efficient, and clean solid-state process for joining thermoplastics, by deploying mechanical vibrations of high frequency to generate localized heating at the interface. The physics underlying ultrasonic welding relies on intermolecular friction, viscoelastic heating, and polymer chain interdiffusion, facilitating the creation of a strong bonds without using external fillers or adhesives (Fig. 1). Engineering-grade EDS-ABS polymer and Polypropylene (PP) blends are progressively being used in aerospace, automotive and electronics sectors, establishing reliable welding of these materials crucial for high-performance assemblies. Literature reports reveals that vital ultrasonic welding parameters – such as amplitude, weld time, welding pressure, hold time, and energy input – directly influence heat creation, melt layer formation, and weld strength. Numerous studies emphasize the significance of the stability of the horn frequency, stack tuning, and efficiency of vibration transmission in accomplishing consistent weld quality. Research has also focused on acoustic impedance matching, the role of material properties, and polymer crystallinity on weld formation, especially for modified polymer or dissimilar polymer systems. Nevertheless, the blend of PP with EDS-ABS offers unique challenges owing to variances in melting temperature, viscous behaviour, and damping properties, demanding precise process parametric optimization. Recent studies specify that analysing the harmonic behaviour of ultrasonic joining systems is imperative for curtailing energy losses and eliminating resonance shifts during welding. The incorporation of MATLAB-based tools for harmonic assessment, signal characterization, and energy-consumption tracking bids powerful capabilities for understanding and controlling the joining process. Monitoring the energy consumed in each weld cycle also presents insights into



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process reproducibility and weld quality forecasting. In this work, experimental studies are carried out on the ultrasonic joining of PP and EDS-ABS polymer blends, complimented by MATLAB-aided harmonic analysis and energy assessment to enable a deeper understanding of the optimization strategies and process dynamics.

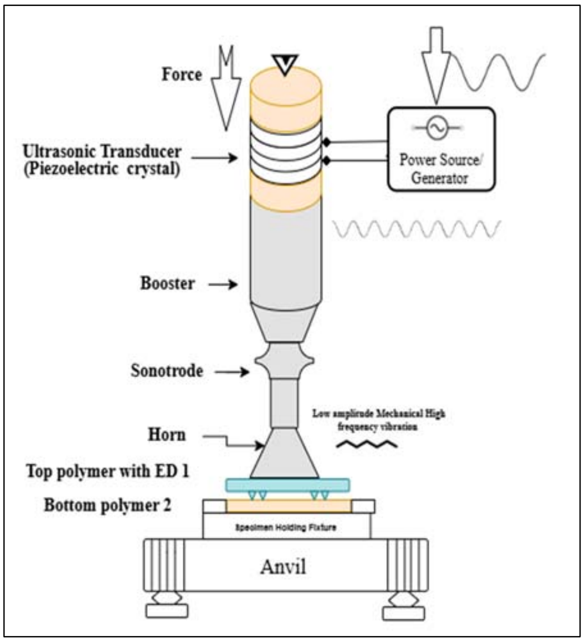



**Fig. 1.** USW working principle

Ultrasonic welding (USW) has been extensively investigated owing to its effectiveness in welding thermoplastic materials, thereby demonstrating advantages in terms of energy efficiency, speed and weld quality. The technique has been successfully deployed to a variety of polymers that are amorphous or semi-crystalline in nature. Yordanov et al. (2020) examined PC/ABS ultrasonic welds and illustrated that weld strength is strongly influenced by amplitude and geometry of the energy-director [1]. Other researchers investigated PP and PE, assigning variations in weld strength to differences in molecular crystallinity and orientation [2]. High-performance polymers namely the PEEK pose additional challenges since at elevated melting temperatures, successful welds have been accomplished through defined preheating and strategies used for pressure management [3]. Investigations on glass-filled PA composites and PA showed that filler content can hamper energy transmission and reduce the weld performance [4]. Works on ultrasonically welded PS likewise described that higher amplitudes of vibration increase the bond strength; however, it also increases flash formation [5]. Current developments have extended toward hybrid and dissimilar polymer welds. The welding of PP/PC combinations has shown that suitable acoustic-impedance matching is important for attaining sound welds [6]. Finite element modelling (FEM) has also been used to ABS welding to visualize temperature distribution and stress development, which assisted in parameter optimization [7]. Contemporary research has also explored the relationship between weld parameters and energy efficiency, such as analyses on LDPE film welding that recognised weld time as the most impacting factor dictating energy consumption [8]. Correlations were established between measured weld energy and tensile strength and have also been recorded [9], and approaches of machine-learning have been employed to forecast tensile performance with respect to input energy in PVC welding [10]. Another research study presents a complete overview of polymer welding, integrating experimental and numerical approaches to overcome the existing technical challenges. It further, details joining technologies, polymer fundamentals, and the deployment of FEA to predict temperature distribution and deformation during joining [11]. Additive manufacturing of polymers is evolving rapidly, offering design freedom and lightweight components, but with associated challenges such as distortion and variability induced by parameter- seeks in depth understanding of material behaviour and process interactions. Machine learning facilitates effective optimization of AM parameters, forecasting of mechanical properties and geometry, and monitoring the real-time quality through data-driven models. Nevertheless, large datasets and robust quality-control techniques remain crucial for attaining consistent and reliable 3D-printed parts [12]. Jointly, these studies, reinforce the significance of material behaviour, process parametric conditions, and energy-based modelling for understanding the physics underlying the ultrasonic joint formation. Effective transmission of ultrasonic energy into polymeric materials remains the fulcrum to accomplishing reliable and effective welds.

In spite of the growing application of ultrasonic joining and its versatility, the literature reports offer incomplete insight into the energy-related features of the process. Several studies highlight material behaviour, welding conditions optimization, or mechanical performance, whereas comparatively less address energy consumption and its economic or operational impacts. Only a small number of publications investigate systematic correlations between input parameters, weld strength, and energy characteristics. The present study seeks to bridge this gap by formulating an approach for examining the relationship between process parameters, tensile performance, and energy utility in polymer welding. The main aim is to enhance the understanding of energy behaviour during ultrasonic joining and create a platform for optimizing both weld quality and process efficiency. Though, ultrasonic welding of polymers is vastly investigated, there is limited or scanty literature reports on dissimilar blends such as PP and EDS-ABS, particularly concerning how process parameters impacts both tensile strength and energy consumption concurrently. Existing surveys also lacks quantified correlation models linking input parameters to dual performance metrics, and almost no reports presented the examination of power-signal behaviour, harmonic distortion and resonance, and to understand electromechanical effects in the process of welding. This creates a gap in attaining optimized, energy-efficient dissimilar polymers welds. The objectives are framed accordingly which are as follows:

- to assess the effects of pressure, amplitude and weld time on the energy consumption and tensile strength of PP-EDS-ABS welds;
- to develop a Pearson correlation model for quantifying parameter - response relationships;
- to analyse resonance, power signals, and harmonic behaviour by utilizing the MATLAB tools to interpret support process optimization. electromechanical and interactions.

## 2. EXPERIMENTS

The experimental work focused on the ultrasonic welding of polypropylene (PP) and EDS-ABS, a blend widely used in optical housings, electronic enclosures, and automotive interior components due to its superior dimensional stability and durability. The primary objective was to examine how variations in three key process parameters – amplitude, welding pressure, and weld time – influence two critical output responses: tensile strength and energy consumption. A structured experimental design based on a 3×3×3 full factorial matrix was adopted, enabling each input parameter to be studied at three distinct levels as summarized in table 1. Prior to welding, all specimens were thoroughly cleaned to remove surface contaminants such as dust, oils, or release agents that could interfere with acoustic energy transmission. The samples were then carefully positioned within the welding fixture, ensuring proper alignment of the joint interface. Adequate clamping was applied to secure the components firmly without inducing pre-stress or deformation, enabling consistent coupling between the horn and workpieces. This systematic preparation and parameter variation ensured reliable experimental conditions for analysing the combined effects of process settings on weld strength and energy utilisation.

**Table 1.** Variation of input parameters versus tensile strength and energy consumption

| Trail | Amplitude [µm] | Pressure [bar] | Weld time [s] | Tensile strength [MPa] | Energy consumption [J] |
|---|---|---|---|---|---|
| 1 | 30 | 1.5 | 0.5 | 18.2 | 112 |
| 2 | 30 | 1.5 | 1 | 21.4 | 140 |
| 3 | 30 | 1.5 | 1.5 | 19.7 | 158 |
| 4 | 30 | 2 | 0.5 | 20.1 | 130 |
| 5 | 30 | 2 | 1 | 22.5 | 142 |
| 6 | 30 | 2 | 1.5 | 24.8 | 165 |
| 7 | 30 | 2.5 | 0.5 | 19 | 135 |
| 8 | 30 | 2.5 | 1 | 23.1 | 155 |
| 9 | 30 | 2.5 | 1.5 | 25.6 | 170 |
| 10 | 40 | 1.5 | 0.5 | 21 | 115 |
| 11 | 40 | 1.5 | 1 | 24.5 | 150 |
| 12 | 40 | 1.5 | 1.5 | 26.2 | 172 |
| 13 | 40 | 2 | 0.5 | 22 | 125 |
| 14 | 40 | 2 | 1 | 25.4 | 162 |
| 15 | 40 | 2 | 1.5 | 28.3 | 180 |
| 16 | 40 | 2.5 | 0.5 | 22.1 | 138 |
| 17 | 40 | 2.5 | 1 | 27 | 170 |
| 18 | 40 | 2.5 | 1.5 | 29.5 | 185 |
| 19 | 50 | 1.5 | 0.5 | 20.5 | 120 |
| 20 | 50 | 1.5 | 1 | 24.9 | 153 |
| 21 | 50 | 1.5 | 1.5 | 27.8 | 178 |
| 22 | 50 | 2 | 0.5 | 23.5 | 135 |
| 23 | 50 | 2 | 1 | 27.1 | 168 |
| 24 | 50 | 2 | 1.5 | 30 | 190 |
| 25 | 50 | 2.5 | 0.5 | 22.5 | 145 |
| 26 | 50 | 2.5 | 1 | 28.2 | 178 |
| 27 | 50 | 2.5 | 1.5 | 23.5 | 200 |

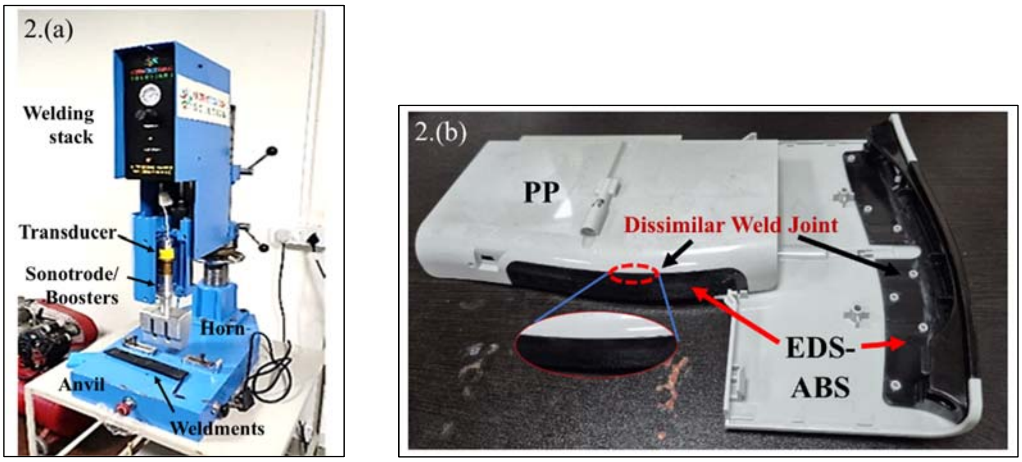



**Fig. 2.** Equipment and materials: a) USW machine; b) the PP: EDS-ABS welded sample

Ultrasonic welding of the PP–EDS-ABS specimens was carried out using a high-frequency sonotrode system, as illustrated in (Fig. 2). The localized, high-speed mechanical vibrations generated by the horn produced frictional heating at the interface of the two materials, enabling the formation of a solid-state weld (Fig. 2). The tensile strength of the welded joints was evaluated for every experimental condition using a universal testing machine in accordance with ASTM D638, ensuring consistent assessment of joint integrity. During each weld cycle, the energy consumption was simultaneously monitored using a calibrated power meter to quantify the total electrical energy delivered to the process. This experimental approach was designed to identify an optimal range of amplitude, pressure, and weld time that maximizes tensile performance while minimizing energy usage. Subsequent data analysis focused on establishing correlations between the process inputs and the resulting mechanical and energy responses, thereby offering insights into the efficiency and viability of ultrasonic welding for joining dissimilar PP and EDS-ABS materials.

## 3. RESULTS AND DISCUSSION

### 3.1. Tensile Strength

The tensile strength of welds was quite different based on the process parameters, which clearly shows the importance of the process parameters in the weld quality. Based on the experiment results, it was seen that tensile strength is impacted by all the input parameters in various capacities which are graded in nature. Figure 3 illustrates the Pearson Correlation Heat Map for Tensile strength Vs various input parameters and their strong or weak correlation. The Pearson correlation coefficient (r) is a statistical measure that quantifies the strength and direction of the linear relationship between two continuous variables.

Its value ranges from –1 to +1: equations 1, 2 and 3 presents the correlation between tensile strength and amplitude, pressure and weld time respectively. It may be observed that weld time and amplitude have significant impact on the tensile strength while pressure has marginal or negligible impact.

The Pearson correlation heatmap provides clear insight into the relative influence of the input parameters on weld performance. Weld time exhibits the strongest positive correlation with tensile strength (r = 0.70), indicating that longer exposure to ultrasonic vibration promotes greater heat generation and molecular interdiffusion at the interface. Amplitude also shows a moderate correlation (r = 0.54), reflecting its role in determining the intensity of ultrasonic energy delivered to the joint. Pressure, however, demonstrates only a weak correlation (r = 0.31), suggesting that while it contributes to maintaining proper contact between the polymer surfaces, it does not significantly affect the amount of thermal energy produced during welding. The overall trends highlight that process parameters associated with energy input – namely amplitude and weld time – are more decisive in achieving strong PP–EDS-ABS joints than pressure. Furthermore, the independence of parameters, as seen from the low correlations among them, supports the robustness of the factorial experimental design used in this study.

Table 2 presents the results of the correlation analysis and clearly shows that weld time exerts the greatest influence on tensile strength. In figure 4, illustrate graphical representations that enhance the visualization of how the input process parameters affect the tensile strength of the welded specimens. The correlation is presented by the equations 1,2 and 3.

$$r_{TS,A} = \frac{\sum(TS_i - \overline{TS})\ (A_i - \bar{A})}{\sqrt{\sum(TS_i - \overline{TS})^2 \sum(A_i - \bar{A})^2}} = 0.54 \tag{1}$$

$$r_{TS,P} = \frac{\sum(TS_i - \overline{TS})\ (P_i - \bar{P})}{\sqrt{\sum(TS_i - \overline{TS})^2 \sum(P_i - \bar{P})^2}} = 0.31 \tag{2}$$

$$r_{TS,T} = \frac{\sum(TS_i - \bar{T})\ (T_i - \bar{T})}{\sqrt{\sum(TS_i - \overline{TS})^2 \sum(T_i - \bar{T})^2}} = 0.7 \tag{3}$$

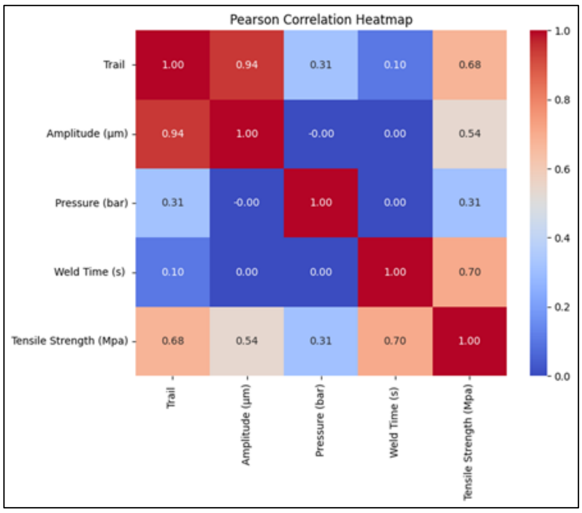



**Fig. 3.** Pearson heat map for input parameters vs. tensile strength

**Table 2.** Correlation Analysis

| Correlation Analysis | |
|---|---|
| **Parameter name** | **Pearson correlation coefficient for tensile strength [MPa]** |
| Amplitude [μm] | 0.54 |
| Pressure [bar] | 0.31 |
| Weld Time [s] | 0.7 |

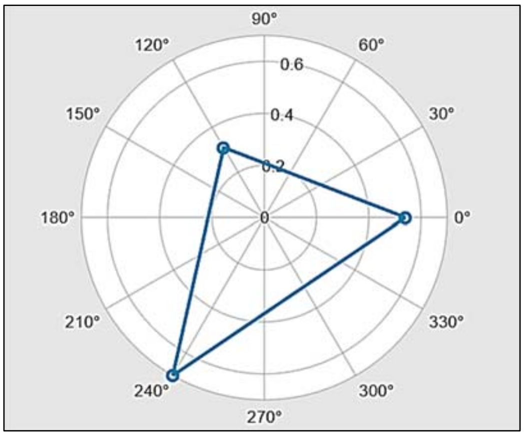



**Fig. 4.** Radar plot correlation analysis of tensile strength

### *3.1.1. Amplitude*

An increase in ultrasonic amplitude consistently led to higher tensile strength across the tested conditions. This behaviour is expected, as greater amplitude delivers more vibrational energy to the weld interface, promoting improved polymer chain mobility, localized melting, and intermolecular diffusion. Among the evaluated levels, an amplitude of 50 μm produced the strongest joints irrespective of pressure or weld time. This indicates that the energy input at this amplitude was optimal for achieving uniform melting without causing material degradation or excessive flash formation.

### *3.1.2. Pressure*

Welding pressure also influenced the tensile performance of PP–EDS-ABS joints. Moderate increases in pressure enhanced strength by ensuring intimate contact between the mating surfaces and facilitating efficient transmission of ultrasonic energy. The most favourable performance occurred at 2.5 bar, which provided adequate consolidation of the melt layer without inducing excessive squeeze-out. Pressures above this threshold resulted in diminishing returns, as excessive force caused material expulsion and flash generation, ultimately weakening the weld interface.

### *3.1.3. Welding Time*

Welding time exhibited a positive effect on tensile strength up to an optimal limit. Longer vibration exposure allowed additional heat generation and melt development, which supported stronger bonding. However, excessively long weld times led to thermal degradation, excessive softening, and potential distortion of the polymer interface. The most effective weld time for PP–EDS-ABS was 1.0s, providing sufficient energy input for fusion while avoiding overheating. Beyond this point, the joint quality deteriorated due to material breakdown or loss of structural integrity.

## 3.2. Energy Consumption

Energy consumption is a critical metric for assessing the overall efficiency of the ultrasonic welding process, as it directly reflects the interaction between material response and process settings. The experimental findings indicate that each input parameter contributes to the total energy usage, though with varying degrees of influence. In figure 5, illustrates the Pearson correlation heat map, which provides a clear comparative view of these relationships. The correlation coefficients presented in equations 4–6 quantify the dependence of energy consumption on amplitude, pressure, and weld time. Among the parameters evaluated, weld time exhibits the strongest positive correlation with energy consumption, demonstrating its dominant role in dictating the energy demand of the process. Amplitude shows a moderate correlation, indicating a secondary yet meaningful influence. In contrast, pressure displays only a weak correlation, suggesting that its contribution to energy variation is marginal. Overall, the heat map confirms that weld time is the most influential parameter, followed by amplitude, while pressure has minimal impact on energy consumption during ultrasonic welding.

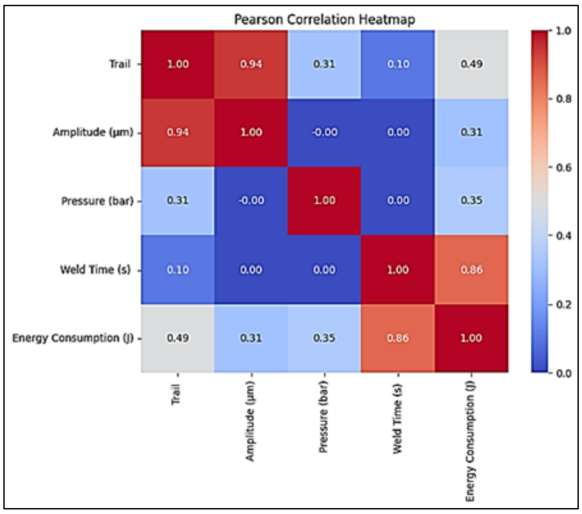



**Fig. 5.** Pearson heat map for input parameters vs. energy consumption

### *3.2.1. Correlation Analysis Equations*

General Equation (equ1) is being used in the Pearson Heat Map - coefficient to examine the influence.

$$r = \frac{\sum(x_i-40)(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2\sum(y_i-\bar{y})^2}} \qquad (4)$$

where:

- $x_i$ is individual values of a welding parameter
- $y_i$ - energy consumption values
- $\bar{x}$ - mean of that parameter
- $\bar{y}$ - mean energy consumption

The numerator measures how both variables vary together, and the denominator normalizes by their individual variations.

A positive r means increasing the parameter increases energy consumption, while a negative value means the opposite.

$$r_{Amplitute}/_{Energy\ Consumption} = \frac{\sum(x_i-40)(y_i-154.5)}{\sqrt{\sum(x_i-40)^2\sum(y_i-154.5)^2}} \qquad (5)$$

Here, 40 µm is the mean amplitude and 154.5 J is the mean energy consumption. The numerator measures how deviations of amplitude from its mean correspond to deviations in energy consumption. The denominator scales this joint variation by the spread of each variable. This equation tells highlights the extent to which ultrasonic amplitude influences energy consumption during welding.

$$r_{pressure}/_{Energy\ Consumption} = \frac{\sum(x_i-2)(y_i-154.5)}{\sqrt{\sum(x_i-2)^2\sum(y_i-154.5)^2}} \qquad (6)$$

Here, 2 bar is the mean welding pressure. The formula measures how changes in welding pressure align with changes in energy consumption. A higher positive value would indicate that increasing pressure tends to increase the energy consumption during the weld. This quantifies the dependency of pressure on energy consumption.

$$r_{weldtime}/_{Energy\ Consumption} = \frac{\sum(x_i-1)(y_i-24.3)}{\sqrt{\sum(x_i-1)^2\sum(y_i-154.5)^2}} \qquad (7)$$

The value 1s represents the mean weld time. The energy term uses 154.5 J, the mean energy consumption. This formula shows how deviations in weld time from the mean affect deviations in energy consumption. A high value of 0.86 means weld time is the dominant factor influencing energy consumption.

In table 3, records the correlation analysis table and clearly indicates that weld time has higher influence on Energy Consumption. In figure 6, depicts the graph for better visualization of the influence of input process parameters on the energy consumption of the welded specimen.

**Table 3.** Correlation analysis table

| Parameter name | Pearson correlation coefficient for energy consumption [J] |
|---|---|
| Amplitude [µm] | 0.31 |
| Pressure [bar] | 0.35 |
| Weld Time [s] | 0.86 |

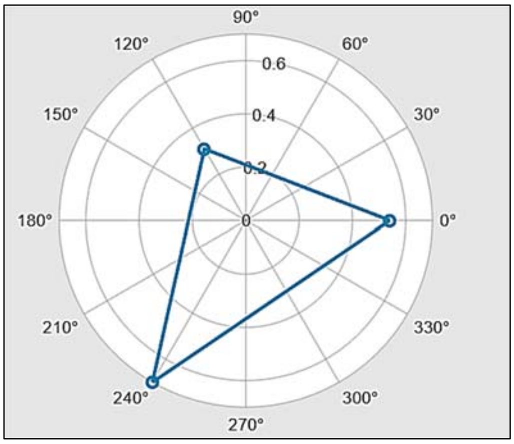



**Fig. 6.** Radar plot correlation analysis of energy consumption

### *3.2.2. Amplitude*

An increase in ultrasonic amplitude naturally raised the total energy delivered to the weld zone. While higher amplitude contributed to stronger welds by promoting better polymer flow, it also resulted in noticeably greater energy consumption. This trend highlights a clear trade-off: although higher amplitudes enhance bonding efficiency, they simultaneously increase the overall energy demand of the welding cycle.

### *3.2.3. Pressure*

Energy consumption also rose with increasing pressure; however, its influence was relatively modest compared to amplitude. Higher pressure facilitated better coupling of ultrasonic energy into the polymer interface, improving heat generation and intermolecular diffusion. Nevertheless, excessive pressure led to inefficient energy use due to premature material squeeze-out and increased flash formation. A pressure level of approximately 2.0 bar appeared to provide a balanced compromise between energy usage and weld quality.

### *3.2.4. Welding Time*

As expected, longer welding times directly elevated the total energy consumption, since the system applied ultrasonic energy for an extended duration. However, longer weld times did not always translate into improved joint quality beyond a certain threshold. A weld time of 1.0 second was found to maximize energy utilization effectively while still supporting optimal weld strength, indicating an ideal balance between sufficient heat generation and avoiding polymer degradation.

## 4. MATLAB MODELLING AND SIMULATION

MATLAB was employed extensively in this study to analyse key signal and process behaviours during ultrasonic polymer welding (UPW). Its advanced computational and signal-processing capabilities make it particularly suited for interpreting high-frequency power data generated during welding. Fast Fourier Transform (FFT) techniques available in MATLAB were used to decompose the acquired power signals into their frequency components, enabling the identification of resonance conditions, harmonic formation, and signal distortions. These insights are critical in ultrasonic welding, where stable resonance around the operating frequency ensures efficient energy transfer and consistent weld quality.

MATLAB's Simulink environment also provides a flexible platform for implementing intelligent control strategies such as fuzzy logic, PID tuning, and adaptive control schemes. Such control frameworks help simulate and understand how real-time adjustments to amplitude, weld pressure, or weld duration can improve process stability and minimize deviations during welding. Additionally, parametric modelling tools were utilized to quantify the influence of key input factors-amplitude, pressure, weld time, and frequency-on output responses such as tensile strength, energy consumption, and thermal behaviour.

Furthermore, MATLAB's statistical toolbox supported deeper interpretation of the experimental data. Regression analysis, ANOVA, correlation mapping, and response-surface visualization were applied to examine trends, interactions, and sensitivities within the dataset. These visualization outputs, such as the plots in figure 7a and 7b, clearly show that both tensile strength and energy consumption increase with higher amplitude and pressure settings.

Figures 8a and 8b, further illustrates the spectral behaviour of the ultrasonic system. The primary peak at 20 kHz corresponds to the machine's operating frequency and confirms resonance stability. The presence of second and third harmonic peaks at approximately 20 kHz and 40 kHz arises from nonlinear polymer viscoelastic behaviour during welding.

Additional distortions in the spectrum point toward acoustic impedance mismatch, slight tool wear, or transient pressure fluctuations during the welding cycle. Such spectral observations reinforce the value of MATLAB-based signal analysis in diagnosing welding performance and guiding process optimization.

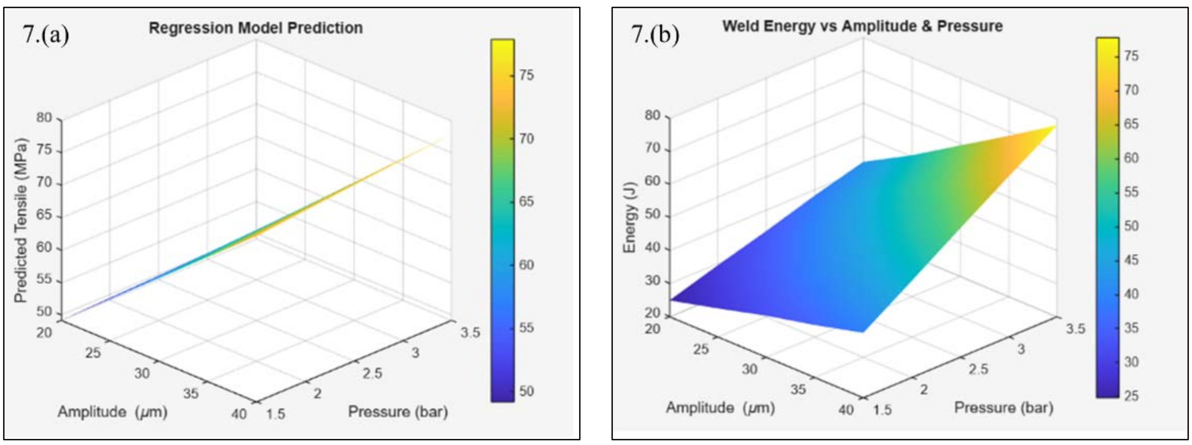
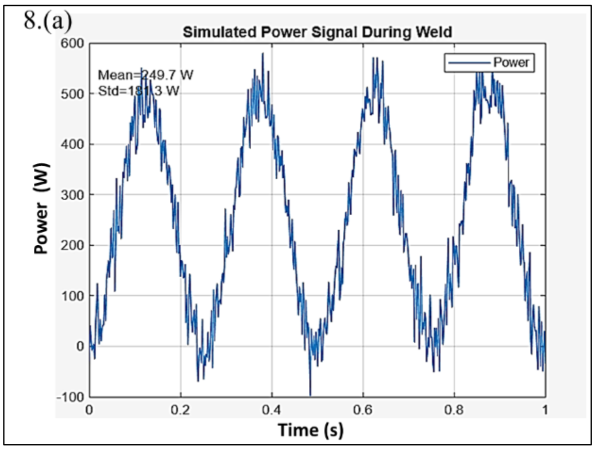



**Fig. 7.** Parametric influences of input parameters on the outcomes-energy and tensile strength



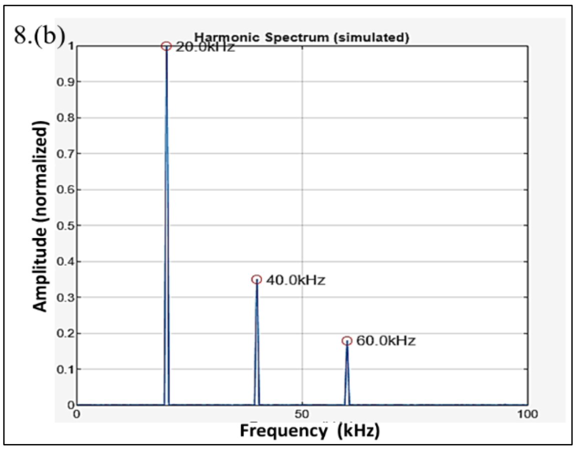




**Fig. 8.** The power signal variations and distortion/harmonic spectrum when the ultrasonic welding process is ON

## 5. CONCLUSIONS

Ultrasonic welding is observed to successfully join dissimilar polymers (PP and EDS-ABS) despite their different thermal and molecular characteristics, confirming the feasibility of such hybrid joints.

The work has involved using MATLAB for the analysis of power signals and harmonics during the weld process. The insights obtained as part of this study can help tune the signals and control mechanisms to achieve an efficient and accurate welding procedure.

The developed correlation-based model supports targeted parameter tuning, helping identify optimal regions where acceptable strength is achieved with controlled energy usage. Pearson correlation reveals positive correlation between amplitude, weld time and tensile strength, indicating their dominant role in improving joint performance in PP-EDS-ABS ultrasonic welding.

These also result in increased energy consumption. Thus, an optimal parametric range must be selected. MATLAB-based power and harmonic analyses exposed real-time electromechanical variations, enabling deeper understanding of the impact of ultrasonic resonance and distortions on the weld characteristics.

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