MULTI-CRITERIA NUMERICAL OPTIMIZATION OF MECHANICAL PROPERTIES IN ULTRASONIC WELDING PROCESS PARAMETERS OF PVC-COATED HYBRID TEXTILES FOR WEATHER PROTECTION

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ABSTRACT

A series of research was carried out to determine the correlation between ultrasonic welding process parameters and weld seam mechanical properties. However, multi-objective numerical optimization of coated hybrid textiles for weather protection has not been addressed. To ensure a comprehensive evaluation of ultrasonic weld seams, the research investigates the optimal solution of the multi-objective function of ultrasonic welding process parameters and formulates a single criteria objective function. Lapped and superimposed types of seams were applied based on 3^3 factorial designs of experiments for 6 and 12 mm welding widths. Single-criteria objective functions instead of three independent problems were developed as a generalized utility function. A single-criteria optimization method was introduced through predetermined weight and normalization within the range of acceptable/unacceptable values. Numerical and graphical optimization methods were also applied to determine possible optimal solutions through generalized utility functions. The best optimal value of the generalized utility function (0.670425 and 0.944374) was attained at welding speed (2 and 2.01564 m/min), power (93.756 and 117.973 W), and pressure force (198.803 and 239.756 N) of 6 and 12 mm welding widths, respectively. The acceptable range of satisfactory values was determined for the roof and wall of awnings and camping tents through standard, in which seam performance level indicated. Nonlinear quadratic numerical models were formulated to estimate the generalized utility function, and their results were close to the regressed diagonal line against the actual points. The statistical analysis was shown a statistically significant effect of welding process parameters on the generalized utility function.

KEYWORDS

Ultrasonic welding; Welding process parameters; Tensile strength; Hydrostatic pressure resistance, Peel strength, Multi-objective optimization.

INTRODUCTION

Ultrasonic welding is one of the most popular industrial welding techniques for joining thermoplastic materials, and it becomes an important method for welding polymeric composites, especially for coated and laminated hybrid textile materials. Ultrasonic welding is a technique that uses high-frequency ultrasonic vibration applied locally to workpieces held together under pressure to generate heat during welding for various technical applications. Ultrasonic welding is also a physical process in which no chemical changes are observed during welding. The other method that has to be discussed in this paper is multi-criteria optimization. The method of multi-criteria decision-making provides a solution when multi-objective optimization is necessary. Multi-criteria optimization issues emerge when there isn't a single criterion to evaluate the quality of a doable solution. It can be troublesome to discover a single viable solution that meets all of the criteria if several criteria are contradictory. Hence, a few compromises are required. Multi-objective optimization has recently become a useful tool for making a decision. There has been a lot of effort put into solving actual industrial challenges with multiple objectives in mind. For example, Szafranska and Korycki [1] have reported the multi-criteria optimization of mechanical properties and explored the impact of temperature, time, and pressure on laminated seam durability and stability. The authors obtained a good mathematical model of generalized utility function to forecast

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variations in seams of mechanical properties due to lamination process parameters. Sathananthan et al. [2] have also achieved the optimal welding condition at maximum weld joint strength using multi-objective optimization of plastic welding parameters through grey relational analysis to improve the weldability of plastic material and production rate. The authors investigated the effect of joint configurations, hold time, weld time, and pressure on welding tensile strength and percent elongation of polymethyl methacrylate.

As Ramesh and Panneerselvam [3] analyzed the optimization of ultrasonic welding in high-density polyethylene 5%-polybenzimidazole composite, the optimal amount of input parameters for multi-objective optimization criteria (shear strength and shore hardness) have been revealed by combining the entropy weight approach with the combinative distance-based assessment technique. The authors attained a relative evaluation score of 2.444 at 60 ms welding time, 21 Hz amplitude, and 2.5 MPa pressure. To clarify these issues further, Meng et al. [4] have studied the multi-objective optimization of peel and shear strengths in ultrasonic metal welding using machine learning-based response surface methodology and optimized both quality indices jointly. Mongan et al. [5] have researched multi-objective optimization of ultrasonically welded dissimilar joints through machine learning and investigated the influence of weld process parameters on lap shear strength, process repeatability, and defects. Satpathy et al. [6] reported the modeling and optimization of ultrasonic welding on dissimilar sheets using a fuzzy-based genetic algorithm and found the optimal amplitude, pressure, and time to tensile shear stress, T-peel stress, and weld area and better results on fuzzy than genetic algorithm. He et al. [7] have studied multi-objective optimization using network-based multi-agent reinforcement learning. Sada [8] has noted the use of the multi-objective genetic algorithm for optimizing the process parameters and predicting weld quality and exploded an optimal weld strength (546.8 N/mm^2) and hardness (159.1 N/mm^2) at welding current (140 A), voltage (24.9 V), gas flow rate (20 l/min), and filler rod diameter (2.4 mm). Zhang et al. [9] have stated the multi-objective optimization of the welding process of glass fiber-reinforced polypropylene composites and investigated the optimal process parameters of weld current (12.5 A), pressure (2.5 MPa), and time (540 s). Cerda-Flores et al. [10] have reviewed the applications of multi-objective optimization to industrial processes that presented a broad panorama of applications, including future perspectives and open questions.

Apart from these, the weld seams of PVC-coated hybrid textile materials were analyzed according to the selected mechanical properties and applied welding widths, including the sewn seam conventionally [11,12]. According to these, the effect of welding process parameters (welding pressure force, power, and speed) for 6 and 12 mm welding widths and sewing parameters (stitch pattern, width, and length) have been investigated on hydrostatic pressure resistance, peel strength, and tensile strength, including thermal and chemical analysis as well as variation in the width of a heat-affected zone of the weld seam [11-13]. The value of hydrostatic pressure resistance decreased with the increase in welding pressure force and speed for both welding widths [12]. Whereas, the value of tensile and peel strength increased with the increase in welding pressure force and power for both welding widths [11, 13, 14]. However, the optimization was performed for every single objective function independently. Szafranska and Korycki [15] have researched on mechanical properties of laminated seams to analyze the seam quality by the influence of lamination process parameters (temperature, time, and pressure) on laminated seam strength properties. Hussen et al. [13] analyzed the parametric influence of ultrasonic welding on the seam quality of peel strength and examined the effective weld locations and morphology at the joining interface. Since the width of the weld seam and depth of weld penetration are the most important factors to determine the weld seam quality, Hussen et al. [11] have used the weld seam width variation to estimate weld seam tensile strength through ultrasonic welding parameters. The influences of ultrasonic welding parameters on the quality of weld seam bond strength, water permeability, and peel strength were discussed further as follows. Wu et al. [16] have investigated the weld strength of polyolefin and reported that the amplitude of vibrations is a dominant factor. Rani et al. [17] have stated the joint strength of ultrasonic welding for acrylonitrile butadiene styrene and high-density polyethylene and found that the welding time and pressure significantly affected the joint strength. Ayse and Bahar [18] investigated the water permeability of ultrasonic seaming on PU-coated fabrics and observed that the waterproofing values decreased with the increase in seaming velocity. Rajput et al. [19] have studied the peel strength of ultrasonic welding on polypropylene and investigated that the amplitude had a significant effect on the peel strength and the most influencing variable than hold time and weld time.

Although a lot of previous studies have been performed on the multi-objective optimization of ultrasonic welding for rigid materials using a plunge type of welding, the research on multi-objective optimization of PVC-coated hybrid textile materials using a continuous type of ultrasonic welding is relatively rare including bonding and heating mechanisms. The impact of ultrasonic welding process parameters on comprehensive mechanical properties with their quality aspect of the weld seam for technical applications, especially for weather protection, has not been addressed to the knowledge of the authors. Most knowledge on ultrasonic welding of hybrid textile materials has been acquired with one objective function. This paper aims to introduce the multi-criteria seam quality optimization of two distinct welding widths for weather protection, concerning the effect of welding process parameters (pressure force, power, and speed) on mechanical properties (hydrostatic pressure resistance, tensile strength, and peel strength) of the seams with their tendencies in the relations. The single-criteria optimization is introduced rather than three independent optimization problems to obtain an objective function called the generalized utility function through a weighted average of criteria with predetermined weight values. A review of available literature has revealed that the multi-criteria optimization of PVC-coated hybrid textile welded seam for 6 and 12 mm welding widths are generally unknown. It is, therefore, that the following points can be recognized originally. (i) Instead of solving three individual optimization problems, the generalized utility function was developed and applied as a weighted average of criteria functions. (ii) Statistical significances of welding pressure force, power, and speed on generalized utility function were analyzed for both weld seams. (iii) The ranges of satisfactory and very good values were determined based on preliminary experimental results according to ISO 10966 standards [20]. (iv) The predetermined weight and acceptable values of the range were used to solve the multi-criteria weighted optimization. (v) The method is ubiquitous and simply necessitates statistical calculations. It is not necessary to conduct new seams tests if alternate satisfactory and very good ranges and/or weights of specific features are adopted.

EXPERIMENTAL PROCEDURE

A hybrid textile material (H5571-0283-ECO) was used in this study. It was provided by a HEYtex Bramsche GmbH Company in Germany as a common tent material for light structures. It had a plain weave construction with the same fabric setting (8 PPC and 8 EPC) using 100 % air-jet polyester filaments at 1100 dtex linear density in both warp and weft directions. It was coated with PVC using a plasticizer to make the material more flexible and durable. It was intended to use for awnings and camping tents. According to ISO 10966 standards [20], the material requirements were split into two levels (A and B) for awnings and camping tents. Level A requirements were applied for the severe strain caused by weather conditions or long-term use; whereas, the requirements for level B were applied for less severe use. The physical and mechanical properties of the tested hybrid textile material listed in Table 1 were fulfilled the minimum requirements of ISO 10966 standards [20] for the roof and wall (the outer tent's fabric directly exposed to the influence of weather in practical use) of awnings and camping tents made of coated fabrics for both levels. Due to this, PVC-coated hybrid textile material was selected for this research purpose in addition to its ultrasonic welding compatibility. It is, therefore, applicable for weather protection or the roof and wall of awnings as snow, residential, and touring awnings and for camping tents as sleeping with standard and light-weight, touring, and residential tents for both levels.

A new-generation NUCLEUS ROTOSONIC DX1 continuous ultrasonic machine was used to carry out welding. It was produced by NUCLEUS GmbH Company in Germany with DG1 1000 W ultrasonic generator at a 35 kHz frequency. Ultrasonic welding was carried out with a flat anvil wheel for 6 and 12 mm welding widths considering the application area of the material. Welding pressure force, speed, and power were considered as input ultrasonic welding process parameters. The working ranges of these welding process parameters for selected PVC-coated hybrid textile material were investigated during the preliminary experiments. The welding power, speed, and pressure force of (40-100 W, 1-3 m/min, and 40-300 N) for 6 mm welding width and (60-120 W, 1-3 m/min, and 40-350 N) for 12 mm welding width were found as a working range of the material, respectively. Experimental design levels for both welding widths were set after identifying the material working range. Thus, 3^3 factorial designs of experiments were developed for both welding widths. It is, therefore, 27 different combinations of welding parameters were used considering three factors and three levels for each 6 and 12 mm welding width. The welding speed, pressure force, and power of ([2, 2.5, and 3 m/min], [150, 225, and 300 N], and [40, 70, and 100 W]) for 6 mm welding width and ([2, 2.5, and 3 m/min], [200, 275, and 350 N], and [60, 90, and 120 W]) for 12 mm welding width were selected level as per the preliminary experiments, respectively.

Table 1. Physical and mechanical properties of H5571-0283-ECO tentorium 650 materials [21].

Parameters	Base Fabric	Coating Material	Total Weight	Tensile Strength (W/F)	Tear Resistance (W/F)	Coating Adhesion	Flex Resistance	Temperature Resistance	Translucency
Specifications	100% PET	100% PVC	650 g/m^2	2200/2000 N/50mm	250/250 N	100 N/50mm	at least 100,000 bends	-30 to 70 ^{0}C	17%
Standards	DIN ISO 2076	DIN ISO 2076	DIN EN ISO 2286-2	DIN EN ISO 1421-1	DIN 53363	DIN EN ISO 2411	DIN 53359 A	DIN EN 1876-1 & N-Q-PA-1057	PA 2001/41

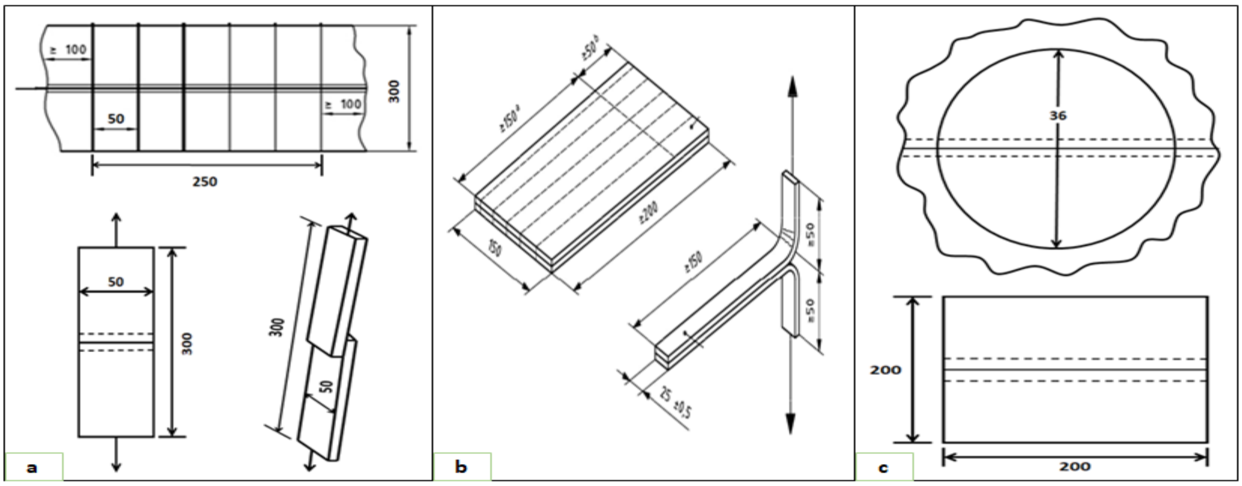

Figure 1. Method of sample preparation and testing procedure for tensile strength (a), peel strength (b), hydrostatic pressure resistance (c), and all measurements are in millimeters.

Based on the developed experimental design and/or welding parameters combinations, the ultrasonic weld samples were prepared using lapped and superimposed types of seams in the warp direction. A suitable lapped type of seam was applied for weld seam tensile strength and hydrostatic pressure resistance, while a superimposed type of seam was used for the case of peel strength during welding. Out of 27 combinations for each welding width and the response variable, only 21 and 24 welding combinations were able to produce welded seams properly for 6 and 12 mm welding widths, respectively. The response or output variables were also selected according to ISO 10966, ISO 8937, and ISO 5912 standards [20, 22 23] as well as the functional requirements of specific end-use or applications. Due to this, the ultrasonic weld seams were tested for tensile strength, peel strength, and hydrostatic pressure resistance. The tensile strength of the ultrasonically welded sample was determined using Zwick/Roell-Zmart.Pro strip tensile testing machine at 100 mm/min rate of extension and 200 mm gauge length according to DIN EN ISO 13935-1 standards [24], cf. Figure 1(a). The adhesive/peel strength of the ultrasonically welded sample was also tested on the Zwick/Roell-Zmart.Pro tensile testing machine with a constant test speed of 100 mm/min and clamping length of 50 mm according to DIN EN ISO 11339 standards [25], cf. Figure 1b. Whereas, the hydrostatic pressure test for water penetration resistance of ultrasonically welded sample was measured on the TEXTEST INSTRUMENTS FX 3000 HYDROTESTER III testing machine with 60 + 3 cmH_2O/min rate of increasing water pressure on the face of the fabric from the bottom side of the test specimen until penetration occurs in three places using distilled water according to DIN EN ISO 811 standards [26], cf. Figure 1c. The method of sample preparation and testing procedure for tensile strength, peel strength, and hydrostatic pressure resistance are further elaborated by Figures 1a, 1b, and 1c, respectively. Furthermore, all measurements were performed under DIN EN ISO 139 standards [27] at a temperature of 20 + 2°C and relative humidity of 65 + 4 % after conditioning for 24 hours. The geometric means of the test results were determined and presented for each combination of welding widths in each tensile strength, peel strength, and hydrostatic pressure resistance test.

RESULTS AND DISCUSSION

The physical and mechanical properties of the material have met the requirements of awnings and camping tents for long-term use in all weather conditions. Hence, it is required to investigate the joint/connection properties of the material. Not only the material but also the joint/connection properties of the material shall meet the requirements specified in ISO 5912 standards [23]. Due to this, multiple-factor experiments were conducted to determine the weld seam mechanical properties (tensile strength, hydrostatic pressure resistance, and peel strength) and their optimal value of ultrasonic welding process parameters (welding power, pressure force, and speed) using hybrid textile material. Five samples were tested for each welding combination in both welding widths for weld seam tensile strength and peel strength. Whereas, three samples were tested for each welding combination in both welding widths for hydrostatic pressure resistance. The geometric mean value of each experiment is presented in Table 2 as weld seam tensile strength (N/50 mm), hydrostatic pressure resistance (cmH_2O), and peel strength (N/welding widths). Because geometric mean better reflects a situation when a shortage in one element limits the result and cannot be compensated by other elements. The joint/connection strength should not be lower than 10 % of the tensile strength of the required strength of connected material for a given application as per ISO 5912 standards [23].

Table 2. Geometric mean (SD) results of weld seam tensile strength (N/50 mm), hydrostatic pressure resistance (cmH_2O), and peel strength (N/welding widths) for 6 and 12 mm welding widths.

For 6 mm welding width						For 12 mm welding width					
Pressure Force (N)	Power (W)	Speed (m/min)	Geometric Mean (SD)			Pressure Force (N)	Power (W)	Speed (m/min)	Geometric Mean (SD)		
			Tensile Strength of F max. (N/50 mm)	Hydrostatic Pressure Resistance (cmH_2O)	Peel Strength (N/6 mm)				Tensile Strength of F max. (N/50 mm)	Hydrostatic Pressure Resistance (cmH_2O)	Peel Strength (N/12 mm)
150	40	2	656.73 (31.75)	177.33 (9.66)	15.23 (1.36)	200	60	2	1499.35 (97.83)	438.58 (10.50)	19.59 (0.80)
		2.5	-	-	-			2.5	384.51 (54.49)	373.93 (9.17)	17.08 (2.13)
		3	-	-	-			3	-	-	-
	70	2	975.22 (86.98)	201.85 (51.91)	16.95 (1.43)		90	2	1853.75 (76.32)	476.89 (12.53)	25.74 (2.11)
		2.5	952.26 (56.75)	152.50 (14.80)	14.65 (1.50)			2.5	1727.85 (74.54)	403.22 (11.68)	21.07 (1.85)
		3	972.84 (38.09)	142.41 (6.26)	13.98 (0.63)			3	735.81 (131.28)	298.21 (20.40)	18.39 (2.14)
	100	2	831.12 (66.64)	206.26 (12.13)	23.72 (0.99)		120	2	2025.48 (40.75)	554.50 (16.44)	30.58 (1.84)
		2.5	943.25 (134.46)	187.94 (6.08)	18.90 (1.39)			2.5	1894.54 (110.82)	478.93 (10.00)	28.36 (2.51)
		3	928.87 (64.28)	144.96 (4.36)	16.40 (1.27)			3	1697.93 (80.56)	379.00 (19.55)	23.56 (2.45)
225	40	2	819.22 (78.54)	166.34 (9.04)	16.16 (1.25)	275	60	2	1544.81 (72.76)	387.92 (9.54)	21.01 (2.70)
		2.5	-	-	-			2.5	483.74 (45.91)	321.54 (11.02)	18.24 (1.99)
		3	-	-	-			3	-	-	-
	70	2	992.75 (62.14)	164.89 (7.55)	18.22 (1.01)		90	2	1895.36 (97.77)	435.13 (16.26)	27.93 (1.32)
		2.5	952.50 (73.61)	163.96 (4.58)	15.67 (1.43)			2.5	1812.03 (19.17)	357.78 (15.39)	23.03 (2.15)
		3	960.99 (55.71)	142.82 (8.89)	15.37 (1.23)			3	827.76 (84.71)	254.66 (16.00)	19.71 (0.62)
	100	2	956.58 (138.34)	177.66 (13.23)	24.80 (0.82)		120	2	2072.73 (19.45)	502.80 (17.52)	32.60 (3.54)
		2.5	1095.93 (115.15)	156.76 (10.54)	19.73 (0.79)			2.5	1952.34 (31.72)	434.13 (16.26)	31.87 (2.24)
		3	1014.08 (28.67)	136.91 (6.08)	17.47 (1.51)			3	1822.83 (48.44)	330.16 (12.90)	26.37 (1.52)
300	40	2	770.46 (48.20)	151.94 (5.29)	17.00 (0.46)	350	60	2	1595.85 (114.06)	348.55 (11.24)	23.41 (1.34)
		2.5	-	-	-			2.5	568.20 (62.99)	278.20 (10.50)	21.38 (1.80)
		3	-	-	-			3	-	-	-
	70	2	1062.42 (119.32)	144.97 (3.61)	19.99 (1.43)		90	2	1919.71 (17.76)	401.06 (18.01)	28.46 (1.31)
		2.5	999.81 (36.40)	134.80 (8.89)	17.28 (1.29)			2.5	1882.19 (104.23)	317.04 (16.50)	25.93 (1.65)
		3	993.38 (51.16)	157.81 (9.54)	15.88 (1.04)			3	1025.22 (61.43)	220.88 (9.00)	21.38 (1.80)
	100	2	1245.21 (56.66)	147.29 (9.50)	25.39 (0.99)		120	2	2113.03 (94.46)	409.18 (13.87)	34.77 (1.32)
		2.5	1045.80 (91.97)	139.40 (6.50)	19.99 (1.53)			2.5	2055.81 (28.75)	341.55 (11.06)	32.67 (2.48)
		3	966.79 (51.26)	139.98 (14.91)	18.16 (1.28)			3	1894.54 (110.82)	301.11 (14.19)	29.17 (1.41)

Table 3 Determination of weight for particular criteria through the pair-wise comparison matrix and normalization

Source	Pairwise comparison matrix			Normalization			Weight
	Tensile strength	Hydrostatic pressure resistance	Peel strength	Tensile strength	Hydrostatic pressure resistance	Peel strength	
Tensile strength	1	2	4	1/1.75	2/3.33	4/8	0.56
Hydrostatic pressure resistance	1/2	1	3	0.5/1.75	1/3.33	3/8	0.32
Peel strength	1/4	1/3	1	0.25/1.75	0.33/3.33	1/8	0.12
Total sum	1.75	3.33	8	-	-	-	1

Due to this, more than 7 % (residential and snow awnings) and 62 % (touring awnings) of the welding combination of weld seam tensile strength investigated for 6 mm welding width attained the required roof standards for severe and long-term use while 62 % (residential, touring, and snow awnings) attending for the wall. Whereas for 12 mm welding width, more than 66 % (residential and snow awnings) and 70 % (touring awning) of the welding combination achieved the required roof standards of weld seam tensile strength for severe and long-term use while 70 % (residential, touring, and snow awnings) attending for the wall. On the other hand, more than 7 % (residential tent) and 62 % (touring tent) of the welding combination of weld seam tensile strength investigated for 6 mm welding width attained the required roof standards for severe and long-term use while 74 % (residential and touring tents) and 77 % (standard-weight and light-weight tents) attending for the wall. Whereas for 12 mm welding width, more than 66 % (residential tent) and 70 % (touring tent) of the welding combination achieved the required roof standards of weld seam tensile strength for severe and long-term use while 74 % (residential tent) and 77 % (touring, standard-weight, and light-weight tents) attending for wall, cf. Table 2. It was found that a higher standard weld seam was possible to produce for a 12 mm welding width than 6 mm for awnings and camping tents. This is due to the impact of welding width on welding pressure force to weld seam strength.

Formulation of generalized utility function

Developing a numerical equation for one selected objective function doesn't give a full picture of one specific application of the material, but it is important to analyze all necessary objective functions and their tendencies in the relationship at once. Thus, the goal of this paper is to evaluate welded seams for 6 and 12 mm welding widths using multi-criteria statistical optimization and generalized utility function, while all three investigated indexes (criteria of weld seam tensile strength, hydrostatic pressure resistance, and peel strength and a higher value of each property corresponds to better quality) change simultaneously. A generalized utility function is used to express a multi-objective function in a single-objective function. There are different solution strategies for converting a set of multi-objective problems into a single-objective problem. One of the most well-known methods is scalarization [28] through the weighted sum method using linear weighting to the quality of importance of different objective functions in the problem. The generalized utility function (*U*) is, therefore, expressed using Equation (1) and described as the weighted geometric mean of criteria functions. Where, 'w_i' denotes the weights assigned to each criterion and '$y^{(i)}$' represents each criterion; $0 \leq w_i \leq 1$; '$y_G^{(i)}$' denotes the minimum value of the criteria while '$y_L^{(i)}$' is assigned to the maximum and 'n' for the number of criteria; i = 1, 2, and n = 3.

$$U = \sum_{i=1}^{n} w_i * \frac{y^{(i)} - y_G^{(i)}}{y_L^{(i)} - y_G^{(i)}}, \qquad \sum_{i=1}^{n} w_i = 1 \tag{1}$$

To convert multi-objective problems into a single-objective problem called a generalized utility function, the first step is determining the weight of particular criteria and the second is scalarization through the weighted sum method. First, the individual criteria are defined by non-negative weighting factors, which reflect the importance of each criterion based on the analytic hierarchy process, regardless of the range of satisfactory values. As per the analytic hierarchy process, the weight of particular criteria was determined according to Saaty's [29,30] scales of relative importance for multi-attributes decision-making problems. The weighting factor's sum should always equal one.

The analytic hierarchy process of this research was started by developing the pair-wise comparison matrix based on the comparison of criteria through their relative scale of importance, and then the step followed the normalization process of the pair-wise comparison matrix through the linear scale transformation (sum) method by dividing each number with their total sum. And finally, the weight of particular criteria was set by taking the average of each row matrix after normalization, cf. Table 3. On the other hand, the weights of particular criteria and ranges of satisfactory values can be adopted depending on the technical requirements and consultations with the garment manufacturer's production engineers. This observation was also supported by Szafranska and Korycki [1] research. Although the weight of each criterion was determined, it required checking their consistency through consistency ratio. Thus to determine a consistency ratio; first, it should be determined consistency index

Table 4. Determination of lambda max through weighted sum value and lambda.

Source	Tensile strength	Hydrostatic pressure resistance	Peel strength	Weighted sum value	Lambda	Lambda Max
Weight	0.56	0.32	0.12	-	-	-
Tensile strength	1*0.56	2*0.32	4*0.12	1.68	1.68/056	3.016
Hydrostatic pressure resistance	1/2*0.56	1*0.32	3*0.12	0.96	0.96/0.32	
Peel strength	1/4*0.56	1/3*0.32	1*0.12	0.3656	0.3656/0.12	

after finding the value of lambda max using Equation (3); where '*n*' is the number of criteria.

$$\text{Consistency Ratio} = \frac{\text{Consistency Index}}{\text{Random Index}} \qquad (2)$$

$$\text{Consistency Index} = \frac{\text{Lambda max.} - \text{n}}{\text{n} - 1} \qquad (3)$$

The value of lambda max was determined through the following steps: first, the pair-wise comparison matrix was multiplied by their weight before normalization and found the weighted sum value. And then the value of lambda was calculated by dividing the weighted sum value by their weight. Finally, lambda max was found by taking the average value of lambda, cf. Table 4. Since the number of criteria for this research is three, the calculated consistency index is equal to 0.008 based on the evaluated result of lambda max. Using the random index (standard value) stated by Saaty [29, 30] for three criteria (0.58), the consistency ratio was calculated by taking a ratio of consistency index to random index (0.008/0.58) as mentioned in Equation (2), which is equal to 0.0138. If the consistency ratio is less than 0.1, the weight is accepted, but if it is greater than 0.1, it needs to re-evaluate the pair-wise comparison matrix. Hence, it can be concluded that the developed weight for this research is accepted. The most essential index, according to the evaluated results of the multi-criteria functions, was the maximum breaking force of tensile strength (N/50 mm) with the greatest weight of 0.56. The other indexes for hydrostatic pressure resistance (cmH_2O) and peel strength (N/welding widths) were distinguished by lower weights of 0.32 and 0.12, respectively. The sum of all three assigned weights is one, as presented in Table 3.

The second step is scalarization through the weighted sum method as mentioned above. To sum up all three criteria into one, the experimental value of each criterion has to be normalized first and determine the weighted sum values of all criteria second; and based on the regression analysis of weighted sum values, the generalized utility function can be developed at the end. The normalization of each criterion was performed with the minimum-maximum normalization method to make all criteria scale-less and to scale down the values between 0 and 1. Thus, all considered values of criteria were ranked on a scale with no dimensions. A scale was created by selecting a range of values for each criterion by limiting the worst and best values. After normalizing each value of the criteria, the weighted sum values of all criteria were determined through a simple additive weighting method as mentioned above. The values of the generalized utility function or weighted sum values were obtained based on the experimental results considering the values with appropriate ranges and weights of specific criteria, cf. Table 2. The value of the generalized utility function is, therefore, characterized by values in the range of 0 to 1. This is because of the normalization process performed early. Numbers near 0 correlate to the feature's most unfavorable values, while numbers close to 1 correspond to the feature's most favorable values. In the other words, the higher the value, the more advantageous the tested weld seam's qualities are seen. Thereby, the specific value of the generalized utility function enabled the evaluation of the tested weld seam in terms of the whole set of adopted criteria and their relative importance. It was included in Table 5 that the values of the generalized utility function for 6 and 12 mm welding widths were tested at varying values of welding pressure force, power, and speed.

The values of the generalized utility function were determined based on the experimental results and ranged from 0.204 to 0.736 for 6 mm welding width and from 0.137 to 0.943 for 12 mm welding width. At the highest welding pressure force (300 N) and highest welding power (100 W) of 2 m/min welding speed, the maximum value of generalized utility function was achieved, but the lowest welding pressure force (150 N) and lowest welding power (40 W) yielded the minimum value of generalized utility function at 2 m/min welding speed for 6 mm welding width, cf. Table 5. In the case of 12 mm welding width, the maximum value of generalized utility function was attained at the lowest welding pressure force (200 N) and highest welding power (120 W) of 2 m/min welding speed, whereas the lowest welding power (60 W) and medium welding pressure force (275 N) of 2.5 m/min welding speed provided the minimum value of generalized utility function, cf. Table 5. According to these results, the minimum and maximum values of generalized utility function were attained at different welding process parameters compared to the minimum and maximum values of tensile strength, hydrostatic pressure resistance, and peel strength independently. This is due to the impact of welding pressure force on tensile strength, hydrostatic pressure resistance, and peel strength

Table 5. Values of generalized utility function for 6 and 12 mm welding widths at different pressure force, power, and speed.

For 6 mm welding width					For 12 mm welding width				
Pressure Force (N)	**Power (W)**	**Speed (m/min)**	**Value of generalized utility function**	**Predicted value of generalized utility function**	**Pressure Force (N)**	**Power (W)**	**Speed (m/min)**	**Value of generalized utility function**	**Predicted value of generalized utility function**
150	40	2	0.204	0.217	200	60	2	0.587	0.572
150	40	2.5	-	-	200	60	2.5	0.147	0.248
150	40	3	-	-	200	60	3	-	-
150	70	2	0.635	0.574	200	90	2	0.780	0.776
150	70	2.5	0.368	0.393	200	90	2.5	0.637	0.525
150	70	3	0.335	0.322	200	90	3	0.197	0.274
150	100	2	0.588	0.655	200	120	2	0.943	0.980
150	100	2.5	0.562	0.466	200	120	2.5	0.813	0.802
150	100	3	0.330	0.387	200	120	3	0.621	0.625
225	40	2	0.319	0.216	275	60	2	0.563	0.553
225	40	2.5	-	-	275	60	2.5	0.137	0.246
225	40	3	-	-	275	60	3	-	-
225	70	2	0.499	0.577	275	90	2	0.769	0.751
225	70	2.5	0.430	0.407	275	90	2.5	0.634	0.518
225	70	3	0.340	0.345	275	90	3	0.194	0.284
225	100	2	0.591	0.663	275	120	2	0.923	0.949
225	100	2.5	0.577	0.485	275	120	2.5	0.813	0.789
225	100	3	0.386	0.415	275	120	3	0.634	0.629
300	40	2	0.217	0.193	350	60	2	0.558	0.535
300	40	2.5	-	-	350	60	2.5	0.144	0.245
300	40	3	-	-	350	60	3	-	-
300	70	2	0.495	0.559	350	90	2	0.747	0.726
300	70	2.5	0.361	0.399	350	90	2.5	0.638	0.510
300	70	3	0.443	0.347	350	90	3	0.237	0.294
300	100	2	0.736	0.650	350	120	2	0.861	0.917
300	100	2.5	0.454	0.481	350	120	2.5	0.763	0.775
300	100	3	0.362	0.421	350	120	3	0.648	0.633

Table 6. Fit and model summary statistics of generalized utility function for 6 and 12 mm welding widths.

Source		**For 6 mm welding width**				**For 12 mm welding width**			
		Linear	**2FI**	**Quadratic**	**Cubic**	**Linear**	**2FI**	**Quadratic**	**Cubic**
Utility Function	R^2	0.8274	0.8291	0.9323	0.963	0.9271	0.955	0.9572	0.9766
	Adjusted R^2	0.8049	0.7779	0.8965	0.9039	0.9176	0.9415	0.9346	0.9391
	Predicted R^2	0.7633	0.6881	0.8239	0.6092	0.8995	0.9278	0.8984	0.8577
	Sequential p-value	0.0001	0.9758	0.0011	0.3886	0.0001	0.0197	0.8293	0.3934
	Remarks	-	-	Suggested	Aliased	-	Suggested	-	Aliased

being different collectively and independently including their difference in weights. This perception was strengthened by research [12] according to which the welding pressure force had an inverse relationship with hydrostatic pressure resistance and had a positive relationship with tensile and peel strength up to certain limits.

Table 7. Coefficients and actual equation factors analysis of generalized utility function for 6 and 12 mm welding widths.

Source		For 6 mm welding width				For 12 mm welding width			
		Coefficient estimate	Actual equation factor	P-values	VIF	Coefficient estimate	Actual equation factor	P-values	VIF
Utility function	Intercept	0.405	1.0737	-	-	0.518	2.25882	-	-
	Pressure Force (F)	0.0026	0.000081	0.8788	1	-0.0073	-0.001028	0.6849	1
	Power (P)	0.2138	0.029472	0.0001	1	0.2713	-0.002491	0.0001	1
	Speed (V)	-0.1159	-1.33834	0.0001	1	-0.2333	-1.03822	0.0001	1
	F*P	0.0049	2.16E-06	0.8167	1	-0.0061	-2.72E-06	0.7797	1
	F*V	0.01	0.000266	0.6353	1	0.0176	0.00047	0.4236	1
	P*V	-0.0082	-0.000543	0.6982	1	0.0737	0.004913	0.0028	1
	F²	-0.0108	-1.92E-06	0.7166	1	-	-	-	-
	P²	-0.1381	-0.000153	0.0002	1	-	-	-	-
	V²	0.0542	0.216939	0.0809	1	-	-	-	-

The statistical analysis was performed for the values of the generalized utility function at a five-percent significance level to formulate the final generalized utility function and to investigate the significant effect of welding process parameters using Design Expert 11. The fit and model summary statistics of the generalized utility function are explained with their suggestion for 6 and 12 mm welding widths in Table 6. Using the result of fit summary analysis, a sequential model sum of square's analysis and model summary analysis based on the values of generalized utility function for both welding widths, nonlinear (quadratic) and linear numerical models were suggested and developed with a two-factor interaction (2FI) for generalized utility function of 6 and 12 mm welding widths, respectively. It was also inferred from Table 8 that the regression equations were formulated based on the range of acceptable values of the generalized utility function and allowed us to estimate the sensitivity of tested weld seam mechanical properties for various factors. For both welding widths, the regression models were significant, indicating that the input variables were a significant predictor of the generalized utility function. Thereby, the derived models adequately characterized the welding process, as evidenced by the value of the coefficient of determination (R^2). The R^2 was quite high (above 0.9) as shown in Table 8; consequently, the fitted models can be utilized to anticipate the relationship between the generalized utility function and input variables. Adequate precision measures the ratio of signal to noise. Since the ratio is more than four as shown in Table 8 for both welding widths, the design space can be navigated using this model. The models were also fitted to the experimental data given the difference between Adjusted R^2 and Predicted R^2 was smaller than 0.2. Moreover, the regression analysis revealed that the following factors had a significant impact: the main independent variables (welding power (P) and speed (V)) were significant predictors of generalized utility function for both welding widths except for the welding pressure force. The interaction effect between the welding power and speed (P*V) was the only significant predictor of the generalized utility function for 12 mm welding width; whereas, the interaction effect of welding power square (P^2) was the only significant predictor of the generalized utility function for 6 mm welding widths. This is supported by the low statistical significance values shown in Table 7, which states the estimated coefficient and actual equation factor analysis of a generalized utility function with a significant P-value for welding widths of 6 and 12 mm.

Substituting the numbers into the generated regression equations presented in Table 8, a set of predicted values of generalized utility function were obtained in the range from 0.041 to 0.663 for 6 mm welding width and from 0.245 to 0.98 for 12 mm welding width, cf. Table 5. These results indicated that the predicted values of the generalized utility function are being stayed within 0 to 1. The feature corresponding to the unfavorable values was specifically marked when the numbers were close to 0, whereas the feature corresponding to the most favorable values was specifically designated when the numbers were close to 1. It is, therefore, possible to anticipate the impact of welding process parameters on multi-objective functions through a single objective equation without experimental investigation on tensile strength, hydrostatic pressure resistance, and peel strength once the equation is formulated. The scale was also created by selecting a range of unsatisfactory, satisfactory, and very good values on the values of the generalized utility function based on standards [20, 22, 23]. It was developed for the roof and walls of awnings and camping tents for long and short-term uses. It indicated the performance level of weld seam for mentioned specific application. The range of values identified as satisfactory and very good scale within the effective application of weld seam required for awnings and camping tents as per the standards [20, 22, 23] based on the experimental test results of PVC-coated hybrid textiles for 6 and 12 mm welding widths, cf. Table 2. Furthermore, a set of values in the range of 0.322 to 0.499 and 0.217 to 0.443 for 6 mm welding width and 0.294 to 0.648 and 0.274 to 0.572 for 12 mm welding width were found as satisfactory values for the roof and wall of awnings to long and short-term use, respectively; whereas, the values of 0.559 to 0.736 and 0.454 to 0.736 for 6 mm welding width and 0.726 to 0.98 and 0.625 to 0.98 for 12 mm welding width were also investigated as very good values. On the other hand, the range of values from 0.322 to 0.577 and 0.217 to 0.443 for 6 mm welding width and 0.294 to 0.648 and 0.284 to 0.572 for 12 mm welding width were found as satisfactory values for the roof of camping tents to long and short-term use, respectively; whereas, the values of 0.65 to 0.736 and 0.454 to 0.736 for 6 mm welding width and 0.726 to 0.98 and 0.625 to 0.98 for 12 mm welding width were also investigated as very good values. Similarly, a set of values in the range of 0.193 to 0.499 and 0.193 to 0.443 for 6 mm welding width and 0.274 to 0.572 and 0.245 to 0.553 for 12 mm welding width were found as satisfactory values for the wall of camping tents to long and short-term use, respectively; whereas, the values of 0.559 to 0.736 and 0.454 to 0.736 for 6 mm welding width and 0.625 to 0.98 and 0.572 to 0.98 for 12 mm welding width were also investigated as very good values. Thus, these satisfactory and very good values were considered to be acceptable values for the roof and wall of awnings and camping tents requirement [20] based on the actual and predicted value of generalized utility functions. The rest unmentioned values were considered to be unacceptable including unsatisfactory and rejected values.

In the vicinity of this range, the generalized utility function is the most vulnerable to change in the value of a particular attribute. The broad range of acceptable and unacceptable values in the generalized utility function precludes the use of any variety of the tested variables. Users and producers want the seam to be maximum as durable and stable as possible. The following variants of variable factors ensured the generalized utility function within the range of satisfactory values for roof and wall of awnings and camping tents to long-term use as well as within the range of very good values. The following are the 6 mm welding width variants: welding pressure force (150, 225, and 300 N), power (70 and 100 W), and speed (2, 2.5, and 3 m/min) for satisfactory values and welding pressure force (150, 225, and 300 N), power (70 and 100 W), and speed (2 and 2.5 m/min) for very good values. The values are listed for welding widths of 12 mm as follows: welding pressure force (200, 275, and 350 N), power (60, 90, and 120 W), and speed (2, 2.5, and 3 m/min) for satisfactory values and welding pressure force (200, 275, and 350 N), power (90 and 120 W), and speed (2 and 2.5 m/min) for very good values. As a result of these findings, more variants of variable factors are possible to apply for 12 mm welding width than 6 mm welding width practically. Fewer variants of variable factors were found for the roof of camping tents compared to awnings for 6 mm welding width within the range of very good values. But in the case of 12 mm welding width, the variants of variable factors were the same for both awnings and camping tents. It was found that the welding speed and power were limited for both welding widths within the range of very good values and only welding power was limited for the 6 mm welding width within the range of satisfactory values for awnings and camping tents. This is due to the higher requirement set for very good values than satisfactory. It very likely causes the number of variants of variable factors in the range of satisfactory and very good values to reduce since the influence of welding pressure force on the value of generalized utility function was statistically negligible for both welding widths. A higher standard requirement was set for the roof compared to the wall of awnings and camping tents. The generalized utility function was used to assess both welding widths, taking into consideration all selected features and their importance. The selected variants of variable factors ensured the generalized utility function was at least within the acceptable range of satisfactory values. The results will be valid for other flexible and lightweight coated/laminated textile material for the roof and wall of awnings and camping tents if the material and welding conditions fulfilled the following aspects: a lower melting temperature difference (<22 °C) and a high amount of thermoplastic content (>65 %) with a closer thickness in addition to performing ultrasonic welding in the working range of welding parameters as part of a high-quality welding process based on a closer welding width and an identical anvil engraving. The values of combination factors resulted in a higher predicted value of generalized utility function of 0.663 and 0.98 for 6 and 12 mm welding widths, respectively.

The surface plots of generalized utility functions were constructed using the equations, to demonstrate the design points above and below the projected value for 6 and 12 mm welding widths at welding speeds of 2, 2.5, and 3 m/min in Figures 2 and 3, respectively. The surface plot also depicted the influence of welding process parameters on the generalized utility function. As the welding power increased from the lowest to the highest value for both welding widths, the generalized utility function of the weld seam drastically increased for all welding pressure forces at 2, 2.5, and 3 m/min welding speeds.

Table 8. Equation of generalized utility function for 6 and 12 mm welding widths based on actual equation factors.

Anvil wheel	General utility function (U)	R^2	Model P-value	Adequate Precision
For 6 mm welding width	$U = 1.0737 + 0.000081*F + 0.029472*P – 1.33834*V + 0.00000216207*F*P + 0.000266*F*V – 0.000543*P*V – 0.00000191775*F^2 - 0.000153*P^2 + 0.216939*V^2$	0.9323	0.0001	15.5604
For 12 mm welding width	$U = 2.25882 – 0.001028*F - 0.002491*P – 1.03822*V – 0.00000272112*F*P + 0.00047*F*V + 0.004913*P*V$	0.955	0.0001	27.7504

The effect of welding power is high for the highest welding speed than the lowest for all welding pressure forces. The effect of welding power is higher for the lowest welding pressure force than the highest at 2 and 2.5 m/min welding speeds while the opposite is true for a welding speed of 3 m/min. These results showed that the welding power positively affected the generalized utility function of the weld seam. The generalized utility function of the weld seam drastically decreased for all welding pressure forces with the rising welding speed from 2 to 3 m/min for both welding widths. The effect of welding speed is high for the lowest welding power than the highest for all welding pressure forces. These results showed that the welding speed had a higher negative effect on the generalized utility function of the weld seam. When the welding pressure force increased from the lowest to the highest value for both welding widths, the generalized utility function of the weld seam slightly decreased for all welding power at a welding speed of 2 m/min. The weld seam generalized utility function similarly decreased for the welding power of 90 and 120 W at 2.5 m/min welding speed with the rising welding pressure force from 200 to 350 N for 12 mm welding width while showing insignificant change for welding power of 60 W. But in the case of 6 mm welding width at 2.5 m/min welding speed, the weld seam generalized utility function for the welding power of 70 and 100 W slightly increased with the rising welding pressure force from 150 to 225 N while decreasing from 225 to 300 N. Whereas, the weld seam generalized utility function slightly increased for 70 and 100 W welding power of 6 mm welding width and 90 and 120 W welding power of 12 mm welding width at 3 m/min welding speed when the welding pressure force increased from the lowest to the highest value. The effect of welding pressure force increased with increasing welding power while decreased with increasing welding speed. Generally, the surface plot of the generalized utility function is quite different for 6 and 12 mm welding widths. It was observed that the influence of welding process parameters is different for each welding width, which is proved by the surface plots of 6 mm welding width, cf. Figures 2a, 2b, and 2c and 12 mm welding width, cf. Figures 3a, 3b, and 3c. The impacts of welding power and speed on the generalized utility function were higher for 6 mm welding width than 12 mm, and both welding widths were particularly sensitive to the welding speed than power according to the developed regression equations. Because the amount of energy transferred into the welding area is determined by the amount of vibration, and the number of cycles of mechanical vibration reached up to the material interface is affected by the welding speed. The surface plot analysis also allowed us to anticipate the maximum value of the generalized utility function for both welding widths. Based on the developed range of acceptable values, the maximum value of the generalized utility function was determined in a more extensive range of welding process parameters for 12 mm welding width while obtaining from a narrow range of values for 6 mm welding width. This observation is also explained and supported by the contour plot of the generalized utility function for 6 and 12 mm welding widths at 2, 2.5, and 3 m/min welding speeds shown in Figures 4 and 5, respectively. Furthermore, the actual verse predicted value of the generalized utility function is shown in Figure 6a for 6 mm welding width and Figure 6b for 12 mm welding width counting zero as a no-weld condition. According to these figures, the actual and predicted points were very close to the regressed diagonal line, especially for 12 mm welding width than that of 6 mm to the generalized utility function.

Statistical optimization

Graphical and numerical optimization methods were used to obtain the optimal value of ultrasonic welding process parameters for the generalized utility function. A generalized utility function is a converted single-objective function from a multi-objective function. It was developed by the regression analysis on the values of the generalized utility function, and these values were determined through a predetermined weight and normalization process. It is, therefore, used to express the multi-objective mechanical properties into a single form, and the statistical optimization was carried out through the generalized utility function. Because a single statistical optimization technique for one selected mechanical property or response variable doesn't show the correct optimal value of ultrasonic weld seam for the selected awnings or/and camping tents application. This is due to mainly the standard requirements set to express the selected application. Tensile strength, hydrostatic pressure resistance, and peel strength were the main important mechanical properties required for awnings and camping tents as per standards [20, 22, 23].

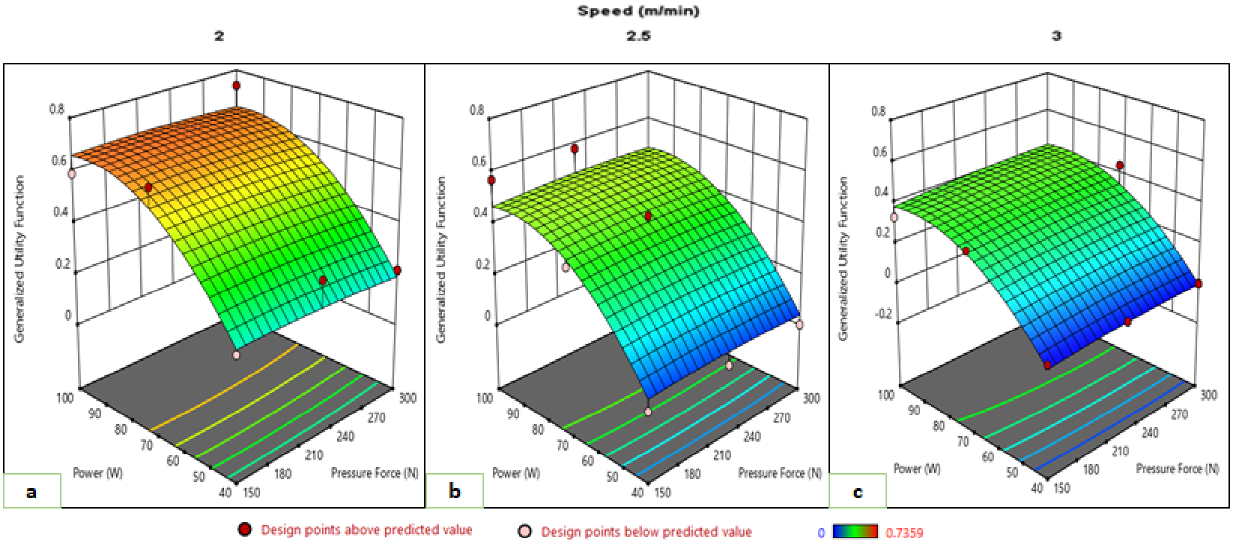

Figure 2. Surface plot of generalized utility function for 6 mm welding width at 2 (a), 2.5 (b), and 3 (c) m/min welding speeds.

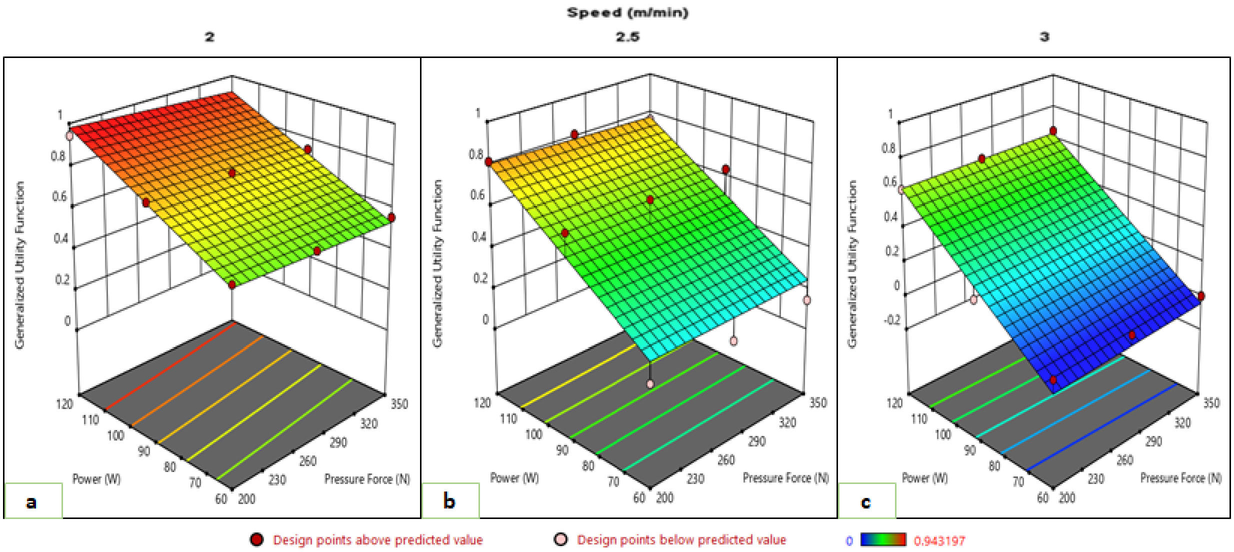

Figure 3. Surface plot of generalized utility function for 12 mm welding width at 2 (a), 2.5 (b), and 3 (c) m/min welding speeds.

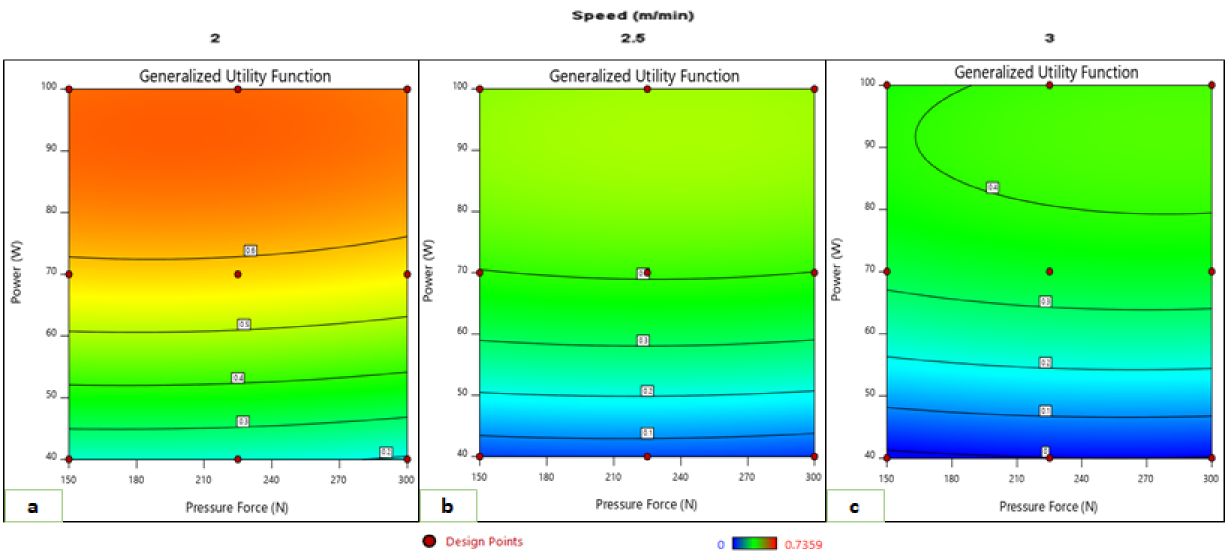

Figure 4. Contour plot of generalized utility function for 6 mm welding width at 2 (a), 2.5 (b), and 3 (c) m/min welding speeds.

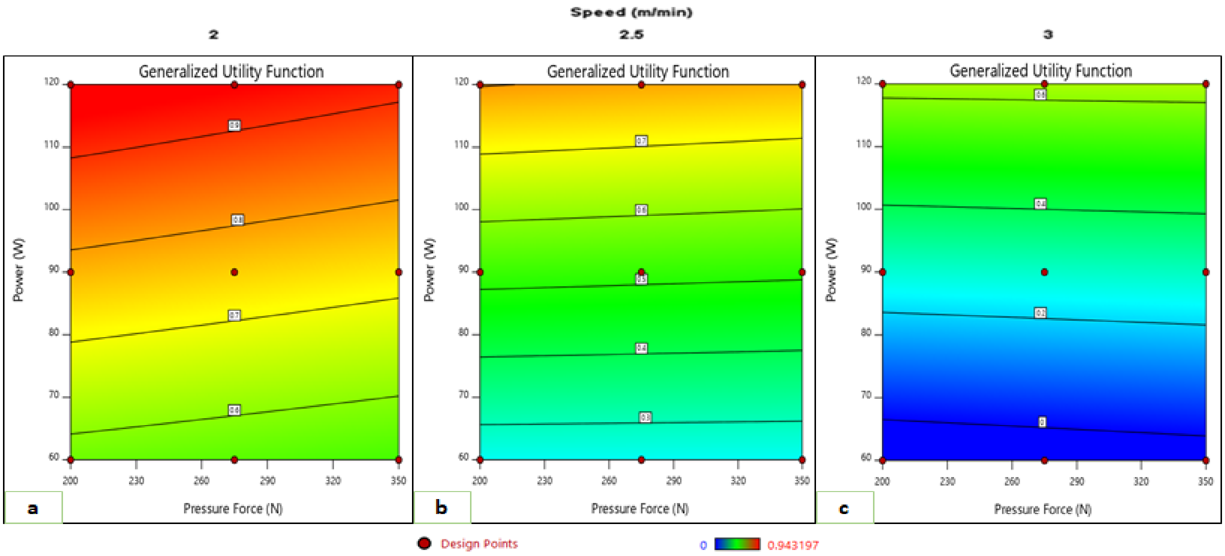

Figure 5. Contour plot of generalized utility function for 12 mm welding width at 2 (a), 2.5 (b), and 3 (c) m/min welding speeds.

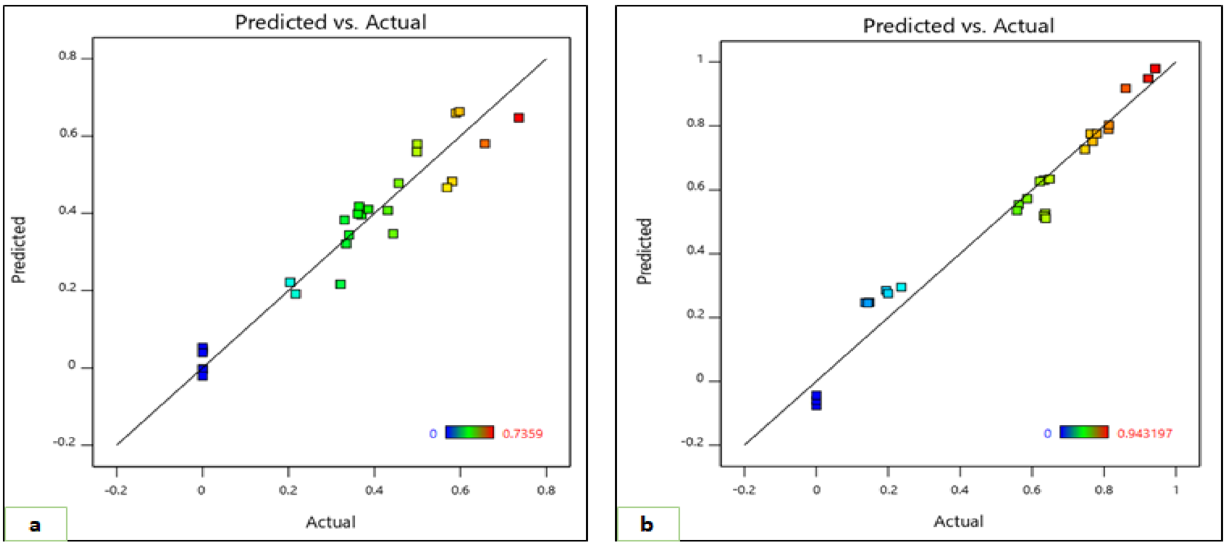

Figure 6. Actual vs predicted values for generalized utility function of 6 mm (a) and 12 mm (b) welding widths.

Additionally, Hussen et al. [11-13] stated that the welding pressure force had an inverse relationship with hydrostatic pressure resistance while having a direct relationship with tensile and peel strength up to certain limits. It is, therefore, important to find out the optimal value for all response variables simultaneously instead of finding them independently. Multi-objective optimization is an optimization technique for more than one desired goal and can be applied directly or indirectly. A direct approach commonly used all response variables at a time directly, while an indirect approach used the values of a single converted representative response variable called the generalized utility function. Both approaches consequently simplify the problem, but expressing a set of the response variable in a single objective function can make the result easy to understand for one selected application. Once the range was set and categorized into unacceptable (unsatisfactory and rejected) and acceptable (satisfactory and very good) values for the roof and wall of awnings and camping tents, it can be simple to understand and decide the weld seam performance in the application without analyzing them independently. On the other hand, it can be applied to a wide range of problems in which difficult to figure out the best solution directly and used the evaluation of standard functions and operations with several design constraints. These are the advantages of the proposed indirect approach. Thus, the optimal value of ultrasonic welding process parameters has been evaluated in graphical and numerical optimization methods where the generalized utility functions are maximized. These two different optimization methods were considered in this research for the seek of comparison purposes. The optimal weld seams are, therefore, produced for the highest values of all criteria.

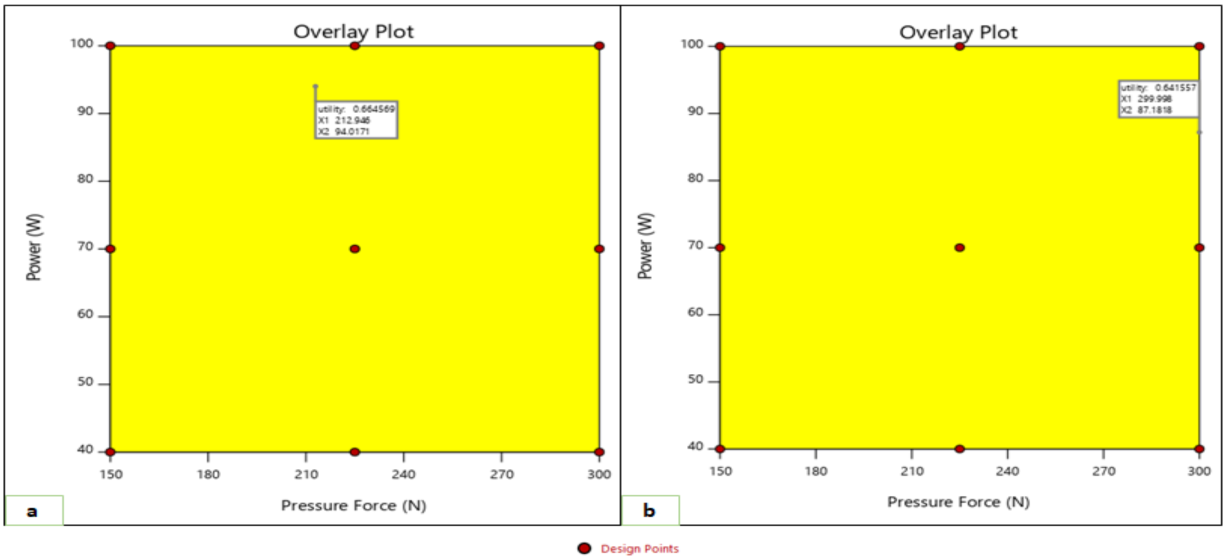

Figure 7. The best (a) and the least (b) optimal overlay plot of generalized utility function at 2 m/min welding speed for 6 mm welding width.

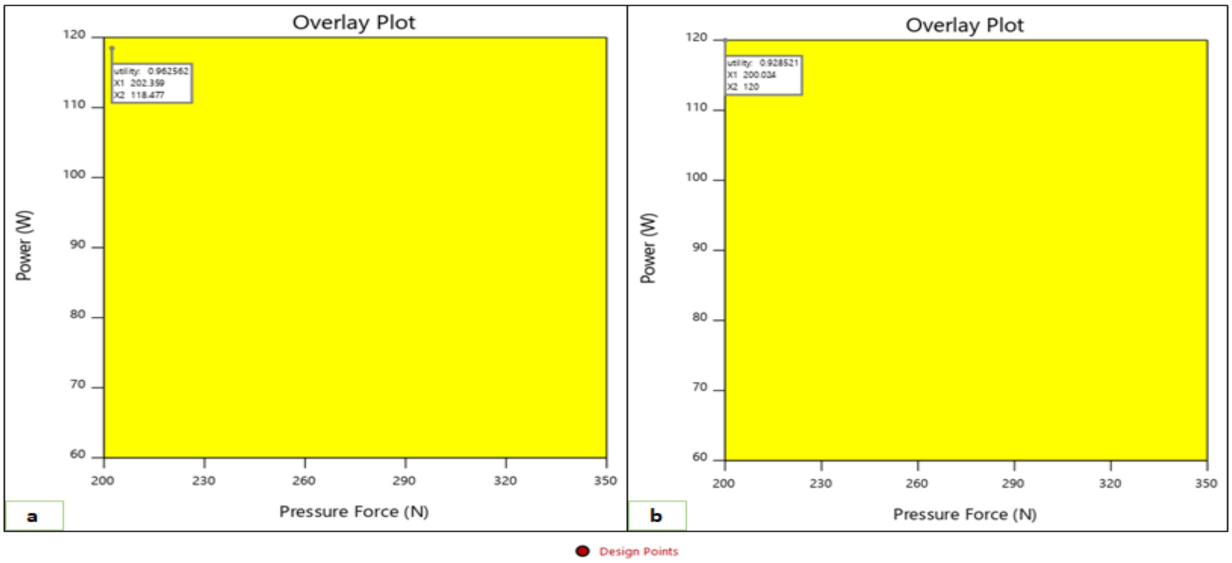

Figure 8. The best (a) and the least (b) optimal overlay plot of generalized utility function at 2.017 (a) and 2.145 (b) m/min welding speed for 12 mm welding width.

Graphical optimization: The minimum and maximum values of the generalized utility function were required to feed as input for further graphical optimization process using Design Expert 11. The values of 0.20357 and 0.7359 were set for the minimum and maximum value of the generalized utility function of 6 mm welding width, respectively; to find the optimal value of ultrasonic welding process parameters in the given range. Whereas for 12 mm welding width, the values of 0.13656 and 0.94318 were set for minimum and maximum values of the generalized utility function, respectively. As per the overlay plot of the generalized utility function, 84 different solutions were investigated for 6 mm welding width while 100 solutions were explored for 12 mm welding width. The solution was presented according to their order starting from the best to the least. The best (1st) optimal solution of the generalized utility function (0.665 at 0.903 desirability) was obtained at a welding speed of 2 m/min, power of 94.017 W, and pressure force of 212.946 N for 6 mm welding width; whereas, the least (88th) optimal solution of the generalized utility function (0.642 at 0.872 desirability) was investigated at a welding speed of 2 m/min, power of 87.182 W, and pressure force of 299.998 N. Similarly for 12 mm welding width, the best (1st) optimal solution of the generalized utility function (0.963 at 1 desirability) was obtained at a welding speed of 2.017 m/min, power of 118.477 W, and pressure force of 202.359 N. Whereas, the least (100th) optimal solution of the generalized utility function (0.929 at 0.984 desirability) were investigated at a welding speed of 2.145 m/min, power of 120 W, and pressure force of 200.024 N. Figures 7a and 7b demonstrate the best (1st) and the least (88th) optimal overlay plot of generalized utility function obtained using 6 mm plain anvil wheel at 2 m/min welding speed. For 12 mm welding width, Figures 8(a) and 8(b) exhibit the best (1st) and the least (100th) optimal overlay plot of the generalized utility function at 2.017 and 2.145 m/min welding speed, respectively.

Numerical optimization: Ultrasonic welding process parameters (welding pressure force, power, and speed) and generalized utility functions were set as a constraint during a multi-objective numerical optimization. This multi-criteria numerical optimization was performed after setting the goal, limit, weight, and importance of all listed constraints on Design Expert 11. The available options for selecting the goal of each constraint included maximize, minimize, in range, equal to, and targets. The upper and lower limits were taken from the actual value of the generalized utility function of the hybrid textile material for 6 and 12 mm welding widths. Each constraint's importance can be adjusted from one to five. Thus, the importance of welding pressure force, power, and speed were assigned as three out of five considering their goal within the range. For a welding width of 6 mm, the lower to upper limits of welding pressure force, power, and speed was established at 150 to 300 N, 40 to 100 W, and 2 to 3 m/min, respectively; while for a welding width of 12 mm, the lower to upper limits were set at 200 to 350 N, 60 to 120 W, and 2 to 3 m/min. Since the sum of all response variable weights was designed to be one as explained above, the weight considered for the generalized utility function was also equal to one. The goal of the weld seam generalized utility function was to maximize the result while staying within the lower to higher limit (0.20357 to 0.7359) for a 6 mm welding width and (0.13656 to 0.94318) for a 12 mm welding width, taking their importance into consideration as five of five.

The optimal value of the generalized utility function (0.665 and 0.963) was obtained at welding speed (2 and 2.017 m/min), power (94.017 and 118.477 W), and pressure force (212.946 and 202.359 N) of 6 and 12 mm welding widths, respectively. According to the numerical optimization results, generated numbers of possible iterated solutions were 88 and 100 for 6 and 12 mm welding widths, respectively; these iterated solutions were ordered based on the importance, desirability, and target setup of the generalized utility function. This observation is supported by Figures 9 and 10 that the first (1st) and the least (88th) optimal solution contour graphs for desirability and generalized utility function are produced for 6 mm welding width at the optimal welding speed of 2 m/min; and also supported by the Figures 11 and 12 that the first (1st) and the least (100th) optimal solution contour graphs are formed for 12 mm welding width at the optimal welding speeds of 2.017 and 2.145 m/min, respectively. Welding power is proportional to cost, while welding speed is relevant to production efficiency. Thus, the best numerically obtained optimal solutions indicated a lower product output rate and energy efficiency in terms of power savings. Furthermore, it was observed the same optimal values through both optimization methods used in this research. According to these findings, the best optimal setting parameters of the ultrasonic welding process should be suggested using either numerical or graphical optimization methods. The best optimal values of the generalized utility function for both welding widths were found in the range of very good values for the roof and wall of awnings and camping tents in which a very good weld seam performance was produced.

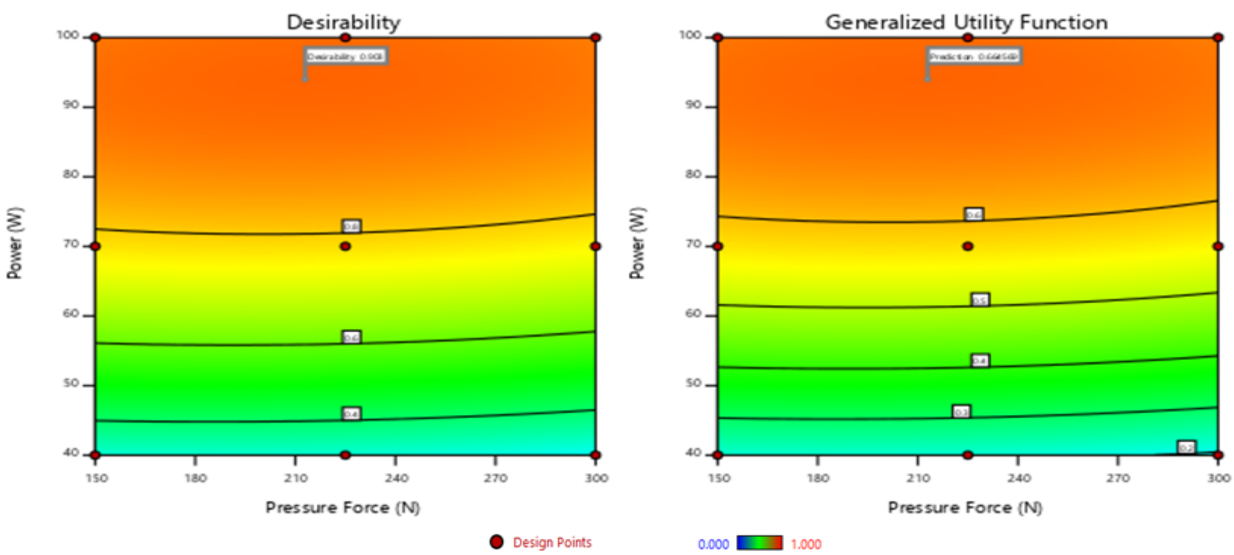

Figure 9. The first optimal solution contour plot of desirability and generalized utility function for 6 mm welding width at 2 m/min welding speed.

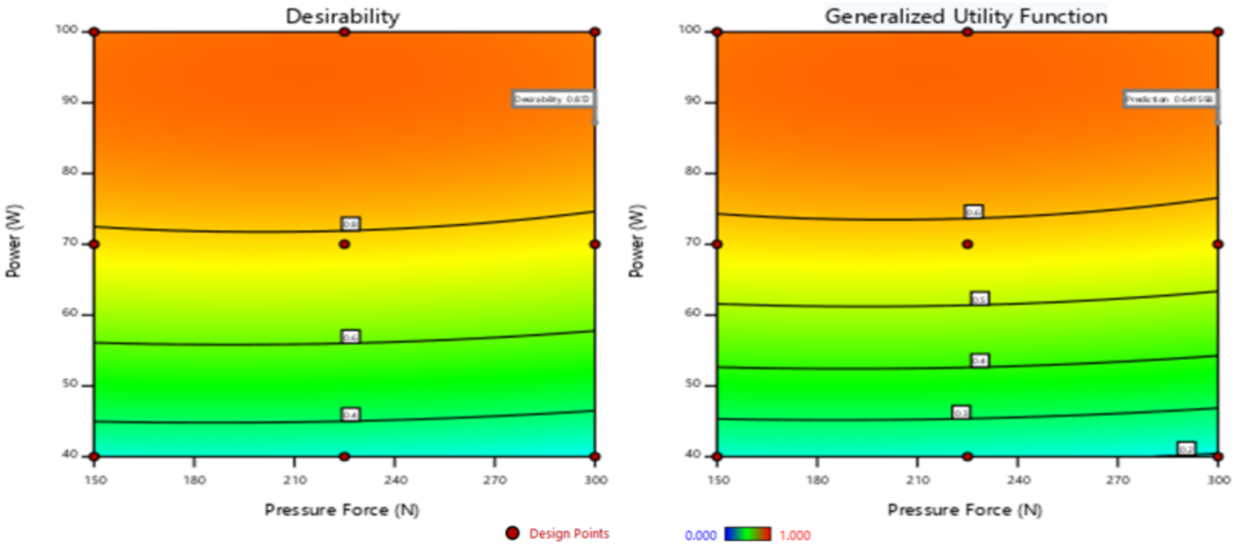

Figure 10. The least optimal solution contour plot of desirability and generalized utility function for 6 mm welding width at 2 m/min welding speed.

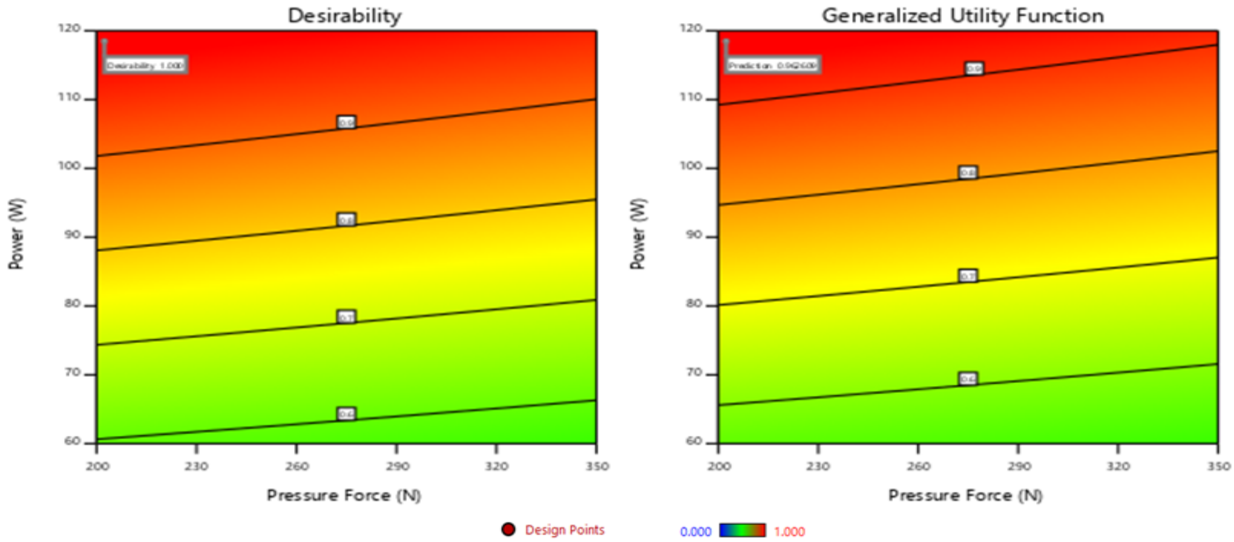

Figure 11. The first optimal solution contour plot of desirability and generalized utility function for 12 mm welding width at 2.017 m/min welding speed.

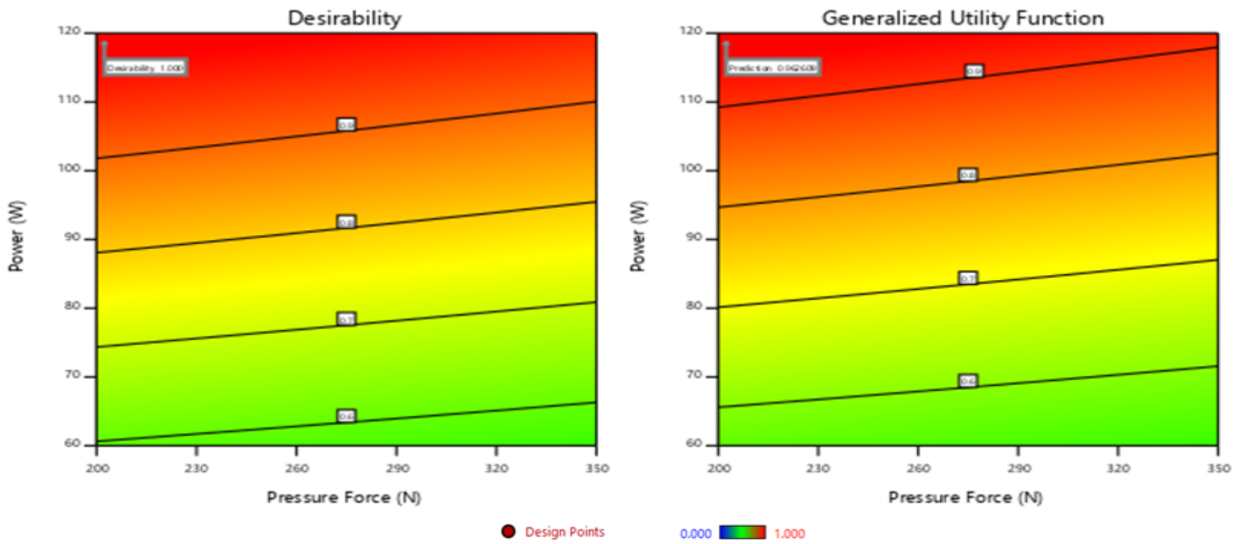

Figure 12. The first optimal solution contour plot of desirability and generalized utility function for 12 mm welding width at 2.017 m/min welding speed.

CONCLUSION

According to the statistical analysis, a significant effect of welding power and speed on generalized utility function was shown for both welding widths except welding pressure force. Tensile strength is the most important index with the greatest weight value of 0.56 than that of hydrostatic pressure resistance (0.32) and peel strength (0.12). It was investigated that the effect of welding power and speed on the generalized utility function was higher for 6 mm welding width than 12 mm. The generalized utility function was particularly sensitive to the welding speed than power for both welding widths. The lowest and highest values of generalized utility function were attained at different welding process parameters compared to the values of tensile strength, hydrostatic pressure resistance, and peel strength independently. It was observed that more variants of variable factors were possible to apply for 12 mm welding width than 6 mm. The number of variants of variable factors was smaller for the roof of camping tents compared to awnings for 6 mm welding width within the range of very good values. It was investigated that the variants of variable factors were higher within the range of satisfactory values compared to very good values for both welding widths. According to the multi-criteria statistical optimization, the optimal value of weld seam generalized utility function (0.665 and 0.963) was obtained at welding pressure force (212.946 and 202.359 N), power (94.017 and 118.477 W), and speed (2 and 2.017 m/min) of 6 and 12 mm welding widths, respectively. The optimal values were found within the range of very good values for both welding widths, and the same results were attained through numerical and graphical optimization methods. It can be concluded that the effect of ultrasonic welding process parameters on multi-objective functions can be predicted through a single equation without the experimental investigation of mechanical properties for PVC-coated textile materials. Furthermore, the research findings are important to adapt in the industrial production of the roof and wall of awnings and camping tents for infrequent and short-term use, moderate weather conditions, and extreme and long-term use.

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