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An Experimental Study on the Tensile Behaviors of Ultrasonic Welded T-joints for Polyamide Composite

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ABSTRACT

In this paper, an experimental investigation on ultrasonic welding of polyamide composites reinforced with glass fiber has been carried out. The effect of ultrasonic welding parameters, such as welding time, air pressure, holding time and the amount of glass fiber in the composite on tensile strength of weld joints were determined using response surface methodology. This methodology was applied for developing a mathematical model which can predict the main effects of the above parameters and their impacts on tensile strength of T-welded ultrasonic joints in 4-mm thick polyamide composite sheets. The analysis of variance was performed to check the adequacy of the developed model. A comparison was also made between the predicted and actual results. The results showed that a maximum failure force of about 4759 N is obtained when vibration amplitude, air pressure welding time, holding time and amount of glass fiber are 35 microns, 3.6 bar, 1.84 seconds, 0.9 seconds and 41 percent, respectively. The joint strength of welded parts increased with the fiber content in the composites.

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1. INTRODUCTION

In recent years, the utilization of glass fiber-reinforced polymer (GFRP) composite materials in many different engineering fields has undergone a tremendous increase [1-3]. Nylons (polyamides - PA) are high performance semi-crystalline thermoplastics with a number of attractive physical, chemical, and mechanical properties. Molded nylon parts are more resistant to fatigue, creep, repeated impact, and challenging chemical environments the parts made of many less-durable thermoplastics [4].

The demand for fiber glass reinforced nylon products is high in the automotive industries. In the automotive industry, metals have been replaced in parts such as air intake manifolds, air filter housings, resonators, timing gears, radiator fans and radiator tanks [5]. Since most applications cannot be molded as a single part, joining of sub components is often required [6].

Ultrasonic plastic welding is the joining of thermoplastics through the use of heat generated from high-frequency mechanical motion. That mechanical motion, along with applied force, creates frictional heat at the plastic components' joint area so the plastic material will melt and form a molecular bond between the parts. The applications of ultrasonic welding are extensive and can be found in many manufacturing industries such as electrical and computer, automotive and aerospace, medical, and packaging [7, 8].

Since the mid-1960s which the first ultrasonic welding was done, various novel papers have been written investigating the effects of ultrasonic welding (USW) process parameters on the joint strength and quality [9]. Prabhakaran et al. [10] studied the effect of contour laser welding parameters on T-joint weld strength of 30% glass reinforced nylon 6. In another study, Węglowska and Pietras presented an application of ultrasonic welding of dissimilar materials joints made of nylon 66 (PA66) and nylon 66 reinforced with 30% glass fibers (PA66 GF30) [11].

Liu et al. [12] optimized the joint strength of ultrasonically welded thermoplastic composites. The materials used were 15 and 35% glass-fiber filled nylon-

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6 composites. Moreover, Orías and Renaud [13] optimized the ultrasonic welding machine parameters such as welding time, holding time, and pressure on the burst strength of the joints of polyurethane specimens using Taguchi robust design. Nikoi et al. [14] experimentally investigated the tensile-shear strength and appearance of overlap joints in PP composites reinforced with GF fibers welded by USW method. The review of previous works shows that ultrasonic welding is used mainly for joining dissimilar materials [15, 16].

Reinforced plastics generally provide higher strength and stiffness than their unreinforced counterparts. Glass reinforced plastics are economical to produce and the addition of glass fibers in moderate quantities does not greatly increase the density of the material [17]. Ultrasonic welding studies have been previously performed on continuously reinforced polyamide, polypropylene. Most of the work done on these materials has involved lap joints. No previous work has been done on T welds using continuously reinforced thermoplastics.

Response surface methodology (RSM) is a statistical analysis technique for determining and representing the cause and effect relationship between true mean responses and input control variables influencing the responses. In RSM, a set of experiments was designed to measure a response of interest. Based on the results of these experiments, a mathematical model was developed to correlate the input control variables and the response [18, 19]. In the present work, Box-Behnken design of RSM was used to develop a model to predict the effect of amount of GF and ultrasonic welding parameters on joint strength of T welds in PA/GF composite samples with thickness of 4 mm and 15, 30 and 45 wt% of GF.

2. MATERIALS AND METHODS

2. 1. Experimental Design

In this work, an experiment was designed, based on a four factor three-level Box Behnken design, for two replications [20]. The Minitab statistical software was used to create the design matrix and analyze the experimental data. Amplitude of vibration, air pressure (P), welding time (T), holding time (H) of the welding process and amount of the glass fiber (G) were selected as the independently controllable input variables for carrying out the experiment to determine their effects on the weld strength. A number of trail runs were performed to determine the limits of the process parameters. On many ultrasonic welding machines, amplitude is dependent on booster and therefore is not easy to vary. Welding at the maximum allowable amplitude of the welder is a common industrial practice for the welding of similar materials to reduce cycle times. Finally for this study, the vibration amplitude was fixed at 35 µm. The criteria of choosing the practical limits of parameters were based on achieving good penetration welds without overheating. The process parameters, their ranges and levels which were used in the experimental design matrix are shown in Table 1.

2. 2. Methodology

In this study PA composite sheets of 150 mm×38 mm×4 mm dimension with different amounts of GF were prepared from extruded granules (PA+GF) by a hot press and no coupling agent was used. Three types of sheets made of PA6 (N215G, N230G, N245G) (KIMIAFOROOZ Co., Iran) were used. Table 2 shows the mechanical properties of the sheets.

Welded joints in ultrasonic welding of plastics cannot be produced without appropriate edge preparation. Basically, there are two types of joint design which are energy director joint and shear joint. However, in this research, energy director joint had been selected. Research done by Volkov [21] indicates that joint design is the most important thing in producing good ultrasonic welding joints where it relies on the type of thermoplastic to be bonded, part geometry and requirement of the weld. An energy director is normally a triangular edge on one of the joint surfaces. It serves to concentrate ultrasonic energy and rapidly initiates melting of the joining surfaces. Standardized samples with geometric energy directors-triangular was used in the experiments [21, 22]. Ultrasonic welding machine (Max whit-Taiwan) with maximum 2000 watt power and 15 kHz frequency is used to make the T welds. A rectangular Slotted horn of aluminum alloy with square cross section of 200 mm×30 mm with rounded corners was used. The fixture was designed to securely hold the vertically positioned web of the T-joint.

TABLE 1. Process control parameters and their limits

Levels	Notification	Unit	Parameters		
3	2	1			
45	30	15	GF	wt%	Glass fiber
4.5	3.5	2.5	P	Bar	Pressure
3	2	1	T	s	Weld Time
0.9	0.7	0.5	H	s	Hold Time

TABLE 2. Mechanical properties of GF/PA sheets based on ASTM/D836

Elongation at break (%)	Tensile stress at break (MPa)	Elastic modulus (MPa)	Type of material
16	89.4	6858.7	PA+15% GF
6	93.8	8553.8	PA+30% GF
4	112.7	22609.2	PA+ 45% GF

After designing the experiment, twenty seven test runs were repeated for two times, in an unordered manner as shown in Table 3 to prevent systematic errors. (Systematic errors in experimental measurements are caused by unknown and unpredictable changes in the experiment).

2. 3. Tensile Testing Method

First of all, the parts were cut from sheets with thickness of 4 mm. The weld geometry chosen in this study was a T-weld geometry selected based on AWS G1.1 standard as proposed by Kagan [22]. The web and the flange of the T-weld geometry and their dimensions are shown in Figure 1. A special tool was designed in order to test T-welded joints in tension. This tool was designed to constrain the flange of the T-joint when the specimen was subjected to a tensile load. Tensile test was done with a speed of 5 mm/min on a Zuker tensile testing machine. The tests were done to determine the failure force of welds, and the collected data were used to model the failure force of weld joints; values of obtained forces from the experiment are shown in Table 3.

3. DEVELOPMENT OF MATHEMATICAL MODELS

Minitab software is used for analysis of the measured responses and determining the mathematical tested using the sequential f-test, lack-of-fit test and the analysis-of-variance (ANOVA) technique using the same software to obtain the best fit model [23].

TABLE 3. Design matrix and measured experimental results

Failure force2 (N)	Failure force1 (N)	Holding time (s)	Welding time (s)	Pressure (bar)	GF %wt	No
1494	1552	0.7	1	3.5	15	1
3942	4099	0.7	1	3.5	45	2
1717	1936	0.7	3	3.5	15	3
3540	3552	0.7	3	3.5	45	4
3451	3732	0.5	2	2.5	30	5
3929	3440	0.9	2	2.5	30	6
3814	3549	0.5	2	4.5	30	7
3620	4002	0.9	2	4.5	30	8
1658	1650	0.7	2	2.5	15	9
3544	3857	0.7	2	2.5	45	10
1630	1537	0.7	2	4.5	15	11
4007	4280	0.7	2	4.5	45	12
3654	3410	0.5	1	3.5	30	13
2922	3284	0.5	3	3.5	30	14
3570	3855	0.9	1	3.5	30	15
3412	3557	0.9	3	3.5	30	16
1903	2252	0.5	2	3.5	15	17
4402	4231	0.5	2	3.5	45	18
2321	2177	0.9	2	3.5	15	19
5065	4975	0.9	2	3.5	45	20
2720	2940	0.7	1	2.5	30	21
2277	2411	0.7	3	2.5	30	22
3243	3400	0.7	1	4.5	30	23
3452	3587	0.7	3	4.5	30	24
4340	4445	0.7	2	3.5	30	25
3837	4122	0.7	2	3.5	30	26
4200	3950	0.7	2	3.5	30	27

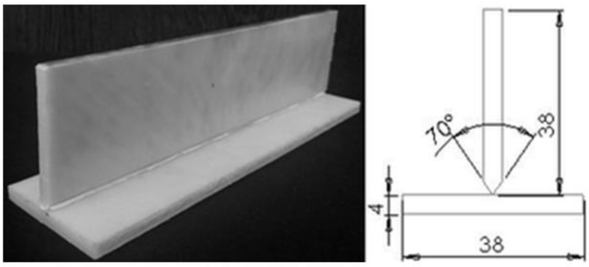

Figure 1. The welded sample in T joint geometry and schematic of sample used for strength test

3. 1. Analysis of Weld Strength

The fit summary for weld strength suggests the quadratic model where the additional terms are significant and the model is not aliased. The ANOVA table of the quadratic model is given in Table 4.

The associated p-value of less than 0.05 for the model (i.e, 0.05, or 95% confidence level) indicates that the model terms are statistically significant. The other model terms are not significant and thus are eliminated by backward elimination process to improve model adequacy. The other model terms are not significant and thus are eliminated by backward elimination process to improve model adequacy [24, 25].

Table of ANOVA for weld strength as affected by input variables is shown in Table 4. Linear effects of pressure, welding time, holding time, and the amount of GF (%) as well as interaction effects of welding time and GF amount (T *%GF) and welding time and pressure (T*P) are important. All effects of squares except holding time (Holding time* Holding time) are effective too. The final mathematical model of response is used to predict the failure force of the weld in the design space which is provided based on uncoded factors as in Equation (1).

In Equation (1), P is the pressure (bar), G is percentage of GF, (T) is welding time (second) and (H) is the holding time. Putting the value of these parameters in this equation can contribute to estimation of failure force (F_{max}).

$$\mathbf{F_{max}} = -11045+317.5G+2367T+691H+3553.4P -3.6G^2 - 667.4T^2 - 529.6P^2-13GT+171PT \quad (1)$$

Normal probability of residuals and chart of residuals are shown in Figure 2. Based on estimated normal residuals having no significant deviation from straight line, one can conclude that this model has sufficient adequacy [26]. The points in Figure 2 show no apparent pattern and abnormal structure.

3. 2. Validation of Developed Model

To validate the developed response surface equations derived from multiple regression analysis, conditions of the actual results, predicted values and calculated percentage error of confirmation experiments are furnished in Table 5.

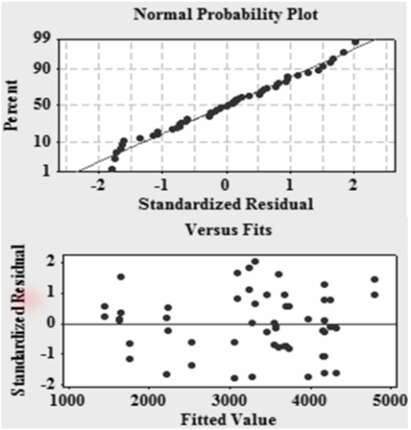

Figure 2. Probability of normal residuals and residuals based on estimated values

TABLE 4. Analysis of variance (after removing ineffective terms)

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P value
Regression	9	45243392	45243392	5027044	95.53	0.000
Linear	4	33409109	13557153	3389288	64.41	0.000
GF(%Wt)	1	31894287	12097103	12097103	229.88	0.000
Welding time (s)	1	207576	1644865	1644865	31.26	0.000
Holding time (s)	1	458990	458990	458990	8.72	0.005
Pressure (bar)	1	848256	2730123	2730123	51.88	0.000
Square	3	11297713	11297713	3765904	71.56	0.000
GF(wt%)*GF(wt%)	1	4268269	780057	7780057	147.84	0.000
Welding time (S)* Welding time (S)	1	3663323	5344784	5344784	101.57	0.000
Pressure (bar)*Pressure (bar)	1	3366120	366120	3366120	63.97	0.000
Interaction	2	536570	536570	268285	5.10	0.010
GF(wt%)*Welding time (s)	1	302642	302642	302642	5.75	0.021
Welding time (S)*Pressure(bar)	1	233928	233928	233928	4.45	0.041
Residual error	44	2315430	2315430	52623		0.009
Pure error	29	951121	951121	32797		
Total	53	47558822				
R-Sq= 95.13%		**R-Sq(pred= 94.14%**		**R-Sq(adj) = 92.58%**		

TABLE 5. Verification tests

Test	GF (%)	Pressure (bar)	Welding time (s)	Holding time (s)	Actual force (N)	Estimated force (N)	Error (%)
1	45	2.5	1	0.5	3201.5	3413.6	6.2
2	30	4.5	2	0.7	3532	3813	7.32
3	30	2.5	3	0.9	2964.6	2642.3	4.65
4	15	3.5	2	0.7	2034.4	2211.9	6.59

It is observed from the validation experiments that there is a small percentage error between the estimated and the experimental values, which indicates that the developed models can yield nearly accurate results. Four confirmation experiments are conducted with welding chosen randomly within the range for which the equations are derived. The actual results are calculated as the average of two measured results for each response.

4. EFFECTS OF PROCESS PARAMETERS ON RESPONSES

Figure 3 illustrates the effect of all factors on weld failure force. This figure shows the effect of each parameter on strength (weld failure force) without considering the condition of other parameters.

As it is evident, increase of percentages of GF has a positive effect on strength. This effect is due to the fact that materials such as glass fiber increase modulus and stiffness of the resin and result in a better transmission of ultrasonic energy throughout the material, particularly for semi crystalline materials. At levels approaching 40%, fibers accumulate at the joint interface and insufficient thermoplastic resin may be the reason for decline of strength. From Figure 3, it can also be observed that increase of welding time (T) has a positive effect on increasing the weld strength when it increases up to a certain level. Increase in welding time increased the heat input to the weld zone which resulted in more volume of the base material being melted. This consequently led to increase in weld strength. At higher time levels, overheating and partial decomposition of the material caused the weld strength to decrease. Applying the weld pressure to the melt for a long time helps the molecular chains of the polymer penetrate through the joint interface and entangle with chains initially on the other side of the interface. This will significantly increase the entanglement of the molecular chains as well as the joint strengths of the parts. A weld pressure is applied to the samples to cause the energy director to flow and fusion bond the parts. If the pressure is too high, squeeze flow is fast and results in molecular alignment transverse to the weld surface, and therefore, results in a decrease in joint strength. This condition is observed by increase of pressure up to 3.5 bar, but more increase of pressure up to 4.5 bar has lower effect on strength.

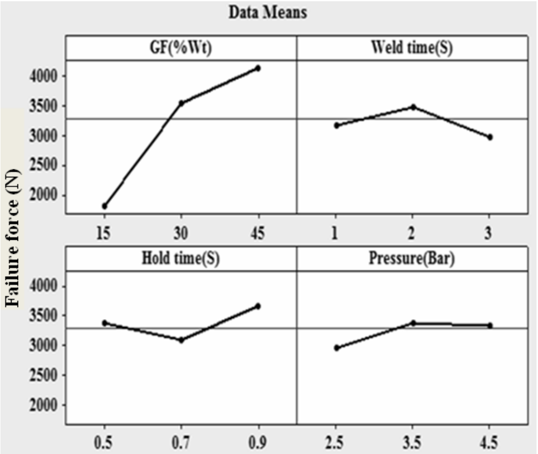

Figure 3. Effects of main parameters on weld failure force (N)

The experimental result in Figure 5 shows that increasing the hold time increased the weld strength, until the strength reached some optimum values. During ultrasonic welding, when two pieces of molten are brought into contact, wetting or close molecular contact first occurs followed by interdiffusion of chain segments back and forth across the wetted interface.

The experimental result suggests that an optimum holding time for welding nylon composites is approximately 0.9 s. It is also noticed that holding time does not have significant effect on weld strength because semi crystalline plastics are characterized by regions of ordered molecular structure. High heat is required to disrupt this ordered arrangement. The melting point is sharp, and resolidification occurs rapidly as soon as the temperature drops slightly. The melt that flows out of the heated region of the joint therefore solidifies rapidly [27].

Due to the effectiveness of interaction effects on response, the associated figure can't be used to optimize the response. Figures 4, 5 and 6 give the contour plots and three dimensional (3D) surface graphs of the interaction effects of the process parameters on weld strength (failure force). Figures 4a and 4b show the interaction effect of welding time and GF% on strength. It is also observed that the increase of the percentage of GF increases the weld failure force to a certain value and further increase of GF makes the failure force remain constant. Increasing welding time up to a certain level lead to increase of weld failure force. It can be seen from this figure that weld strength increases up to 2.0 sec. Beyond 2.0 sec, weld strength starts decreasing for any value of GF%. To optimize the weld strength, proper combination of the percentage of GF and welding time can be selected at 40-45% and 1.5-2 s, respectively.

It is clear from Figure 5 that the weld failure force increases with the increase of welding time and pressure to a certain value and then decreases. By analyzing the response surfaces and contour plots, the maximum achievable failure force value is found to be 4500 N. The corresponding parameters that yielded this maximum value are welding time of 2 s and pressure of 3.5 bar. This can be further investigated by microstructural studies and can be undertaken as the work for future.

Figure 6 shows the interaction effect of GF and holding time on weld strength. It is seen that weld strength increases with the GF up to 40% and thereafter it becomes almost constant. The trend does not differ with any of the level of holding time that does not have significant effect on weld strength. Weld strength can be optimized when an appropriate combination of GF of 35-45% and hold time of 0.6-0.9 s are selected.

According to ANOVA which is seen in Table 4, the degrees of freedom are same for all of the input parameters.

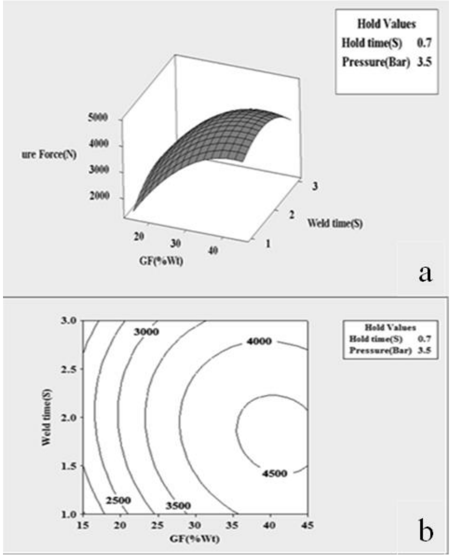

Figure 4a. Surface response of the effect of GF% - welding time on weld failure force **4b.** Two-dimensional plot

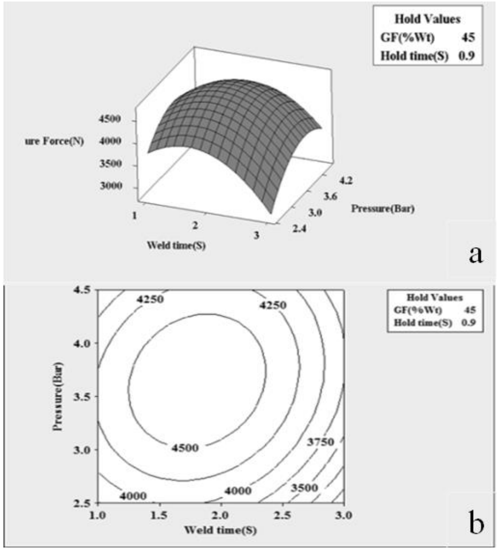

Figure 5a. Surface response of the effect of pressure - welding time on weld failure force **5b.** Two-dimensional plot

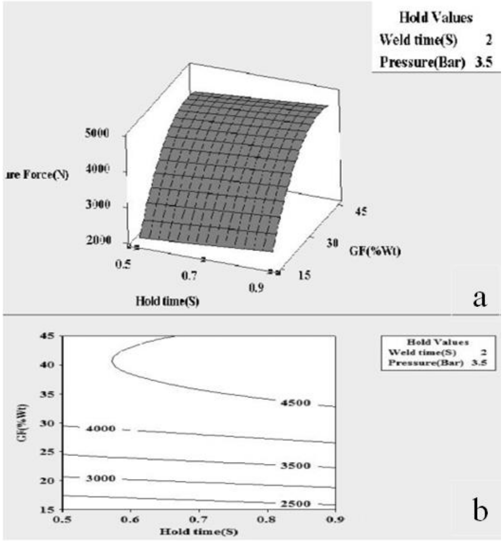

Figure 6a Surface response of the effect of GF% and holding time on weld failure force **7b.** Two-dimensional plot

The higher F ratio value implies that the respective term is more significant and vice versa. From the F ratio values, it can be concluded that the percentage of GF is contributing more to tensile failure load, and it is followed by pressure, welding time and holding time for the range considered in this investigation, it is found that the effect of GF%-welding time interaction is the most significant, and the interaction of GF%-holding time has minimal effect on strength of the weld.

5. CONCLUSION

Ultrasonic welding of T-joints with 4 mm thickness for polyamide composite sheets has been successfully implemented from the studies carried out as presented in the previous sections; the following points can be highlighted.

- Second-degree model was developed to estimate the weld failure force within an experimental design space.
- According to the results of ANOVA, amount of GF is the most important factor affecting the weld strength and it is followed by air pressure, welding time and holding time.
- The weld strength increased from 2500 N to 4500N when the amount of GF increased from 15 to 45 percent.
- Increasing the pressure towards 3.5 bar has an increasing effect on weld strength, whereas beyond 3.5 bar the weld strength was decreased.
- Based on interaction effects, maximum strength can be obtained at 30-33 micron amplitude, 41 percent GF, and 3.65 bar pressure, 1.84 second welding time, and 0.9 second holding time.

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Weld Failure Force

چکیده

در این مقاله، یک تحقیق تجربی در زمینه جوشکاری فرا صوت کامپوزیت پلی آمید تقویت شده با الیاف شیشه انجام شده است .اثر پارامترهای جوشکاری فرا صوت مانند زمان جوشکاری ، فشار جوشکاری ، زمان نگهداری و مقدار الیاف شیشه در کامپوزیت بر مقاومت کششی اتصالات جوش با استفاده از روش سطح پاسخ انجام شد. این روش یک مدل ریاضی است که می تواند اثرات پارامترهای اصلی فوق را براستحکام کششی اتصال T شکل ورق های کامپوزیت پلی آمید به ضخامت ۴ میلی متر که به روش جوشکاری اولتراسونیک اتصال داده شده است را پیش بینی نماید. تجزیه وتحلیل واریانس برای بررسی کفایت مدل توسعه یافته و مقایسه بین نتایج پیش بینی شده و واقعی انجام شده است. نتایج نشان می‌دهد بیشترین نیروی گسیختگی حدود N ۴۷۵۹ را می توان در دامنه ارتعاش ثابت ۳۵ میکرون ، فشار هوای ۳/۶ بار، زمان جوشکاری۱/۸۴ثانیه، زمان نگهداری ۰/۹ ثانیه و مقدار الیاف شیشه ۴۱٪ به دست آورد.

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