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# Statistical Analysis and Optimization of the Yield Strength and Hardness of Surface Composite Al7075/$Al_2O_3$ Produced by FSP via RSM and Desirability Approach

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ABSTRACT

In order to improve the properties of aluminum and its alloys, some various approaches (e.g. reduction of grain size, addition of alloying elements and composite manufacturing) have been considered. Among all these processes, the use of solid-state processes such as the friction stir processing (FSP) is highly convenient to create surface composites at temperatures below the melting point. Therefore, in this research, considering the FSP's ability as a thermo-mechanical process and its advantages in the production of surface composites, the Al7075 surface composites were produced using reinforcing particles ($Al_2O_3$) and based on the FSP process in accordance with the design of experiments (DOE) approach. So, the response surface methodology (RSM) was selected as the experiment design method and variable factors such as: tool rotational speed, tool feed rate, diameter of tool shoulder and size of reinforcing particles were determined as the input variables. Statistical analysis and optimization of those parameters which affect the mechanical properties (yield strength and hardness) of surface composite Al7075/$Al_2O_3$ were performed. The results of the ANOVA and regression analysis of the experimental data approved the accuracy of regression equations and showed that the linear, interactional and quadratic terms of the input variables affect the yield strength and hardness of the composite specimens. Also, the optimal condition of the input variables was determined using the desirability method. In addition to the high values of desirability function (0.835, 0.822, 0.764), it could be found that the procedure of optimization has well fulfilled the pre-determined targets. In addition, the optimal condition has been confirmed by implementing the verification test.



## 1. Introduction

Desirable properties of aluminum and its alloys have caused the wide application of this group of metals in automotive, marine and aerospace industries [1, 2]. In the meantime, the 7XXX group are also of high importance due to their high strength and high fatigue strength [3, 4]. When these alloys are exposed to abrasion, they show weak mechanical and tribological behaviors [5]. So, in order to improve their properties, various approaches such as: addition of alloying elements [6], reduction of grain size [7] and composite manufacturing [8] are considered. Among them, severe plastic deformation (SPD) is used in a wide range in order to produce the ultrafine microstructure from aluminum alloys [9-11].

One of the most important techniques of SPD is the friction stir processing (FSP). In fact, this thermo-mechanical process is derived from the friction stir welding [12, 13]. FSP process is a new method for severe plastic deformation and is intended to improve the microstructure of materials. This process was invented

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in 1999 [14]. In this process, applying the high shear strain to the material creates an ultrafine microstructure within a temperature below the melting point of the material [15]. Principles of the FSP process are shown in Fig. 1 [16].

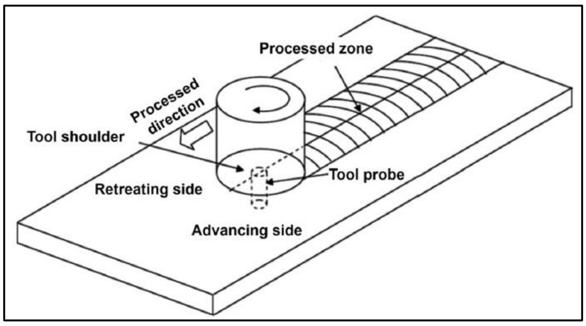



**Fig. 1.** Outline of the FSP process [16].

Gholami et al. [17] studied the effects of temperature and time of aging treatment on the microstructure, mechanical properties and wear behavior of Al7075 under the FSP process. Findings show that the microstructure, with a homogenous structure and coaxial grains caused by the recrystallization process, would be produced. Moreover, the hardness values of the stir zone (SZ) and base metal (BM) increased by 30 and 80 percent respectively. Abrahamas et al. [18] studied the effect of the FSP process parameters on the mechanical properties of aluminum alloys 5005-H34 and 7075-T651. Findings show that increasing the tool feed rate is much more effective on the improvement of the hardness and mechanical properties of aluminum alloys than the tool rotational speed.

On the other hand, compared to aluminum alloys, aluminum metal matrix composites (AMMC) are a new group of materials with more desirable properties, such as: wear resistance, corrosion resistance, toughness and hardness [19]. Addition of filler materials especially ceramic reinforcing particles would improve the wear and corrosion resistance in aluminum alloys [20]. Therefore, the FSP process could be used for the modification of the microstructure and improvement of the mechanical properties of aluminum alloys to produce the surface composite [21, 22]. For this purpose, Ahmadifard et al. [23] studied the microstructure and mechanical properties of the surface composite Al5083/$TiO_2$ which is produced by the FSP process. They found that increasing the pass number caused better distribution of the particles as well as the increase of the hardness and strength of the material. In another study, they also produced a type of hybrid nano-composite Al2024/Gr/$ZrO_2$ by the FSP process [24]. Findings show that using graphite and zirconia increases the hardness and wear resistance.

Another group of researchers investigated the effect of the input parameters of the FSW process on the production of the composite joint Al7075/WC [25]. The results showed that the tool rotational speed, the welding speed and the pin profile geometry have the greatest impact on the strength of the welding joint. Kumar et al. [26] studied the corrosion behavior of Al7075/TiC composite which was produced by the FSP process. They showed that the addition of TiC particles would increase the corrosion resistance of the composite. Another group of researchers investigated the effect of adding three different types of filler materials (carbon nanotube, copper, silicon carbide) to Al7075 alloy under the FSP process and aging treatment [27]. They found that the use of silicon carbide has an effective role in increasing the hardness, impact toughness and wear resistance of the surface composite.

In spite of these efforts, in order to complete and develop all the previous researches done in this field and by considering the ability and advantages of the FSP, in this paper, the aluminum matrix surface composites Al7075/$Al_2O_3$ have been produced using the reinforcing particles (aluminum oxide). To study the effects of variable parameters, the response surface methodology (RSM) was used as one of the best DOE methods. In the following sections, the statistical analysis and optimization of the parameters affecting the mechanical properties of the surface composites will be carries out. The accuracy and precision of the regression equations were evaluated using the results of the ANOVA and regression analysis of the experimental data. Also, the influence of the input variables such as: tool rotational speed, tool feed rate, tool shoulder diameter and reinforcing particle size on the yield strength and hardness of the specimens were studied. Finally, the optimal condition of the input variables was extracted by using the desirability method.

## 2. Methodology of Statistical Analysis

The process used in this study can be represented by the model shown in Fig. 2.

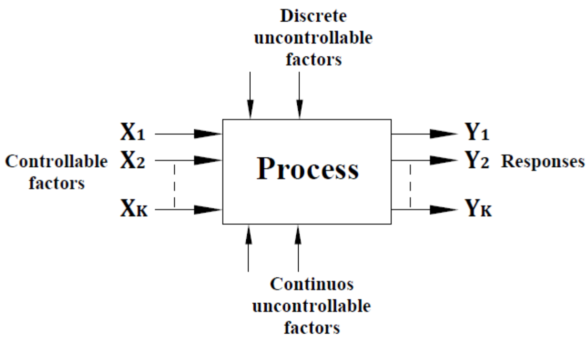



**Fig. 2.** General model of the process.

It is assumed that the controllable factors (X) and the process responses (Y) are independent. So, the aim is to account the relationship between the response variables and the input variables with the least errors as the mathematical model. Therefore, the methodology of the statistical analysis in this research includes the following seven steps:

- Selection of the response variables
- Selection of the controllable factors
- Selecting the experiment design
- Experiment implementation
- Measuring the response variables
- Data analysis
- Optimization and confirmation

## 3. Selection of Response Variables

In order to evaluate the mechanical properties of $Al7075/Al_2O_3$ composite samples, the yield strength and micro-hardness were considered as the process responses. There are four zones in the cross-section of the produced samples as follows: base material (BM), heat affected zone (HAZ), Thermo-mechanically affected zone (TMAZ) and stir zone (SZ). On the other hand, to investigate the micro-hardness variations in these zones (HAZ, TMAZ and SZ) compared to the base metal (BM), it is better to use the MHD parameter (micro-hardness deviation). This parameter indicates the micro-hardness deviation of the processed cross-section compared to the base metal hardness (Al7075). The mean value of the micro-hardness deviation to the base metal (MHD) can be derived as follows [28]:

$$\mathrm{MHD} = \sum_{i=1}^{n} \frac{(x_i - x_{bm})^2}{n} \qquad (1)$$

Where $x_i$ is the micro-hardness of different points in the sample cross-section and $x_{bm}$ is the micro-hardness of the base metal. Also, the number of points whose micro-hardness are measured is shown with n. As can be seen, there is a direct relationship between the MHD parameter and micro-hardness. Thus increasing the micro-hardness would lead to an increase in the MHD. So, in this research, the yield strength of the produced samples and the micro-hardness deviation of the processed sections were selected as the response variables, rather than the base metal (MHD).

## 4. Selection of Controllable Factors

By taking into account the research background in the field of the FSP process, four parameters named: the tool rotational speed (N), tool feed rate (S), tool shoulder diameter (D) and reinforcing particle size (P) were selected as the input variables, and each of them was considered at three levels of low (-1), central (0) and high (+1). The high and low levels of each parameter are coded by (+1) and (-1). The coded value of each intermediate level is calculated through the following relation [29],

$$\mathrm{X} = \frac{2x - (x_{max} + x_{min})}{(x_{max} - x_{min})} \qquad (2)$$

Where X is the coded value of the concerned parameter with the actual value of $x$ (between $x_{min}$ and $x_{max}$). $X_{min}$ and $x_{max}$ have the actual low and high values of the parameter accordingly. The variation range of these factors was determined based on the primary experiments, which lead to the safe production of the specimen (Table 1).

Table 1. Input variables and their range of variation

| Input variable | Notation | Unit | -1 | 0 | +1 |
|---|---|---|---|---|---|
| Tool rotational speed | N | rpm | 400 | 800 | 1200 |
| Tool feed rate | S | mm/min | 20 | 60 | 100 |
| Tool shoulder diameter | D | mm | 9 | 15 | 21 |
| Reinforcing particles size | P | μm | 20 | 50 | 80 |

## 5. Selecting the Experiment Design

In the present research, the response surface methodology (RSM) is used as the experiment design technique [30-33]. Thus the first step in this method is to find a suitable approximation of the real relation existing between the response variable ($y$) and the set of input variables ($x$). The approximating functions are in form of the linear and quadratic models and are written in the form of the following relations:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \qquad (3)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j + \varepsilon \qquad (4)$$

Where $\beta_0$ is the constant value, $\beta_i$ is the first-order (linear) coefficient, $\beta_{ii}$ is the second-order (quadratic) coefficient, $\beta_{ij}$ is the interaction coefficient, $k$ is the number of independent variables, and $\varepsilon$ is the rate of error.

In this research, the second-order model is used. The software used for the experiment design and statistical analysis is Design Expert [34]. Table 2 shows the design matrix with 31 tests in the form of coded runs. Seven tests are repeated at the central levels of the parameters (zero level).

Table 2. Design matrix with the measurement results

| Test no. | Input variables | | | | Output variables | |
|---|---|---|---|---|---|---|
| | N | S | D | P | Yield strength (MPa) | MHD parameter |
| 1 | -1 | -1 | -1 | 1 | 272 | 393.833 |
| 2 | -1 | 1 | 1 | 1 | 340 | 209.833 |
| 3 | -1 | 1 | 1 | -1 | 331 | 223.333 |
| 4 | 1 | 1 | 1 | -1 | 345 | 153.833 |
| 5 | 1 | 1 | -1 | 1 | 390 | 161.500 |
| 6 | 0 | 0 | -1 | 0 | 368 | 226.500 |
| 7 | -1 | -1 | 1 | 1 | 305 | 255.833 |
| 8 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 9 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 10 | 0 | 1 | 0 | 0 | 421 | 221.833 |
| 11 | 0 | -1 | 0 | 0 | 312 | 236.167 |
| 12 | 1 | -1 | -1 | -1 | 217 | 208.167 |
| 13 | 1 | -1 | 1 | 1 | 351 | 266.667 |
| 14 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 15 | -1 | -1 | -1 | -1 | 310 | 282.333 |
| 16 | -1 | 1 | -1 | -1 | 317 | 214.500 |
| 17 | 1 | -1 | -1 | 1 | 308 | 265.833 |
| 18 | -1 | 0 | 0 | 0 | 327 | 231.000 |
| 19 | 1 | -1 | 1 | -1 | 345 | 259.333 |
| 20 | 1 | 0 | 0 | 0 | 338 | 382.667 |
| 21 | 0 | 0 | 0 | 1 | 345 | 285.667 |
| 22 | 1 | 1 | -1 | -1 | 330 | 179.833 |
| 23 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 24 | 1 | 1 | 1 | 1 | 375 | 213.667 |
| 25 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 26 | 0 | 0 | 1 | 0 | 345 | 257.167 |
| 27 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 28 | 0 | 0 | 0 | 0 | 415 | 183.167 |
| 29 | -1 | -1 | 1 | -1 | 315 | 180.833 |
| 30 | 0 | 0 | 0 | -1 | 405 | 241.167 |
| 31 | -1 | 1 | -1 | 1 | 292 | 390.667 |

## 6. Experiment Implementation

Table 3 shows the chemical composition of Al7075-T6 alloy which is used in this experimental work.

Table 3. Chemical composition of Al7075-T6 [35]

| Element | Weight percent (%) |
|---|---|
| Aluminum (Al) | 87.1 - 91.4 |
| Zinc (Zn) | 5.1 - 6.1 |
| Magnesium (Mg) | 2.1 - 2.9 |
| Copper (Cu) | 1.2 - 2.0 |
| Iron (Fe) | 0.50 |
| Silicon (Si) | 0.40 |
| Manganese (Mn) | 0.30 |
| Chromium (Cr) | 0.18 - 0.28 |
| Titanium (Ti) | 0.20 |

In order to prepare Al7075 alloy at T6 position, the alloy plates were subject to aging treatment in accordance with the AMSH6088 standard [36]. For this reason, at the first solution treatment, Al7075 plates were heated up to 480ºC for 1 hour. Then, the plates were subject to quenching to obtain super-saturated solid solution. Next, aging treatment was done on the plates for 24 hours at 120˚C. Finally, the plates were cooled in the air.

The reinforcing particles which were used in the production process of the surface composite were aluminum oxide ($Al_2O_3$). These particles were prepared with a purity of more than 99% in three sizes of 20, 50 and 80 microns (Fig. 3).

**Fig. 3.** Aluminum oxide powder.

FSP tools made of H13 steel were designed and manufactured in three shoulder diameters of 9, 15 and 21 mm and in three pin diameters of 3, 5 and 7 mm, respectively, with a slotted conical geometry. The pin and shoulder diameters are shown with "a" and "d" letters in the tool drawing (Fig. 4).

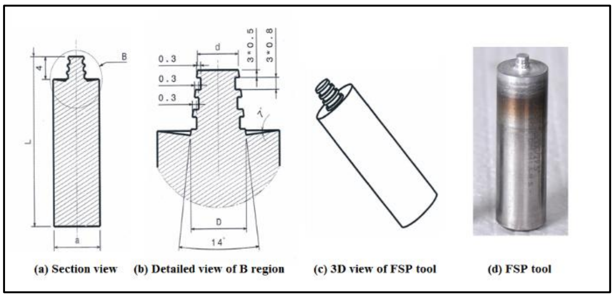



**Fig. 4.** Design and manufacturing of a sample of the FSP tool.

The pieces were prepared in the circular form with a diameter of 90 mm and a thickness of 10 mm. Fig. 5 shows the position of the workpiece in the fixture.

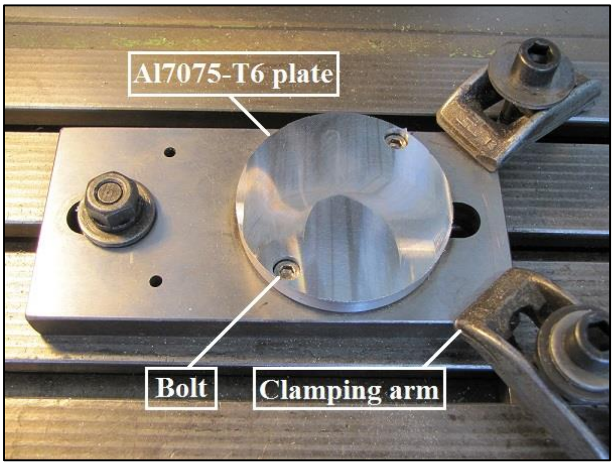



**Fig. 5.** Position of the workpiece in the fixture.

In order to locate the $Al_2O_3$ micro-particles on the workpiece surface, 18 holes were created with a diameter of 2 mm and a depth of 3 mm at 4 mm intervals along the workpiece diameter (Fig. 6). After filling the holes with aluminum oxide powder, the holes were closed by the pinless tool. Then, 31 FSP experiment tests were carried out in accordance with the design matrix in Table 2 by the universal milling machine of FP4MK. Fig. 7 shows a sample of the Al7075/$Al_2O_3$ surface composite (sample #11).

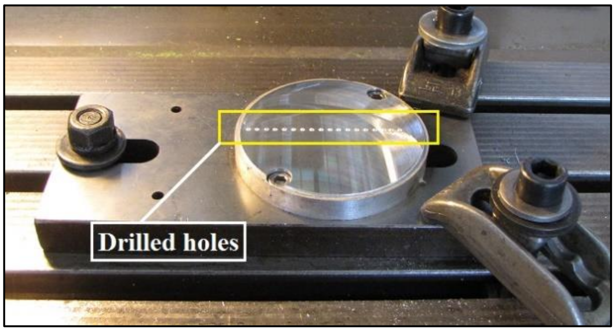



**Fig. 6.** Drilling the workpiece surface.

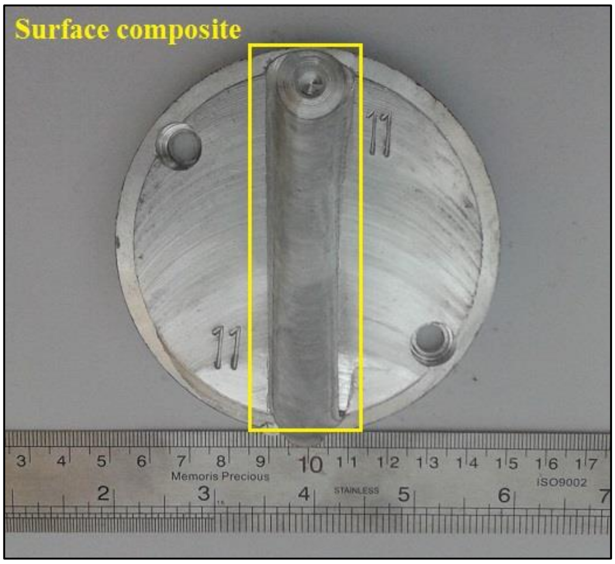



**Fig. 7.** Image of the Al7075/$Al_2O_3$ surface composite (sample #11).

## 7. Measuring the Response Variables

### *7.1. Tensile test*

The tensile test is used to measure the yield strength of the composite parts fabricated by the FSP. The tensile specimens were prepared perpendicular to the FSP direction using the wire-EDM machine according to the ASTM E8 standard. Each sample was tested in the tensile device of INSTRON by a feed rate of 2 mm/min at room temperature. Fig. 8 shows a number of fractured samples after the tensile test.

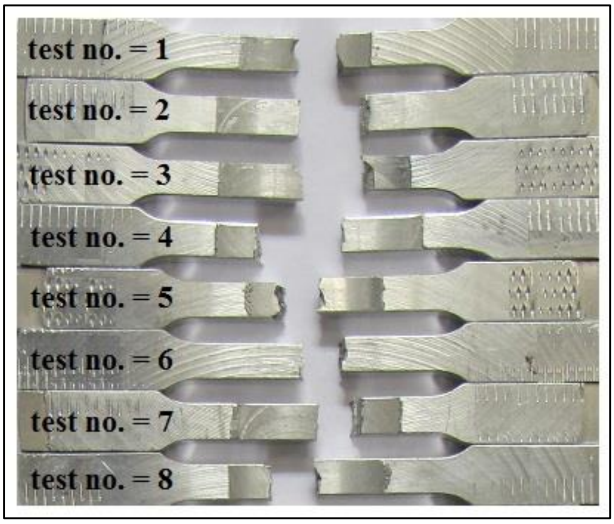



**Fig. 8.** A number of drawn samples.

### *7.2. Hardness test*

The Vickers test was used to measure the hardness of the composite sample cross-sections. So, the produced components were subject to cutting and polishing processes in order to prepare the cross-sections. Each one of these 31 cross-sections was tested by the hardness test in the four zones of BM (A), HAZ (B), TMAZ (C) and SZ (D) as it is shown in Fig. 9. These tests were conducted based on the ASTM E384 standard by the micro-hardness device of BUEHLER. The amount of load and the time of loading were 300 gr and 10 seconds, respectively.

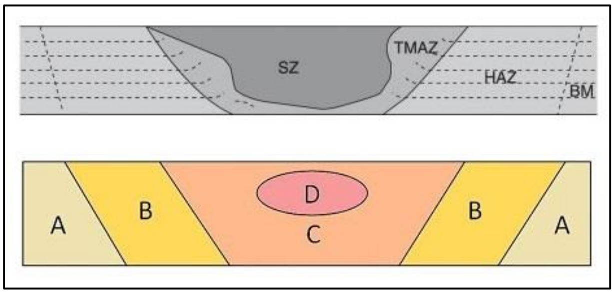



**Fig. 9.** Hardness measurement in four zones of the composite cross-section.

After recording the hardness test data, the MHD parameter was calculated according to Eq. 1 for each one of the composite cross-sections. Table 2 shows the measurement results of the yield strength and the MHD parameter for all of the composite samples.

## 8. Data Analysis

Analysis of the experimental data was performed by analysis of variance (ANOVA). ANOVA is a powerful means to study the importance of a parameter and identify the significance of its effect. In addition, for creating the mathematical functions between the response variables and the effective parameters, the regression analysis was applied [29]. Confidence level (α) in the analysis was considered equal to 0.05, and statistically, it means that the final model can predict the data with an error rate less than 5%. Tables 4 and 5 show the ANOVA results of the regression model for the yield strength and the MHD parameter, respectively.

Table 4. ANOVA results of the regression model (yield strength)

| Source of variation | Degree of freedom | Sum of squares | Mean squares | F-value | P-value |
|---|---|---|---|---|---|
| Regression model | 7 | 2.763E+007 | 3.947E+006 | 6.97 | 0.0002 |
| N | 1 | 3.449E+005 | 3.449E+005 | 0.61 | 0.4430 |
| S | 1 | 4.538E+006 | 4.538E+006 | 8.02 | 0.0095 |
| D | 1 | 1.524E+006 | 1.524E+006 | 2.69 | 0.1145 |
| P | 1 | 91797.56 | 91797.56 | 0.16 | 0.6909 |
| N.P | 1 | 1.844E+006 | 1.844E+006 | 3.26 | 0.0842 |
| $N^2$ | 1 | 2.382E+006 | 2.382E+006 | 4.21 | 0.0518 |
| $D^2$ | 1 | 8.113E+006 | 8.113E+006 | 14.33 | 0.0010 |
| Residual error | 23 | 1.302E+007 | 5.660E+005 | - | - |
| Lack of fit | 17 | 1.012E+007 | 5.952E+005 | 1.23 | 0.4248 |
| Pure error | 6 | 2.899E+006 | 4.831E+005 | - | - |
| Total | 30 | 4.065E+007 | - | - | - |

Table 5. ANOVA results of the regression model (MHD parameter)

| Source of variation | Degree of freedom | Sum of squares | Mean squares | F-value | P-value |
|---|---|---|---|---|---|
| Regression model | 5 | 41.58 | 8.32 | 2.88 | 0.0346 |
| N | 1 | 1.69 | 1.69 | 0.59 | 0.4514 |
| S | 1 | 9.08 | 9.08 | 3.14 | 0.0884 |
| D | 1 | 4.12 | 4.12 | 1.43 | 0.2435 |
| P | 1 | 12.96 | 12.96 | 4.49 | 0.0443 |
| N.D | 1 | 13.73 | 13.73 | 4.75 | 0.0389 |
| Residual error | 25 | 72.22 | 2.89 | - | - |
| Lack of fit | 19 | 70.36 | 3.7 | 11.96 | 0.0628 |
| Pure error | 6 | 1.86 | 0.31 | - | - |
| Total | 30 | 113.8 | - | - | - |

Thus with the assumption of $\alpha = 0.05$ and based on the results obtained from ANOVA, the first-order parameter of S (tool feed rate) and the second-order term of $D^2$ (squared of the tool shoulder diameter) were determined as the effective terms on the yield strength of the samples. Also, the first-order parameter of P (reinforcing particle size) and the interactional term of N.D (product of the tool rotational speed in the tool shoulder diameter) were determined as the effective terms on the MHD parameter. In order to investigate the accuracy of the regression model, the lack of fit (LOF) test was used. The significance of this test (P-value LOF $\leq 0.05$) indicates that the data are not well placed around the model and it is not possible to use the model to predict the response variable. Thus with the confirmation of the insignificance of the LOF test (P-value LOF > 0.05), it is possible to conclude that the model can be well fitted to the data. As it is observed in Tables 4 and 5, the LOF test for the response variables is not significant, and consequently the presented models show the data trends well. On the other hand, the best analysis is performed when the regression is significant and the LOF is insignificant concurrently [29]. Thus with regard to the P-values it can be said that the regression terms are significant and the LOF terms are insignificant.

Equations (5) and (6) present the yield strength regression equations as a function of the coded and actual input variables, respectively:

$$(Yield\ Stress)^{1.47} = 6797.47 + 131.84N + 502.12S + 290.93D + 71.41P + 339.44NP - 705.51N^2 - 1212.15D^2 \quad (5)$$

$$(Yield\ Stress)^{1.47} = -4332.23 + 5.97N + 12.55S + 1058.61D - 20.25P + 0.028NP - 0.00441N^2 - 33.67D^2 \quad (6)$$

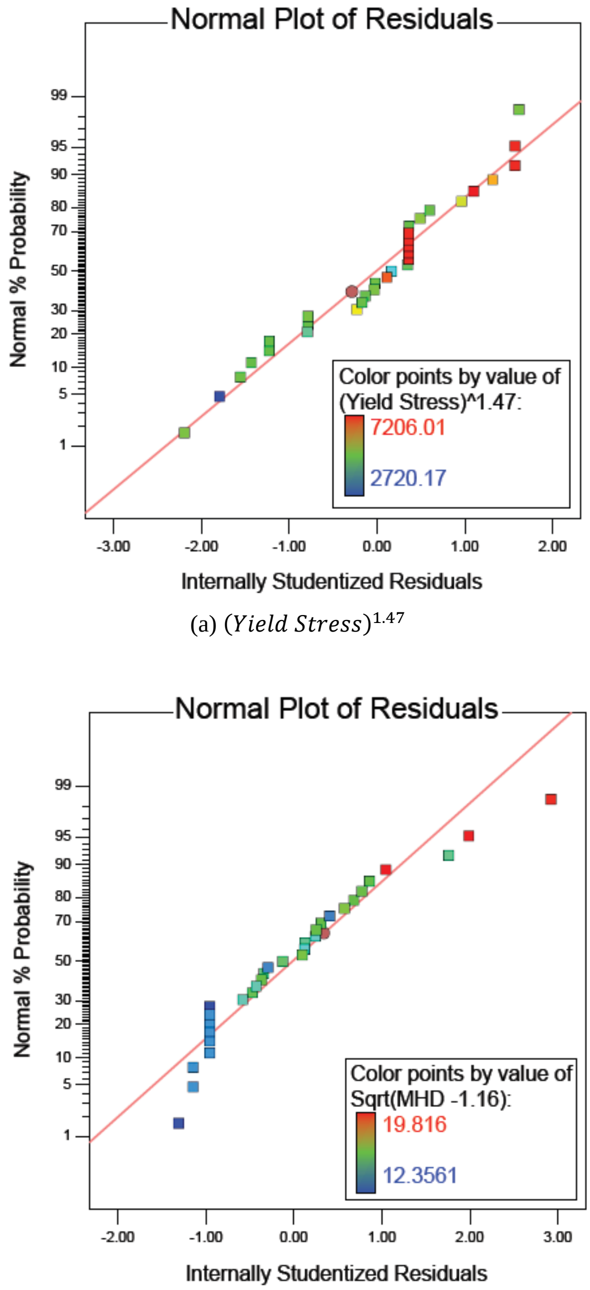
Also, equations (7) and (8) present the MHD parameter regression equations as a function of the coded and actual input variables, respectively:

$$\sqrt{MHD - 1.16} = 15.07 - 0.28N - 0.71S - 0.48D + 0.85P + 0.93ND \quad (7)$$

$$\sqrt{MHD - 1.16} = 21.11 - 0.0065N - 0.018S - 0.39D + 0.028P + 0.00039ND \quad (8)$$

In addition to the extraction of the regression equations for the yield strength and MHD parameter, it is possible that the values of the response variables would be predicted in terms of the input variables before the process implementation. Hence it is possible to select an appropriate combination of the input variables in order to reach the maximum point of the yield strength and MHD parameter.

The residual is defined in the form of the difference between the measured response in the experimental test and the predicted response by the regression model. The plot of normal probability is a useful means to check the accuracy of the normal distribution of the residuals. As can be seen in Fig. 10, it is evident that residuals were scattered on the straight line and the errors have a normal distribution on the normal probability plot.




(a) $(Yield\ Stress)^{1.47}$



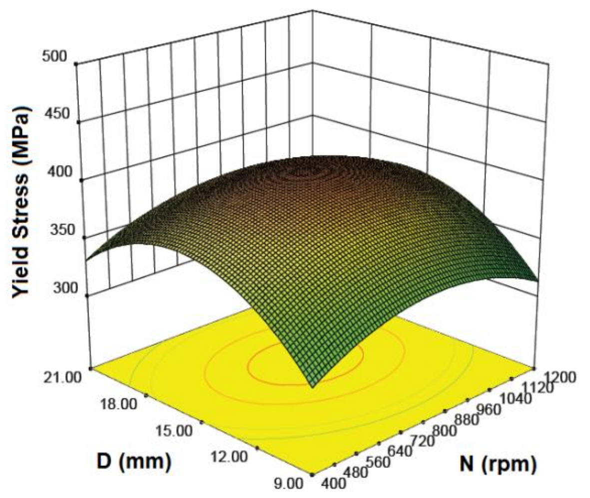
(b) $\sqrt{MHD - 1.16}$

**Fig. 10.** Normal probability plot.

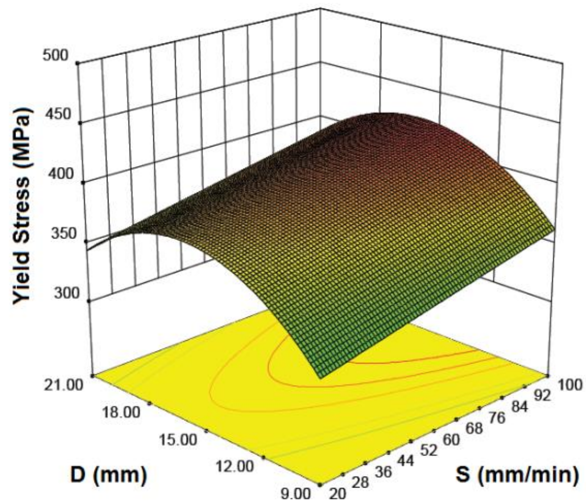
In order to reach the desired situation of the response variables, the role of the input variables was studied. The behavior of the response variables can be shown in terms of the input variables in the form of 3D diagrams (surface plot). In these diagrams, the interactional effects of both input variables on the response variable are visible and the values of other input variables are considered fixed at the central levels (zero level).

As can be seen in Fig. 11(a), adjustment of the tool rotational speed and the tool shoulder diameter in the middle level can lead to the maximum level of the yield strength for a composite sample. So, if the tool shoulder diameter is 15 mm, increasing the tool rotational speed from 400 rpm to 800 rpm can increase the yield strength. In this situation, increasing the tool rotational speed can increase the material flow followed by the improvement of the distribution of the reinforcing particles ($Al_2O_3$) in the matrix (Al7075). On the other hand, increasing the tool rotational speed from 800 rpm to 1200 rpm can decrease the yield strength. In this situation, increasing the tool rotational speed can increase the material temperature (especially in the stir zone) and this event leads to the growth and coarsening of the grains, or the dissolution of the precipitates.

The relationship between the yield strength and the two other parameters of the tool feed rate and tool shoulder diameter is shown in Fig. 11(b). In this situation, if the tool shoulder diameter is 15 mm, increasing the tool feed rate from 20 mm/min to 100 mm/min can increase the yield strength. In this case, the reduction of the tool feed rate can result in an increase in the contact time between the tool and workpiece, and this event increases the temperature of the stir zone as well as the dissolution and growth of the grains.




(a) The effect of N and D

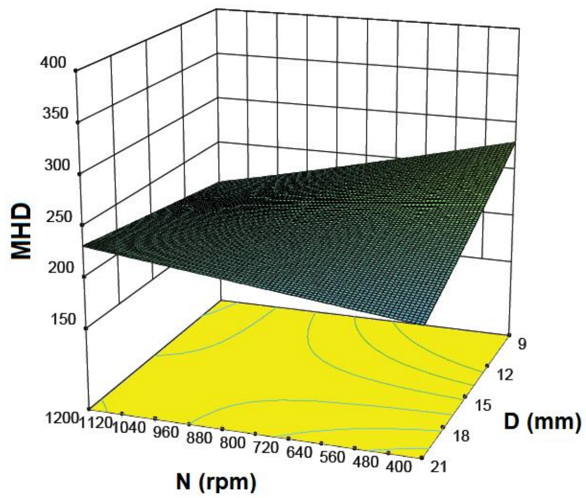



(b) The effect of S and D

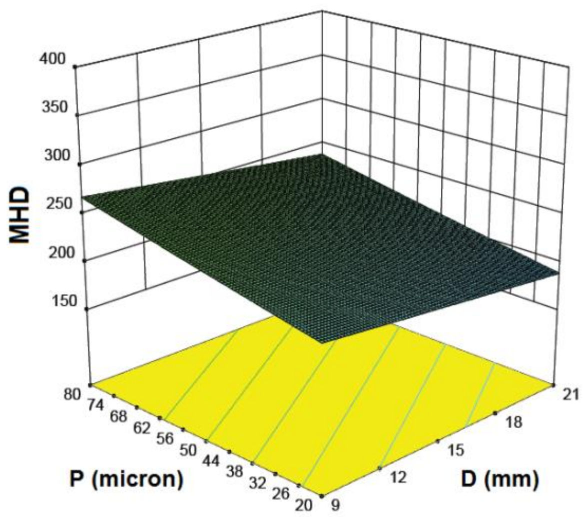
**Fig. 11.** Influence of the input variables on the yield strength.

As it is shown in Fig. 12(a), using a tool with the lowest shoulder diameter at a higher tool rotational speed can decrease the MHD parameter and as a result this event decreases the hardness in the SZ, TMAZ and HAZ zones compared with the base metal. One of the reasons behind this is the local dissolution of the hard phases and material softening due to the increase in the temperature of these zones (especially in SZ and TMAZ) that would usually happen in heat-treatable alloys. Whereas using a tool with the highest shoulder diameter at a higher rotational speed can increase the MHD parameter. One of the possible reasons to justify this situation is related to the imposition of more shearing force to the material and finally the fracture and division of the microstructure into smaller grains.

The relationship between the MHD parameter with the other two parameters of the tool shoulder diameter and the reinforcing particles size is shown in Fig. 12(b). In this situation, increasing the particles size can increase the MHD parameter. This effect could be strengthened by decreasing the tool shoulder diameter. It should be noted that according to Table 2 and by considering the high values of the MHD parameter, adding the reinforcing particles could be really effective in increasing the hardness of the processed zones in comparison with the base metal.




(a) The effect of D and N




(b) The effect of D and P

**Fig. 12.** Influence of the input variables on the MHD parameter.

## 9. Optimization and Confirmation

In this research, the desirability method was used as the optimization technique [30]. In this technique, the output response ($y_i$) is converted into the dimensionless desirability of $d_i$ ($0 < d_i < 1$), so that the higher value of $d_i$ signifies the greater desirability of the response value ($y_i$) and if the response is outside the acceptable limit, $d_i = 0$. Thus for the output response a separate desirability function with a range of 0 to 1 is obtained. In this research, the goal of the desirability function was the maximization of the response variables (yield strength and MHD parameter). Thus desirability was defined in the following form [37, 38]:

$$d = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{U-L}\right)^r & L \le y \le U \\ 1 & y > U \end{cases} \quad (9)$$

In the above equation, the $L$ and $U$ parameters are low and high limits of the response value ($y$) respectively. The shape of the desirability function depends on the weight field ($r$) which is used to express the degree of the significance of the target value. Here, the weight value was assumed equal to one ($r = 1$), and consequently the desirability function was defined in a linear mode. Table 6 shows three combinations of the optimized values for the input variables with the highest level of desirability function in order to reach the maximum values of the yield strength and MHD parameter.

Table 6. Optimized values of the process input variables

| No. | N (rpm) | S (mm/min) | D (mm) | P (µm) | Values of response variables: Yield strength (MPa) | Values of response variables: MHD parameter | Value of desirability function (d) |
|---|---|---|---|---|---|---|---|
| 1 | 860.71 | 81.13 | 15.56 | 80 | 421.001 | 240.465 | 0.835 |
| 2 | 736.73 | 99.21 | 14.18 | 80 | 421 | 236.875 | 0.822 |
| 3 | 1025.10 | 100 | 16.32 | 55.74 | 421 | 207.779 | 0.764 |

So, in addition to the high values of the desirability function, it could be found that the procedure of optimization has well fulfilled the pre-determined targets.

To confirm the parameter combination in the first row of Table 6, the experimental test was done by a tool with a shoulder diameter of 15 mm and by using $Al_2O_3$ particles with a size of 80 microns. The values of the tool rotational speed and tool feed rate were adjusted next to the optimized input variables. Table 7 shows the results obtained from the confirmation test and its comparison with the optimized results. In addition to the insignificant difference between the optimization results and the experimental test, the accuracy and precision of the optimization procedure to determine the optimized combination of the input variables were confirmed.

Table 7. Comparison between the results obtained from the optimization process and confirmation test

| Response variable | Optimization process | Confirmation test | Difference percent |
|---|---|---|---|
| Yield strength (MPa) | 421.001 | 411 | 2.38 % |
| MHD parameter | 240.465 | 236.17 | 1.79 % |

## 10. Conclusions

In this paper, the statistical analysis and optimization of the parameters affecting the mechanical properties of the surface composite (Al7075/$Al_2O_3$) produced in the FSP process were performed using the response surface methodology and desirability approach. Regarding the experimental tests and statistical analyses, the following conclusions can be drawn:

- The ANOVA results show that the first-order parameter of S (tool feed rate) and the second-order term of $D^2$ (squared of the tool shoulder diameter) were determined as the terms affecting the yield strength of the samples.
- The ANOVA results show that the first-order parameter of P (reinforcing particle size) and the interactional term of N.D (product of the tool rotational speed in the tool shoulder diameter) were determined as the terms affecting the MHD parameter.
- The competency of the regression models was investigated by the lack of fit (LOF) test and normal probability plot. Consequently, the ability of the fitted models and accuracy of the regression equations in describing and predicting the behavior of the yield strength and MHD parameter of the composite samples were confirmed.
- Investigation of the surface plots shows that the adjustment of the tool rotational speed and the tool shoulder diameter in the middle level (800 rpm, 15 mm) could reach the maximum of the yield strength for a composite sample. Also, increasing the tool feed rate can increase the yield strength.
- Investigation of the surface plots shows that using a tool with the lowest shoulder diameter at a higher tool rotational speed can decrease the MHD parameter and as a result this event decreases the hardness in the SZ, TMAZ and HAZ zones compared to the base metal. Also, increasing the particle size can increase the MHD parameter. This effect could be strengthened by decreasing the tool shoulder diameter.
- The optimal values of the input variables were extracted to access the maximum of the yield strength and MHD parameter of the composite samples. The high values of the desirability function showed that the optimization procedure has successfully fulfilled the pre-determined targets.
- The low difference between the results of the optimization and confirmation tests (lower than 3%) can approve the accuracy and precision of the optimization procedure in order to determine the optimized combination of the input variables.

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# تحلیل آماری و بهینه سازی استحکام تسلیم و سختی کامپوزیت سطحی Al7075/$Al_2O_3$ تولید شده در فرآیند FSP با استفاده از متدلوژی سطح پاسخ و تابع مطلوبیت

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**چکیـــده**

برای بهبود خواص آلومینیم و آلیاژهای آن، راهکارهای متنوعی همچون کاهش اندازه دانه، افزودن عناصر آلیاژی و کامپوزیت سازی، مورد توجه قرار گرفته است. در این میان، استفاده از فرآیندهای حالت جامد همچون فرآوری اصطکاکی اغتشاشی (FSP) به منظور ایجاد کامپوزیت سطحی در دمای زیر نقطه ذوب، بسیار مناسب است. از این‌رو، با توجه به قابلیت فرآیند FSP به عنوان یک فرآیند حرارتی – مکانیکی و مزایای آن در تولید کامپوزیت سطحی زمینه فلزی، در پژوهش پیش‌رو، کامپوزیت‌های سطحی Al7075 با به کارگیری ذرات تقویت کننده ($Al_2O_3$)، با استفاده از این فرآیند و منطبق بر اصول طراحی آزمایش، تولید شدند. بدین منظور، متدلوژی سطح پاسخ به عنوان روش طراحی آزمایش، انتخاب گردید و متغیرهای سرعت دورانی ابزار، نرخ پیشروی ابزار، قطر شانه ابزار و اندازه ذرات تقویت کننده به عنوان متغیرهای ورودی فرآیند، تعیین شدند. در ادامه، تحلیل آماری و بهینه سازی پارامترهای موثر بر استحکام تسلیم و سختی کامپوزیت سطحی Al7075/$Al_2O_3$ به انجام رسید. نتایج حاصل از آنالیز واریانس و تحلیل رگرسیون داده‌های حاصل از آزمون‌های تجربی، صحت و دقت معادلات رگرسیون را مورد تأیید قرار داد و نشان داد که عبارات خطی، تعاملی و سهموی از متغیرهای ورودی فرآیند، بر استحکام تسلیم و سختی نمونه‌های کامپوزیتی موثر هستند. همچنین، شرایط بهینه متغیرهای ورودی فرآیند با استفاده از روش مطلوبیت، تعیین شد. با توجه به مقادیر بالای تابع مطلوبیت (۰/۸۳۵، ۰/۸۲۲، ۰/۷۶۴)، می‌توان دریافت که روند بهینه سازی به طور موفقیت‌آمیزی، اهداف از پیش تعیین شده را به صورت مناسب و مطلوب، محقق نموده است. علاوه بر این، شرایط بهینه با اجرای آزمون صحه‌گذاری، به تأیید رسید.

**واژه‌های کلیدی:** تحلیل آماری، بهینه سازی، خواص مکانیکی، کامپوزیت سطحی، فرآوری اصطکاکی اغتشاشی