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PROCESS OPTIMIZATION OF THE MECHANICAL PROPERTIES OF AISI 1020 STEEL QUENCHED USING MAIZE-STOVER ASH POTASH SOLUTION

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ABSTRACT

The process parameter optimization of maize-stover ash potash (MSAP) as a quenching medium for heat treatment of AISI-1020 steel was conducted in this study to improve the mechanical properties of steel after carburization and quenching. The optimization process utilized Taguchi $L_9(3^2)$ orthogonal array method to determine the individual Signal to Noise (S/N) ratio and Analysis of Variance (ANOVA). A multi-response weighted analysis technique was applied to derive combined quality responses of the heat treated test pieces. The result shows that the optimal factor level of MSAP solution strength was achieved at $A_{M1}B_{M1}$, which offered 57.6 HRC hardness, 39 J toughness and 1971 N/mm^2 tensile strength as improved mechanical properties for the heat treated steel.

Keywords: *Optimization, MSAP, quenching, Taguchi, ANOVA.*

1. INTRODUCTION

Low carbon steel such as AISI-1020 steel, has good ductility and toughness, moderate strength in tension, compression and shear, it could be used where stresses are not high [1]. However, for more versatile applications, its mechanical properties or responses such as hardness, toughness and tensile strength can be improved by heat treatment [2]. Pack-carburization has been used to induce high carbon value up to 2 mm case depth on the surfaces of low carbon steel [3], while the core remains with low carbon value [4]. Maize-stover ash potash (MSAP), is a double chlorides salts of K, Na and Ca, as an alkaline salt derived from maize-stover ash by thermal processing of the filtrate [5, 6]. The quenching severity which is the intense ability of a quenchant to extract heat from a test piece can be determined by measuring the quenchant hardening [7] or cooling power [8]. After quenching operations, such data collected would be analysed in order to optimize and validate the experiment. Optimization is the process of choosing trade-offs in the best way or selecting a desirable outcome among different possible solutions [9], while validation is the process of authenticating the optimized value with a regression analysis using design of experiment (DOE) [10]. Design of experiment is an analytical tool for the optimization of a design system to produce a robust design by considering the individual and interactive effects of many factors that could affect the output results in the design [11, 10]. Though, different analytical methods may be used such as fractional factorial method (FFM), Taguchi method, Response surface method (RSM), etc., but in this study, Taguchi

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method in Minitab 16 software was utilised due to the minimal number of experiments required with the use of orthogonal array (OA) design [12, 13]. This method was used to determine the individual quality response (mechanical properties) of the AISI-1020 steel test pieces quenched in MSAP solution, while a multi-response weighted analysis technique was used to determine the combined quality responses of the heat treated test pieces, since optimization of a single quality response is more focused in Taguchi method [14]. It has been pointed out that signal-to-noise (S/N) ratio is the process of optimizing the quality characteristic using the criteria "Larger the Better or Smaller the Better" variation due to uncontrollable parameter [14]. To arrive at a combined S/N ratio for a multi-quality response, a weight was assigned to the S/N ratio of each response derived from Taguchi method and the mean value of the level weight was used to determine the optimal factor levels. This method was proposed as an effective approach for solving a multi-response problem in Taguchi method that resulted to combined responses [14]. This is because in today's high-tech, manufactured products have more than one quality response, and since there are three quality responses to be considered for the test piece in this study, a multi-response approach was adopted.

2. MATERIALS AND METHODS

The quenching medium (MSAP solution) was prepared by dissolving a measured quantity of MSAP in water, considering the factor levels for the process parameters. Taguchi $L_9(3^2)$ Orthogonal array design method was used to vary the weight as shown in Table 1. The study considered two input factor variables, "MSAP + water" (A_M+B_M) that formed the solution strength of the quenchant. The test pieces (AISI-1020) collected from Aladja steel rolling mill, Delta State, Nigeria, with the initial hardness of 187.3 HV, toughness 49 J and tensile strength 439 N/mm^2, pack-carburized with 70% coal and 30% $CaCO_3$, to obtain 0.75% C [15]. The test pieces were heat treated and quenched in a prepared nine (9) runs of "MSAP + water" solution as quenching medium. An $L_9(3^2)$ orthogonal array was generated with Minitab 16 software, indicating experimental runs, as shown in Table 1. In conventional brine, salt and water solution ranges between 4 % - 9 % by weight concentration.

Meanwhile, it has been observed that heavy concentrations of sodium chloride (10 wt%) in water, slow down the brine cooling rate, and could cause soft spots and cracking in the quenched steel [16]. In this study, the solution strength "MSAP + water" solution was chosen as 3 %, 6 % and 9 % by weight. The experimental runs obtained from the OA is shown in Table 2.

Table 1: Factor levels for Process Parameters using $L_9(3^2)$ OA.

	Factors/Levels	L_1	L_2	L_3
A_M	MSAP (wt%)	3	6	9
B_M	Water (wt%)	97	94	91

Table 2: Level combinations (LC) of process parameters.

S/No	Level Combination (LC)		Inputs Factors	
	Variable A MSAP (Salt)	Variable B Water	Variable A Mass (wt%)	Variable B Mass (wt%)
1	1	1	3	97
2	1	2	3	94
3	1	3	3	91
4	2	1	6	97
5	2	2	6	94
6	2	3	6	91
7	3	1	9	97
8	3	2	9	94
9	3	3	9	91

2.1 Signal-to-noise ratio analysis using Taguchi method

After the experiment was conducted, the three quality response values (hardness, impact and tensile strength) were determined and are shown in Table 3. The signal-to-noise (S/N) ratios of the three quality responses were determined based on the characteristics criterion for each of the responses i.e. "smaller-the-better (STB) or larger-the-better (LTB)". To obtain optimum combination output of design from the orthogonal arrays with Minitab 16, a signal-to-noise (S/N) ratio was generated for each response to achieve the main effect plot using the characteristic equation STB or LTB. The result from the characteristic criteria serves as the calculated/empirical value. When the S/N is large, the magnitude of the signal is large relatively to the noise, as measured with standard deviation. The optimized values obtained from the main effect plot were substituted in the empirical model generated with the use of Minitab 16 software to obtain the theoretical optimal value.

Table 3: OA response value of MSAP + water on mechanical properties of AISI-1020 steel

S/No	Variable (A_M) MSAP	Variable (B_M) Water	Hardness (Hardened and Tempered) HRC	Toughness (Joules)	Tensile Strength (N/mm^2)
1	1	1	57.6	39	1971
2	1	2	50.3	27	1691
3	1	3	63.4	17	2253
4	2	1	60.0	26	2035
5	2	2	57.5	17	2192
6	2	3	62.5	32	2436
7	3	1	52.4	24	1879
8	3	2	59.2	23	2370
9	3	3	57.3	26	2198

The S/N ratio for "smaller the better" characteristics [13] is calculated using the following equation:

$$S/N = -10log_{10}\sum\left(\frac{y^2}{n}\right) \qquad (1)$$

While the S/N ratio for "larger the better" is calculated using:

$$S/N = -10log_{10}\frac{1}{n}\sum\left(\frac{1}{y^2}\right) \qquad (2)$$

Where: y = response or measured value in a run, n = number of measurement in a trial, in this case, n = 1, representing the mean average of three (3) samples measured.
In this study, three LTB type quality responses as the required mechanical properties were selected at three levels, namely: hardness, toughness and tensile strength; while two process controllable factors "MSAP + Water" were investigated.

2.2 Multi-response weighted analysis technique

To obtain a combined S/N ratio for the determination of the optimal factor level, the following three steps are enumerated according to [14]**:**

Step 1:
Let r be the number of responses in OA. Let $\eta_j(j$ = 1, ..., r) be the S/N ratio of response j. Then calculate η_j for all j values using equation 1 or 2. In this case equation 2, LTB applies.

Step 2:
Assume a process factor l is assigned at k level (k = 1, ..., k) of factor l, and $\bar{\eta}_{jlk}$ be the average of η_{jlk}. Calculate $\bar{\eta}_{jlk}$ of each factor level for all responses.

Step 3:
Let w_{jlk} be the weight of level k for factor l from response j, which is stated as:

$$w_{jlk} = \frac{max_k\bar{\eta}_{jk}}{\bar{\eta}_{jk}} \text{ for the STB type response} \qquad (3)$$

Or

$$w_{jlk} = \frac{\bar{\eta}_{jk}}{max_k\bar{\eta}_{jk}} \text{ for the LTB type response} \qquad (4)$$

Then calculate the values of w_{jlk} of factor l from each response j. The values of w_{jlk} should lies between zero and one. Then let $\bar{w}_{jlk}$ be the average of w_{jlk} over all responses. Estimate $\bar{w}_{jlk}$ values for all levels of factor l. The larger $\bar{w}_{jlk}$ indicates better performance. Finally, identify the factor level corresponding to the maximum of $\bar{w}_{jlk}$ (k = 1, 2, ..., k) as the optimal level of factor l.
This study is considering three (3) combined responses which include hardness, toughness and tensile strength. These properties were measured using standard testing techniques like hardness testing machine, Tensile strength machine and Charpy testing machine. The properties were used to evaluate the influence of MSAP on the plain carbon steel. Due to these combined responses, there is need to design a combined factor through multi-response weighted technique analysis. Meanwhile, it has been reported that Taguchi method only focuses on a single response [14] which did not meet the requirement for this study. To this end, in this study, adopting the proposed methods [14], an average S/N ratio ($\bar{\eta}_{jlk}$**)** was calculated for each factor level and then weighted with respect to the level of the largest average S/N ratio for the factors using equation 4. The factor level with the largest level weight was selected as the optimal level for that factor.

Table 4: OA response and S/N ratio (η_j) of AISI-1020 steel in MSAP + water solutions

S/N0	A_M	B_M	Hardness (HRC)	S/N Ratio	Toughness (J)	S/N Ratio	Tensile (N/mm^2)	S/N Ratio
1	1	1	57.6	35.20845	39	31.82129	1971	65.89373
2	1	2	50.3	34.03136	27	28.62728	1691	64.56287
3	1	3	63.4	36.04179	17	24.60898	2253	67.05522
4	2	1	60	35.56303	26	28.29947	2035	66.17129
5	2	2	57.5	35.19336	17	24.60898	2192	66.81681
6	2	3	62.5	35.9176	32	30.103	2436	67.73355
7	3	1	52.4	34.38663	24	27.60422	1879	65.47854
8	3	2	59.2	35.44643	23	27.23456	2370	67.49497
9	3	3	57.3	35.16309	26	28.29947	2198	66.84055

(η_j) = individual S/N Ratio.

This method produced a single combined quality response for the Multi-Response problem of the study. To satisfy this, a three LTB responses were considered for the S/N ratios. From the calculated individual S/N ratio (η_j) detailed in Table 4, the combined average weighted factor level (L_W) of the three responses and their optimal factors were determined with: v

$$(L_W) = (\sum \bar{w}_{jlk}) \quad (5)$$

3. RESULT AND DISCUSSION

Table 4 shows the orthogonal array (OA) response i.e., hardness, toughness and tensile strength and individual calculated S/N ratio of AISI-1020 steel quenched in various solutions of MSAP + Water.

From Table 4, the MSAP solution $A_{M1}B_{M3}$ strength provided the highest value of hardness as 63.4 HRC, $A_{M1}B_{M1}$ gave the highest value of toughness as 39 J and $A_{M2}B_{M3}$ gave the highest value of tensile strength as 2436 N/mm^2. But it is clear here that there are discrepancies in the results because there is no singular solution strength of MSAP that offered a combined optimal value of response.

3.1 Main effects plot for Hardness of steel in MSAP Solutions

Figure 1 shows S/N Ratio main effect plot that was achieved for hardness of the test piece quenched in MSAP solutions, generated from Table 4 in Minitab 16 software. The highest values from the main effect plot are the optimized values. In this case, the optimized values are $A_{M2}B_{M3}$ for MSAP + Water. where A_{M2} is MSAP = 2, and B_{M3} is Water = 3. Note: 2 and 3 are level combinations (LC).

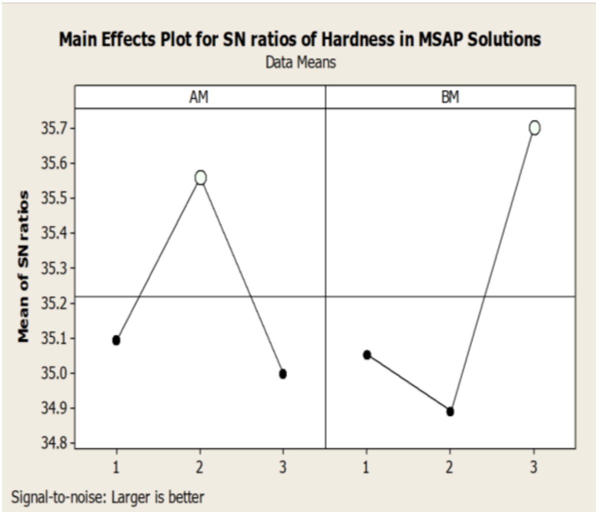

Figure 1: Main effect plot for hardness in MSAP solutions, optimized value is $A_{M2}B_{M3}$.

3.1.1 Theoretical optimal value for hardness

The empirical regression equation for Hardness (HRC) is:

$$HRC = 127.5 - 0.133\ A_M - 0.733\ B_M \quad (6)$$

R^2 = 50.54%, R^2 (adj) = 41.01%.

From Table 2, the optimised values 2 and 3 i.e $A_{M2}B_{M3}$, represents 6 % MSAP, 91 % Water by weight. Substituting 6 % for A_M and 91 % for B_M in equation (6), the calculated value gave 60 HRC. While from Table 4 the experimetal value gave 62.5 HRC in $A_{M2}B_{M3}$. This implies that the difference in hardness between expemimental and the empirical result generated was 2.5 HRC. It should be noted that equation (6) can be used to determine other values that are not considered in the study to replicate other applications.

3.1.2 Contour plot of hardness in MSAP solutions

Figure 2 shows the contour plot that was achieved for hardness of the test piece quenched in MSAP

Solutions. The result shows that a specific hardness value could be designed using the contour plot. For example, to achieve a range of hardness value between 60 to 62 HRC, a mixture of 7 % MSAP could be dissolved in 91.5 % Water by weight.

3.1.3 Analysis of variance to determine P-Value for hardness

Table 5 shows the ANOVA that was achieved for hardness of steel quenched in MSAP + water solution. The percentage concentration (%P) shows that achieving hardness of steel in MSAP solution, water (**B_M**) in the MSAP solution formulation has more interactive effect, contributing 56.5 % while the percentage error is 5%. This implies that the formulation is 95 % effective. This is conformance with the established [10] that % error should be ≤ 5%.

3.2 Toughness of steel in MSAP solutions

Figure 3 shows the S/N Ratio main effect plot that was achieved for toughness of test piece quenched in MSAP Solutions generated from Table 4 in Minitab 16 software. The highest values from the main effect plot are the optimized values. In this case, the optimized values are $A_{M1}B_{M1}$ for MSAP + Water. Where A_{M1} is MSAP = 1, and B_{M1} is Water = 1. Note: 1 and 1 are level combinations (LC).

3.2.1 Theoretical optimal value for impact toughness in MSAP solutions

The empirical regression equation of Impact Toughness J is given by:

$$J = -34.1 - 0.56 A_M + 0.78 B_M \qquad (7)$$

$R^2 = 62.98$ %, R^2 (adj) = 54.11 %.

From Table 2, the optimized values 1 and 1 i.e $A_{M1}B_{M1}$, represents 3 % MSAP, 97 % Water by weight. Substituting 3 % for A_M and 97 % for B_M in equation (7), the calculated value gave 39.88 J. While the experimental value for $A_{M1}B_{M1}$ from Table 4 gave 39 J. This implies that the difference in toughness between expemimental and the empirical result generated was 0.88 J. Note that equation (7) can be used to determine other values that are not considered in the study to replicate other applications.

3.2.2 Contour plot for impact toughness in MSAP solutions

Figure 4 shows the contour plot that was achieved for toughness of test piece quenched in MSAP Solutions. The result shows that a specific toughness value could be designed using the contour plot. For example, to achieve a toughness value greater than 36 J, a mixture of 3 % MSAP could be dissolved in 97 % Water by weight.

3.2.3 Analysis of variance to determine P-Value for impact toughness in MSAP solutions

Table 6 shows the ANOVA that was achieved for toughness of steel quenched in MSAP+Water solution. The percentage concentration (%P) shows that achieving impact toughness in MSAP solution, water (B_M) in the MSAP solution formulation has more interactive effect, contributing 56 % while the percentage error is 5 %. This implies that the formulation is 95 % effective. This is in conformance with the established [10] that % error should be ≤ 5%.

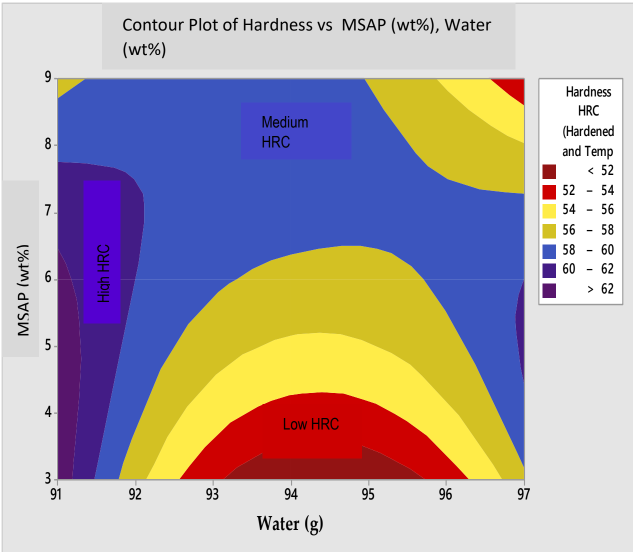

Figure 2: Contour plot of hardness in MSAP solutions.

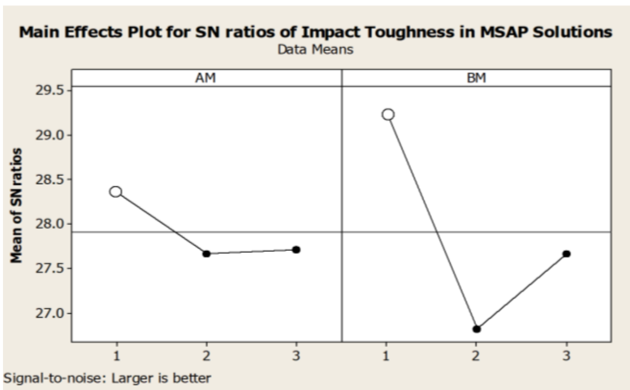

Figure 3: Main effect plot for S/N ratio of impact toughness in MSAP solutions, optimized value is $A_{M1}B_{M1}$.

Table 5: ANOVA for hardness in MSAP + Water solution.

Factor	DOF	SS	MS	F-Value	% P
A_M	2	55.74	27.87	14.32905	38.16763
B_M	2	82.52	41.26	21.21337	56.50507
Error	4	7.78	1.945		5.327308
Total	8	146.04	18.255		100

Table 6: ANOVA for impact toughness in MSAP+Water solution

Factor	DOF	SS	MS	F-Value	% P
A_M	2	148.67	74.335	15.93462	39.12368
B_M	2	212.67	106.335	22.79421	55.96579
Error	4	18.66	4.665		4.910526
Total	8	380	47.5		100

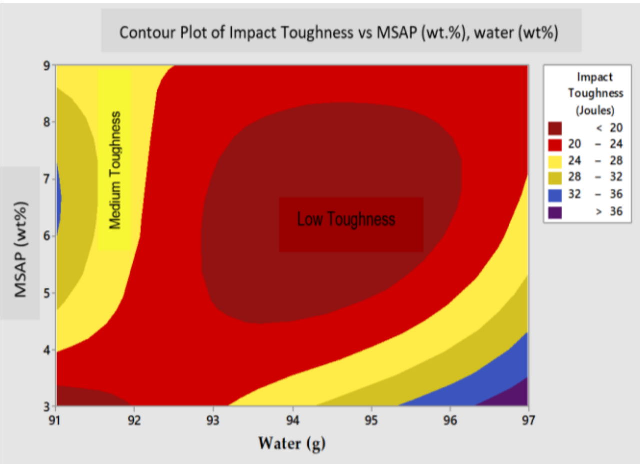

Figure 4: Contour plot of impact toughness in MSAP solutions

3.3 Tensile strength of steel in MSAP solutions

Figure 5 shows the S/N ratio main effect plot achieved for tensile strength of the test piece quenched in MSAP Solutions, generated from Table 4 in Minitab 16 software. The highest values from the main effect plot are the optimized values. In this case, the optimized values are $A_{M2}B_{M3}$ for MSAP + Water. Where A_{M2} is MSAP = 2, and B_{M3} is Water = 3. Note: 2 and 3 are level combinations (LC).

3.3.1 Theoretical optimal value for tensile strength

The empirical regression equation of Tensile Strength (TS) in (N/mm^2) is:

$$TS = 7169 + 29.6\, A_M - 55.7\, B_M \qquad (8)$$

R^2 = 76.38%, R^2 (adj) = 66.12%.

From Table 2, the optimised values 2 and 3 i.e $A_{M2}B_{M3}$, represents 6 % MSAP, 91 % Water by weight. Substituting 6 % for A_M and 91 % for B_M in equation (8), the calculated value gave 2277.9 N/mm^2. While the experimental value for $A_{M2}B_{M3}$ from Table 4 gave 2436 N/mm^2. This implies that the difference in tensile strength between expemimental and the empirical result generated was 158.1 N/mm^2. Note that equation (8) can be used to determine other values that are not considered in the study to replicate other applications.

3.3.2 Contour plot of tensile strength in MSAP solutions

Figure 6 shows the contour plot achieved for tensile strength of steel quenched in MSAP solutions. The result shows that a specific Tensile Strength value could be designed using the contour plot. For example, to achieve a Tensile Strength value greater than 2400 N/mm^2, a mixture of 6 % MSAP could be dissolved in 91 % Water by weight.

3.3.3 Analysis of variance to determine P-Value for tensile strength

Table 7 shows the ANOVA achieved for Tensile Strength of steel quenched in MSAP+Water solution. The result with P-Value shows that achieving tensile strength in MSAP solution, water (B_M) in the MSAP solution formulation has more interactive effect, contributing 56.5 % while the percentage error is 3 %. This implies that the formulation is 97 % effective. This is in conformance with the established [10] that % error should be ≤ 5%.

From the analysis in Tables 5, 6 and 7, it could be stated that the optimum factors derived from Taguchi method for hardness is $A_{M2}B_{M3}$, toughness is $A_{M1}B_{M1}$, and tensile strength is $A_{M2}B_{M3}$ respectively. It is clearly observed from this analysis that discrepancies exist among the optimal factors. These discrepancies were addressed by using the multi-response weighted analysis technique.

3.4 Multi-response S/N ratio for the MSAP solution (MSAP + Water).

Table 8 shows the combined S/N Ratio average of MSAP + water solution, for hardness, toughness and tensile strength of the test pieces quenched in MSAP solution.

The highest factor levels were selected for each response as the optimal factors. For hardness, the optimal factor is $A_{M2}B_{M3}$, toughness is $A_{M1}B_{M1}$, and tensile strength is $A_{M2}B_{M3}$ respectively. These are in agreement with the optimal values obtained with Taguchi method as shown in the main effect plots Figures 1, 3 and 5 respectively. Meanwhile, from Table 8, it is clear that discrepancies exist among the optimal factor levels for the three responses. In order to resolve these discrepancies, a level weight was assigned to the S/N ratio (LTB) of each quality response, to have combined S/N ratios for the determination of the final multi-response optimal factor levels [14], as shown in Table 9. The minimum average S/N ratio value in Table 8 was divided by the maximum average S/N ratio value to obtain the S/N ratio for each factor at each level of response. The result in Table 9 showed the final optimal factor level for the three combined responses for MSAP solution is $A_{M1}B_{M1}$ obtained by assigned level weight using equation 5.

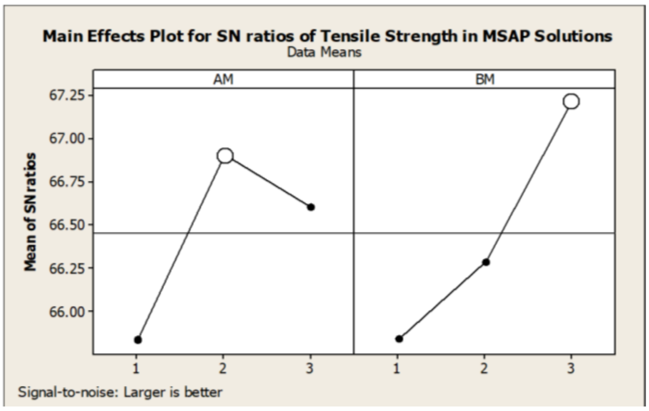

Figure 5 Main effect plot for S/N ratio of tensile strength in MSAP solutions, optimized value is $A_{M2}B_{M3}$

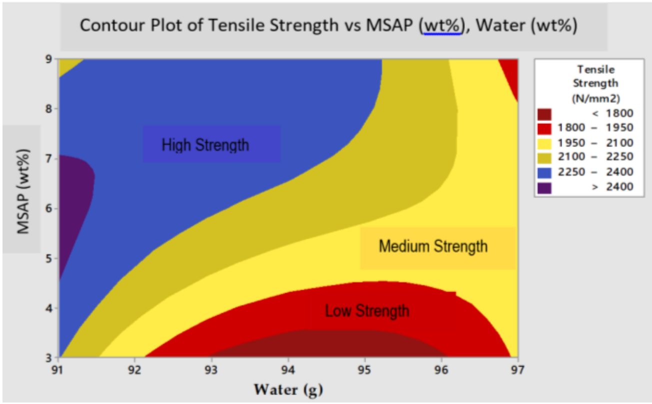

Figure 6: Contour plot of tensile strength in MSAP solutions.

Table 7: ANOVA for tensile strength in MSAP+Water solution

Factor	DOF	SS	MS	F	% P
A_M	2	188798	94399	30.30003	40.81899
B_M	2	261265	130632.5	41.9302	56.48669
Error	4	12461.9	3115.475		2.69432
Total	8	462524.9	57815.61		100

Table 8: Combined S/N ratio average for MSAP + Water solution

Response (dB)	Factor / Level	A_M $(\bar{\eta}_{jlk})$	B_M $(\bar{\eta}_{jlk})$	Optimal Factors
	1	35.0938667	35.0527033	
Hardness	2	35.5579967	34.8903833	$A_{M2}B_{M3}$
	3	34.9987167	35.7074933	
	1	28.3525167	29.24166	
Toughness	2	27.6704833	26.8236067	$A_{M1}B_{M1}$
	3	27.71275	27.6704833	
	1	66.6046867	65.8478533	
Tensile Strength	2	66.9072167	66.29155	$A_{M2}B_{M3}$
	3	66.6046867	67.2097733	

Note: $(\bar{\eta}_{jlk})$ = **average** S/N ratio, where j = response $_{(j = 1, 2, 3)}$, l = factor $_{(l = 1, 2, 3)}$, and k = level $_{(k = 1, 2, 3)}$.

Table 9: Assigned level weight for MSAP + Water solution

Response (dB)	Level \ Factor	A_M (w_{jlk})	B_M (w_{jlk})	Final Optimal Factors
Hardness	1	0.98694724	0.98166239	
	2	1	0.97711657	
	3	0.98427133	1	
Impact Toughness	1	1	1	
	2	0.97594452	0.91730793	
	3	0.97743528	0.94626924	
Tensile Strength	1	0.99547837	0.97973628	
	2	1	0.98633795	
	3	0.99547837	1	
		$(\sum\overline{w}_{jlk})$	$(\sum\overline{w}_{jlk})$	
Level weight (L_W)	1	0.994141868	0.987132891	$A_{M1}B_{M1}$
	2	0.991981507	0.96025415	
	3	0.985728324	0.982089746	

Note: w_{jlk} = $(\bar{\eta}_{jlk}/_{\text{Max}}\bar{\eta}_{jlk})$, $(\bar{\eta}_{jlk})$ **= average** S/N ratio, $(_{\text{Max}}\bar{\eta}_{jlk})$ **= maximum average** S/N ratio, where j = response (j = 1, 2, 3),

Therefore, the anticipated optimal values for hardness, impact toughness and tensile strength for the MSAP + water factors were calculated from the level weight as $A_{M1}B_{M1}$. Therefore, relating the achieved optimal factor level with Table 3, the test samples quenched in the MSAP optimal solution ($A_{M1}B_{M1}$), produced combined response of 57.6 HRC, 39 J and 1971 N/mm^2 respectively in the test pieces.

4. CONCLUSION

In conclusion, the followings were drawn from this study:

1. An optimal factor of $A_{M1}B_{M1}$ for MSAP solution was achieved with the use of Taguchi method coupled with multi-response weighted analysis technique.
2. The combined response values (properties) of AISI-1020 steel were improved with the use of the optimized MSAP solution.
3. The optimised properties of the steel were achieved, with hardness 57.6 HRC, tensile strength 1971 N/mm^2, and toughness 39 J.
4. The study shows that the mechanical properties of AISI-1020 steel were improved for more versatile applications where high case hardness, good core toughness and high tensile strength are of importance.

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