DOI: 10.5604/01.3001.0014.1597
Volume 99 • Issue 1 • March 2020

Journal of Achievements in Materials and Manufacturing Engineering

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

# Parameters optimization of MAG welding for enhancing the mechanical properties and buckling behaviour of welded steel

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## ABSTRACT

**Purpose:** The influence of metal active gas welding variables, including current, wire feeding speed and gas flow rate on the ultimate tensile strength and critical buckling load of steel (St.24) and the optimized welding conditions were discussed.

**Design/methodology/approach:** The experimental steps are firstly designing the experiments, secondly conducting the mechanical tests, thirdly analysing the results through Minitab 16 and finally determining the optimum welding parameters. Confirmation tests of the optimized variables were validated.

**Findings:** ANOVA approach manifested that the significant effect of welding variable on the tensile strength was the gas flow rate, while the current was on the critical buckling load. The results are confirmed and given the optimum values.

**Research limitations/implications:** The influence of MAG welding variables (current, wire feeding speed and gas flow rate) on the tensile and buckling strengths of steel will be investigated in order to avoid the failure of many welded assemblies in the structures due to the buckling, in addition to reduce the requirement of long time and high cost to produce such assemblies. Therefore, it is necessary to find a solution to encounter the difficulties in their welding process.

**Practical implications:** The major challenge was how to reduce the time and cost beside gaining the optimum properties through the designed experiments.

**Originality/value:** The results may be helpful to design any welded joints in machine frames, structural steel connections and crane structures at the optimum condition.

**Keywords:** MAG welding parameters, Critical buckling load, Taguchi method, ANOVA, Optimization

**Reference to this paper should be given in the following way:**

A.H. Alwan, N.Y. Mahmood, Parameters optimization of MAG welding for enhancing the mechanical properties and buckling behaviour of welded steel, Journal of Achievements in Materials and Manufacturing Engineering 99/1 (2020) 5-13. DOI: https://doi.org/10.5604/01.3001.0014.1597

ANALYSIS AND MODELLING

## 1. Introduction

The welding technique in different mechanical structures is used to minimize the manufacturing time and mechanical properties enhancement. This process has more efficient, economical and reliable. In the gas metal arc welding (GMAW), an arc is generated between wire electrodes and the base metal together with the shielding gas or gases around a weld bead to prevent it from the pollution and to improve the mechanical properties [1]. The welding parameters of the GMAW that effect on the welding quality are current, gas flow rate, voltage, feeding speed, electrode angle and diameter of electrode, etc. [2]. Due to many welding variables that give various mechanical properties, the researchers are firstly planned the experimental proceedings to optimize the variables through the Taguchi approach [3-5], which is becoming a suitable way to obtain the preferable results and minimize the cost and experimental duration. Taguchi technique is also utilized for the other manufacturing processes or any parametric optimization [6-8].

N. Ghosh et al. studied the effect of the welding parameters (current, gas flow rate and distance between nozzle and plate) on the tensile strength of stainless steel. Taguchi approach was applied to design the experiments and make an optimization for the ultimate strength. The best tensile result was obtained by decreasing the current to 100 A, but the other parameters had different behaviours [5]. I. A. Ibrahim et al. used the current, voltage and welding speed as welding parameters of mild steel. It was obtained that the raising of current increases the depth of penetration; also voltage and speed have the same behaviour. While, the hardness increased due to decreasing the current [9]. A. A. Shukla et al. investigated the influence of current, polarity of electrode and torch angle on the welding penetration of AISI 1020 steel. It was concluded that the maximum penetration was enhanced as increasing of electrode angle and current for DCEN polarity [10]. M. Muthukumar et al. discussed the effect of (Argon and $CO_2$) gases with various mixture percentages on the hardness, corrosion and microstructure. The corrosion strength decreased as compared with the original metal. The results enhanced owing to increasing the Argon percentage [11]. S. A. Swami et al. utilized the current, gas flow rate and $CO_2$ percentage as input parameters to Taguchi approach for designing an experimental process and getting an optimum tensile strength of mild steel. The results revealed that the significant effect on the ultimate tensile strength was due to the shielded gas flow rate [12].

The critical buckling load of welded steel has been investigated by few attempts such as [13], which compared between two types of steel using different welding electrode types, but the other welding variables were fixed. Therefore, in the present work, the influence of MAG welding variables (current, wire feeding speed and gas flow rate) on the tensile and buckling strengths of steel will be investigated since many welded assemblies in the structures may fail due to the buckling.

## 2. Experimental procedure

Rectangular plates with dimensions of (200 mm x 250 mm) and 2 mm thickness of low carbon steel (No. 1.0327) were used in this investigation for welding process to prepare the welded specimens. The MAG welding process of this study was carried out in the workshop of University of Technology with ESAB Origo™ Mig C280 Pro welding machine, and the gases were mixed between 20% $CO_2$ and 80% Argon. The welded plates were allowed to cool at the room temperature and then the slag was removed by hammer to ensure the gap was completely filled. After the plates have been welded for all experiments, the specimens were produced by using a cutting machine as shown in Figure 1, then burrs of the all welded samples edges were removed and finally these edges were smoothened with different grades of abrasive sheets. Three samples for each experimental test were examined, and the average results were taken. Tensile and buckling samples were made according to ASTM D 638-02a and ASTM E 9-89a standards, respectively. Fixed-fixed ends condition for buckling tests as shown in Figure 2 was applied with a compression speed of (1 mm/min).

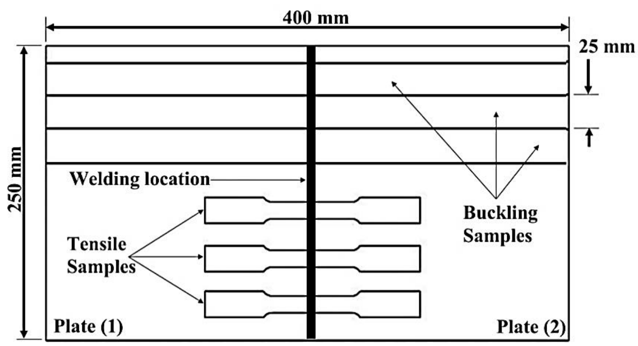


Fig. 1. Tensile and buckling samples of welding plates

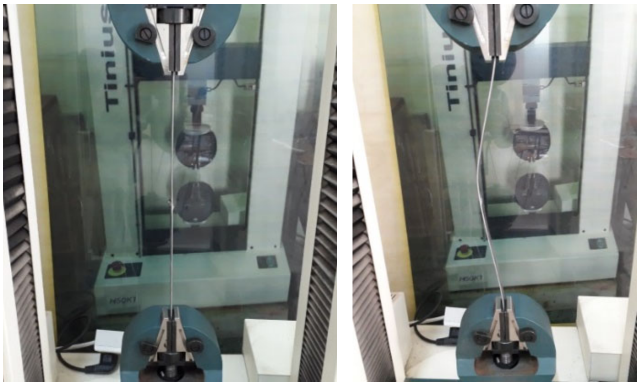

Fig. 2. Buckling samples before and after test

## 3. Experimental design method

The number of trails was reduced by designing of the experiment to minimize the time, and the optimum study of the effect of welding variables on the tensile strength (TS) and critical buckling load (CBL) was achieved. The optimal welding variables that maximize the ultimate tensile and buckling strength were achieved by using Minitab 16 after designing an experiment. Table 1 illustrates the welding factors and their levels, which were designed as listed in Table 2 with three factors and three levels.

Table 1.
Input variables to Minitab program

| Input variables | Current | Wire feeding speed | Gas flow rate |
|---|---|---|---|
| Unit | Ampere | m/min. | L/min. |
| Symbol | A | B | C |
| Levels | 84 | 5 | 17 |
| | 140 | 7 | 20 |
| | 196 | 9 | 23 |

Many welding trials have been applied before recording the welding parameters, which are listed in Table 1 with considering the good penetration and bead profile to achieve good results. Hagazi Abrha reported that the wire feeding speed and welding current are the most important MAG welding variables for penetration, while the shielding gas and wire feeding speed are more dominant for the welding porosity controlling [14].

Taguchi technique is a highly procedural planning applied to estimate the major influences through a few practical trials. The main influences of the input variables having greater than two levels of each parameter were investigated by these trials [15]. In this technique, ANOVA is done through the signal to noise ratio (S/N). The objective of this research is to maximize the ultimate tensile and buckling strengths through the input variables. The signal to noise ratios for every trial of L9 were estimated using larger the better approach with three variables and nine trials. The signal to noise ratio for each trial was calculated by using Minitab 16 after the experimental tests and illustrated in Table 2.

## 4. Results and optimization

Table 2 presents the tensile strength and critical buckling load results of all experiments and shows that the maximum tensile strength is (320 MPa) at (196 Amp., 7 m/min and 17 L/min.), while the maximum critical buckling load is (2891 N) at (196 Amp., 9 m/min and 20 L/min.). In general, the tensile strength increased with the increasing current due to the increasing of penetration depth during the welding process [9]. The welded assembly with a good penetration is always powerful than other [12] due to the increase of heat generation in weld bead [16], as well as the mixture of 20% $CO_2$ with 80% argon has the same results in this study, while the other parameters have different behaviours. ANOVA mentions to the analysis of variance and is a statistical method utilized to test two or more parameters in an experiment. In most experiments, a variance commonly refers to an important finding from the investigation. The optimum variables were predicted through the signal to noise ratio and the Analysis of Variance (ANOVA) method. A validation test was used to confirm the optimal conditions obtained from the parameter design. The reliably optimized model was tested through an ANOVA technique. Calculation of the Pareto ANOVA with three factors and three levels is demonstrated in Table 3 [8,15,17]. Pareto ANOVA was applied for the ultimate tensile strength and critical buckling load to investigate the contribution ratio of the process variables. The good selection of the welding variables has made the results very close to the original used material results, as depicted in Table 2.

The contribution ratio as presented in Tables 4 and 5 of three parameters (A, B and C) was obtained through the calculation of all items in Table 3 for tensile strength and critical buckling load.

Table 2.
Taguchi experimental design and results with S/N ratio

| No. | Variables | | | TS (MPa) | S/N of TS | CBL (N) | S/N of CBL |
|---|---|---|---|---|---|---|---|
| | A | B | C | | | | |
| Base metal | --- | --- | --- | 355 | --- | 3010 | --- |
| 1 | 84 | 5 | 17 | 280 | 48.9432 | 797 | 58.0292 |
| 2 | 84 | 7 | 20 | 302 | 49.6001 | 578 | 55.2386 |
| 3 | 84 | 9 | 23 | 159 | 44.0279 | 1676 | 64.4855 |
| 4 | 140 | 5 | 20 | 270 | 48.6273 | 989 | 59.9039 |
| 5 | 140 | 7 | 23 | 255 | 48.1308 | 865 | 58.7403 |
| 6 | 140 | 9 | 17 | 263 | 48.3991 | 700 | 56.9020 |
| 7 | 196 | 5 | 23 | 254 | 48.0967 | 745 | 57.4431 |
| 8 | 196 | 7 | 17 | 320 | 50.1030 | 2833 | 69.0449 |
| 9 | 196 | 9 | 20 | 290 | 49.2480 | 2891 | 69.2210 |

Table 3.
Pareto ANOVA calculation method [8,15,17]

| | | Factor A | Factor B | Factor C | Total |
|---|---|---|---|---|---|
| Sum at factor levels | 1 | Σ A1 | Σ B1 | Σ C1 | T(i) |
| | 2 | Σ A2 | Σ B2 | Σ C2 | |
| | 3 | Σ A3 | Σ B3 | Σ C3 | |
| Sum of the differences squares | | SA(ii) | SB(iii) | SC(iv) | ST(v) |
| Degrees of freedom | | 2 | 2 | 2 | 6 |
| Contribution ratio | | SA/ST | SB/ST | SC/ST | 1 |

(i) T = Σ A1 + Σ A2 + Σ A3
(ii) SA = $(\Sigma A1 - \Sigma A2)^2 + (\Sigma A1 - \Sigma A3)^2 + (\Sigma A2 - \Sigma A3)^2$
(iii) SB = $(\Sigma B1 - \Sigma B2)^2 + (\Sigma B1 - \Sigma B3)^2 + (\Sigma B2 - \Sigma B3)^2$
(iv) SC = $(\Sigma C1 - \Sigma C2)^2 + (\Sigma C1 - \Sigma C3)^2 + (\Sigma C2 - \Sigma C3)^2$
(v) ST = SA + SB + SC + SE

Table 4.
Tensile results analysis by Pareto ANOVA

| | | Factor A | Factor B | Factor C | Total |
|---|---|---|---|---|---|
| Sum at factor levels | 1 | 142.5712 | 145.6672 | 147.4453 | 435.1761 |
| | 2 | 145.1572 | 147.8339 | 147.4754 | |
| | 3 | 147.4477 | 141.675 | 140.2554 | |
| Sum of the differences squares | | 35.7140 | 58.5642 | 103.8239 | 198.1021 |
| Degrees of freedom | | 2 | 2 | 2 | 6 |
| Contribution ratio | | 0.1802 | 0.2956 | 0.5240 | 1 |
| Optimum level | | (3) | (2) | (1) | |
| | | A3=196 | B2=7 | C2=20 | |

Table 5.
Critical buckling load analysis by Pareto ANOVA

| | | Factor A | Factor B | Factor C | Total |
|---|---|---|---|---|---|
| Sum at factor levels | 1 | 177.7533 | 175.3762 | 183.9761 | 549.0085 |
| | 2 | 175.5462 | 183.0238 | 184.3635 | |
| | 3 | 195.7090 | 190.6085 | 180.6689 | |
| Sum of the differences squares | | 733.8169 | 348.0364 | 24.7377 | 1106.5910 |
| Degrees of freedom | | 2 | 2 | 2 | 6 |
| Contribution ratio | | 0.6631 | 0.3145 | 0.02235 | 1 |
| Optimum level | | (1) | (2) | (3) | |
| | | A3=196 | B3=9 | C2=20 | |

The optimum conditions of tensile strength and critical buckling load are (A3, B2 and C2) and (A3, B3 and C1), respectively, which are presented in Tables 4 and 5. These results indicate that the significant effect of welding variable on the tensile strength and the critical buckling load is the gas flow rate (as similar to results in [12]) followed by wire feeding speed and current for tensile strength, current and wire feeding speed for the critical buckling load, respectively.

These results were plotted in Figures 3 and 4 by using Minitab 16 to reveal the influence of welding variables on the S/N ratio and means response. The maximum means and S/N ratios values of the tensile strength are at current of A3, wire feeding speed of B2 and gas flow rate of C2. While, the critical buckling load have the maximum values at current of A3, wire feeding speed of B3 and gas flow rate of C2.

Also, Figures 3 and 4 manifest that the tensile strength and the critical buckling load increased with the increasing of current, while the tensile strength decreased when the other variables are increased. The critical buckling load improves as the wire feeding speed increases but it decreases as the gas flow rate increases. The highest tensile strength was found at 20 L/min of the gas flow rate. For preventing the occurrence of oxidation during the welding process, shielding gases are utilized for allowing more penetration in the welded joints. The welded joints have better strengths than others when the suitable fusion with the good penetration achieved [12]. The tensile strength reduction after 20 L/min of the gas flow rate may be due to unsuitable fusion [12].

Phenomenon of the increasing and decreasing response can be due to the change of the microstructure of welded metal during solidification, and the defects in the different welding conditions have more chances to create. Also, it can be indicated that the increasing in strength may be due to the brittleness in the welded joints which will become more than the original material; hence, it becomes a necessary to optimize the mechanical properties [18]. The most declared changes in the microstructure and mechanical properties (diminution in the plasticity, toughness and strength) of the original material are due to the changes in the grain sizes, overheating and the formation of cracks which occured in the near-weld zone [19]. Differents microstructural defects, like martensite, carbide precipitation and coarsen grains often happen in the heat effected zone which decrease the toughness of welded joint with tending to brittle behaviour [19]. The mixture of shielding gases (Argon and $CO_2$) produced the acceptable mechanical properties of welded joints due to the balance between the cooling rate and the formation of acicular ferrite which enhances the tensile strength and toughness [20]. The generated contour plots in Figure (5A to 5F) manifest a special shape, which explains the relationship between variables and response, in addition, they are used to display the optimal region, which indicates the optimum variables.

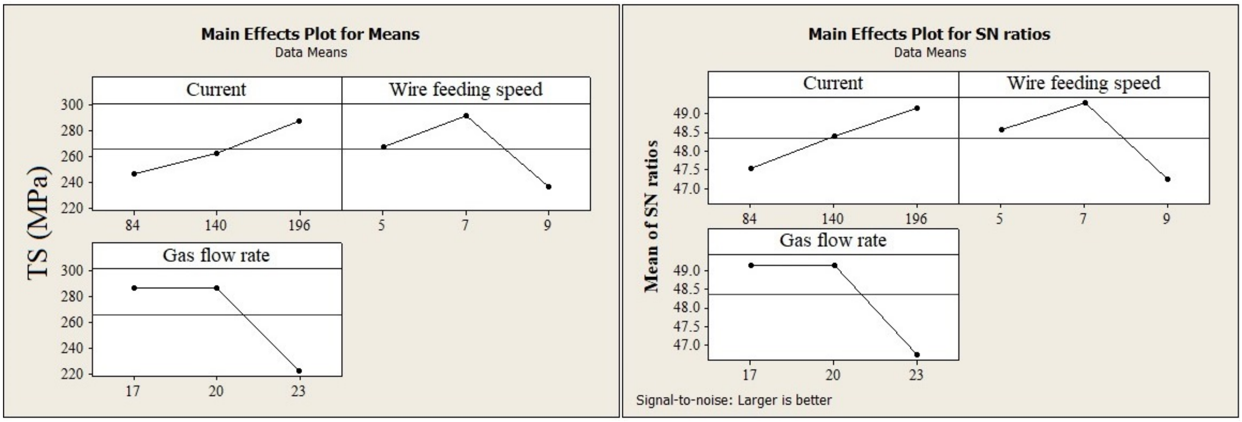


Fig. 3. Tensile strength according to S/N ratio and means

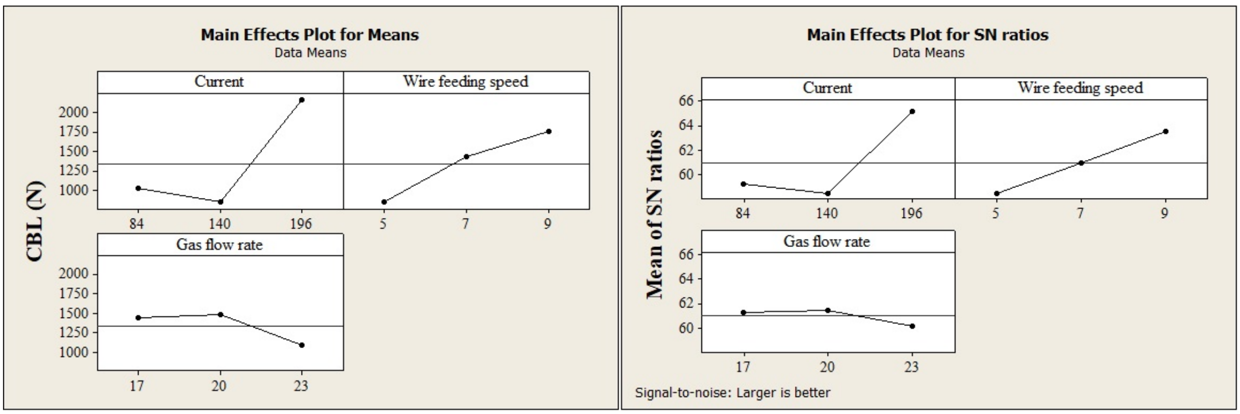


Fig. 4. Critical buckling load according to S/N ratio and means

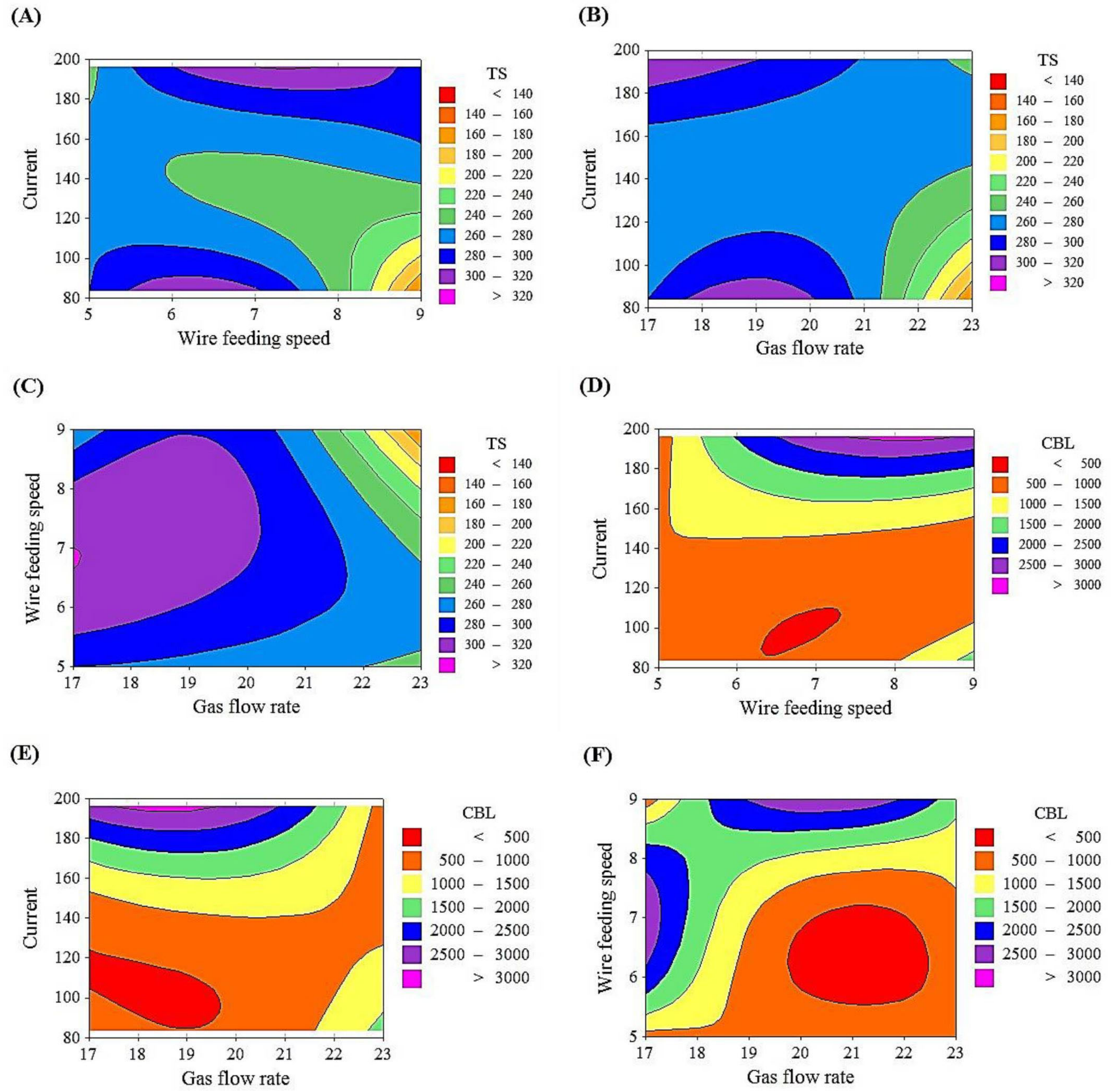


Fig. 5. Contour behaviour of tensile strength (A, B & C) and critical buckling load (D, E & F) as welding variables

The contour plots are generated to characterize whether the region found is a maximum, or a minimum response or a range between them. The optimum region in the created contour plots by Minitab 16 program can be existed with a high credibility by describing the shape of the region. If a shape of contour is circular, the variables effects tend to an independence, but the elliptical shape may suggest the parameter interactions [21]. The contour behaviour demonstrated the optimum results as achieved from ANOVA. It is observed that the best tensile properties are achieved at high current and moderate wire feeding speed and gas flow rate. The high current, the high wire feeding speed and the moderate gas flow rate have the highest results for the critical buckling load (CBL). These figures may be helpful for the manufacturing engineers to design the welded joints with the required properties according to the suitable welding parameters.

It is easier to realize the contour behaviour in Figure 5 (A & B) that the variation in the welding current is more susceptible to the change in tensile strength (TS) than to the change in the wire feeding speed and gas flow rate, but Figure 5 (C) elucidates that the tensile strength is more sensitive to the variation in the gas flow rate than the wire feeding speed, thus the tensile strength decreased at a gas flow rate of 20 L/min which concerned with the ANOVA in Figure 3. An interaction influence of welding current, wire feeding speed and gas flow rate on the critical buckling load also occurred, as manifested through the contour plots in Figure 5 (D, E & F). The critical buckling load is very sensitive to the change in welding current than wire feeding speed and gas flow rate, the highest critical buckling load (CBL) was found at a high level of welding current and wire feeding speed with a moderate gas flow rate, Figure 3 proved this behaviour. It appears to be an evidenced interaction influence of welding current and wire feeding speed on the critical buckling load when the welding current was utilized after 140 A at a wire feeding speed after 5.5 m/min. The contour plot exhibited in Figure 5 (E) obviously explains that the effect of welding current on the critical buckling load is greater than that of gas flow rate, and Table 5 demonstrated that the welding current has a major effect than others. The interaction between a wire feeding speed and a gas flow rate on the critical buckling load is viewed in Figure 5 (F) which proved that the critical buckling load is more affective with a wire feeding speed than the gas flow rate.

### 4.1. Validation test

Confirmation tests were accomplished to validate the optimized welding parameters. The results are listed in Table 6. The optimum condition proved that the tensile strength and the critical buckling load have the maximum results; these values exhibit the validation of the suggested optimization.

Table 6.
The results of confirmation tests

| Properties | TS | CBL |
|---|---|---|
| Optimum parameters | 196A, 7m/min., 20 L/min. | 196A, 9m/min., 20 L/min. |
| Predicted value | 335.889 MPa | 2714.89 N |
| Experimental value | 324 MPa | 2891 N |
| Difference | -3.7% | 6% |

## 5. Conclusions

In this research, the influence of welding variables on the tensile and buckling strengths of steel was studied. It is shown from the literature that the critical buckling load of welded steel has been investigated by few attempts. Therefore, the influence of MAG welding variables (current, wire feeding speed and gas flow rate) on the tensile and buckling strengths of steel was considered in the present work since many welded assemblies in the structures may fail due to the buckling occurrence. All the calculated, predicted and optimized values in this research were carried out using Minitab 16 software. From the above results, it is evinced that the concluding remarks are as following:

1. From the nine experimental trials, it was found that the best results were 320 MPa of TS and 2891 N of CBL at (196 A, 7 m/min and 17 L/min) and (196 A, 9 m/min. and 20 L/min), respectively.
2. The optimized results (324 MPa of TS and 2891 N of CBL) were very close to those of the experimental trials and the base metal which emphasize that the selection of welding variables were correct.
3. The time duration and cost of trials were improved by using the optimization approach.
4. ANOVA approach manifested that the significant effect of welding variable on the tensile strength was the gas flow rate, while the current was for the critical buckling load.
5. The significant effect of welding parameter on the ultimate tensile strength and critical buckling load is the current, since the tensile strength and critical buckling load improved as the current is increased.
6. The optimum results, which are obtained through the Taguchi optimization approach, were confirmed by the validation test.

This investigation can be beneficial to design any welded joints with the optimum input parameters for achieving the optimal results and to avoid the weldment difficulties in producing assemblies with numerous expensive welding trials. It is a remarkable method in determining the welded joint quality of assemblies, which can resist the subjected loads on them while utilizing in machineries.

In the future, it is recommended to investigate the relation between the optimized longitudinal and transverse mechanical properties through comparing the obtained results and discussing the microstructure of welded samples.

## 6. Abbreviations

MAG welding – Metal Active Gas welding,
ANOVA – Analysis of Variation,
MIG welding – Metal Inert Gas Welding,
GMAW – Gas Metal Arc Welding,
DCEN polarity – Direct Current Electrode Negative polarity,
TS – Tensile Strength,
CBL – Critical Buckling Load,
S/N – Signal to Noise ratio,
Ai, Bi and Ci – The Current, Wire feeding speed and Gas flow rate parameters at i level, i.e. level 1, 2 and 3,
Σ A1, 2, 3 – The sum of S/N ratio response for Current at levels 1, 2, 3,
Σ B1, 2, 3 – The sum of S/N ratio response for Wire feeding speed at levels 1, 2, 3,
Σ C1, 2, 3 – The sum of S/N ratio response for Gas flow rate at levels 1, 2, 3,
SA, SB and SC – Sum of the differences squares for Current, Wire feeding speed and Gas flow rate,
ST – Total Sum of the differences squares for Current, Wire feeding speed and Gas flow rate.

## Acknowledgements

The authors are thankful to the University of Technology - Iraq, Baghdad, Iraq, especially the Department of Mechanical Engineering and the Center of Training and Workshops for all assistance and support.

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