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# Application of Taguchi Method in Optimizing Charpy Impact Al-Si-Cu Cast Alloys Weld by TIG Welding

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# Application of Taguchi Method in Optimizing Charpy Impact Al-Si-Cu Cast Alloys Weld by TIG Welding

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***Abstract***— *The increasing demand for automotive parts of lightweight metals is led engineers and researchers to develop new alloys and/or improve existing with attractive properties and thus, higher performance levels. The Al-Si-Cu (Aluminum-Silicon-Copper) cast alloys are among those alloys gaining prominence by automotive industry sectors. The welding quality of Al-Si-Cu alloys can be improved further using Taguchi Design of Experiments (DOE). This research work focuses in optimizing charpy impact of Al-Si-Cu cast alloys weld by TIG welding process. The $L_9$ orthogonal arrays (OA) matrix are chosen with 3-levels and 4-factors (gas flow rate, current, filler rod and gas nozzle cap) are carried out to optimize welding factors for double-V butt joint weld of the aluminum cast alloys. The measured results of charpy impact energies are analyzed by CV* (signal/noise, S/N) and ANOVA (analysis of variance). The higher impact energies are achieved in experiments No.1 and No. 2 with average values of 5.18 and 5.31 Joule respectively, while the lower impact energy is given by experiment No.7 with average value of 4.07Joule. The optimal welding factors of 9L/min gas flow rate, 140A current, ER4043 filler rod and gas nozzle cap number 6 give charpy impact of 5.43 joule and the most affected factors are gas flow rate and filler rod.*

***Keywords***— *Aluminum-Silicon-Copper Cast Alloy, Impact Energy, Microstructures, TIG, Taguchi Method*

## I. Introduction

Welding is permanent joining of two or more metals at their contacting surfaces in which localized coalescence occur by application of heat and/or pressure. TIG welding process uses a non-consumable electrode and an inert gas for arc shielding, and produces high quality welds, no post-weld cleaning, and no weld spatter. Filler metal can be added to facilitate coalescence [1].

There are several studies found in the literatures dealing with the effects of process parameters on weld quality. Kumar et al.[2] studied the influence of welding current on butt joint of 3 mm thick commercial 1050 aluminum plate. They found that the weld joint revealed columnar dendritic structure in fusion zone while mixed columnar and equiaxed dendritic structures in HAZ, and an improvement of strength with increase in welding current. The effect of filler on weld metal structure of AA6061 aluminum alloys by tungsten inert gas (TIG) welding was reported by M. Ishak et al.[3]. They indicated that the filler ER5356 produce a finer grain size and higher strength of 171.53 MPa compared to the weld joints using fillers ER4043 and ER4047 with values of 167.34 MPa and 168.03 MPa, respectively. Milyardi et al.[4] investigated the effect of current and welding speed on porosity in Autogenous Tungsten Inert Gas (TIG) welding of aluminum alloys A1100 butt joint. The welded best results without porosity found by using the welding parameter of welding current of 160 A and the welding speed of 1.1 mm/ s. Lately, Taguchi design of experiments was applied in the field of engineering to optimize properties and to determine the influence of process parameters on performance responses. Welding quality of aluminum alloys can be further improved by applying Taguchi method. Optimization of TIG welding parameters for 6061 aluminum alloy using Taguchi design of experiments was investigated by P.K. Jayashree et al[5]. They reported that the selection of 220A current, 140mm/min welding speed and 16L/min gas flow rate show higher hardness value, and the most affected parameter was welding current, followed by welding speed and gas flow rate for welded 6061 aluminum alloy. Hatab et. al [6-11] applied Taguchi method in several studies namely, optimization and determination parameter design in wind turbine airfoil coefficient, extension and retraction velocities for double acting cylinders, building energy efficiency, tensile properties of 6061 aluminum alloys, RRA properties of 7079 aluminum alloy, and friction welding of aluminum alloy. Rania Ramadan [12] studied the effects of heat input on the microstructure and impact toughness of aluminum cast alloys using TIG welding process. CV* (Signal/noise, S/N) and ANOVA (analysis of variance) are used to evaluate the experimental results. The temperature distribution and the heat input are obtained. The optimal heat input is achieved in experiments obtaining high hardness value with finer microstructure and high impact value with coarser microstructure. This research work is aimed to investigate the influence of individual welding factors; current, gas flow rate, nozzle cap, and welding filler rod on impact energy of Al-Si-Cu cast alloys weld by TIG welding process for specific set of experiments.

## II. Materials and Experimental Procedure

### *A. Materials*

The materials used in this study are cut from ingot of aluminum alloys. The chemical compositions are performed at Higher Vocational Center of Casting, Libya. Table 1 gives the alloy chemical compositions. The analyzed alloy

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

indicates that the alloy is similar to AA384.1 [13] aluminum casting alloy, with excess of copper.

TABLE 1. Chemical composition of Al-Si-Cu cast alloy.

| Al | Si | Cu | Fe | Mn | Mg | Zn | impurities |
|---|---|---|---|---|---|---|---|
| Bal. | 10.8 | 7.83 | 1.06 | 0.28 | 0.28 | 1.8 | 0.5 |

### B. Sample Preparation

In this research work, specimens are prepared by cutting several small pieces of the aluminum alloy from the ingot and then they are put into crucible for melting the alloys using electrical melting furnace. When the temperature reached 800$^{o}$C, the liquid is stirred several times to ensure complete mixing and poured into designed mold. Then, the casting alloys are machined to have final shapes with dimensions of 5cm x 15cm x 1cm as shown in Figure 1. The welding specimens are performed using the Eastwood's TIG 200 AC/DC Welder at private weld workshop. TIG welding operation with sinusoidal AC wave, pure Argon gas (as a gas protection for arc welding and pool from surrounding environment), and pure tungsten electrode 2.4mm in diameter are used for welding application of the specimens. The charpy impact specimens are cut by electric saw with dimensions of 10 mm by 10 mm by 55mm with 2-mm-deep V-notch for the base alloy and un-notch for the welded specimens. The WP 400_Pendulum Impact Tester, scale 15 Nm is connected to PC Data Acquisition impact energy. The average value of the charpy impact energy for base alloy is 4.9 Joule.

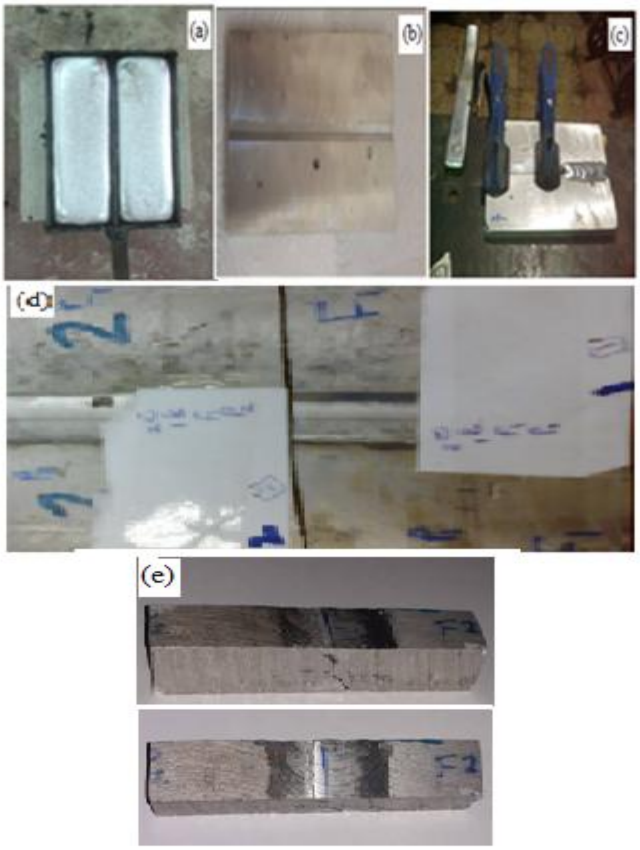


Fig.1. (a) cast alloys, (b) specimens with double V groove, (c) welded specimen, (d) machined welded specimen, (e) impact specimen cut from welded specimen.

### C. Design of Experiments

The complicated welding process with several variables can be optimized by Taguchi method [14]. Gas flow rate, current, filler rods and gas nozzle cap are considered welding factors that can influence the microstructure of fusion and heat affected zones and thus impact energy. A standard Taguchi design of experiment of the $L_9$ ($3^4$) orthogonal arrays matrix is selected and the interactions between the factors are neglected. Experimental layout of $L_9$ ($3^4$) orthogonal arrays for welding Al-Si-Cu cast alloys is given in Table 2. Conducting the experiments is the next step in Taguchi DOE. CV* (S/N) and ANOVA are used to evaluate the experimental results to determine which factor is affected the impact energy and to optimize factors for optimal impact energy. The calculations of CV* (signal/noise, S/N) and ANOVA (analysis of variance) are calculated using excel software.

TABLE 2. Experimental layout of the $L_9$ ($3^4$) orthogonal arrays for welding Al-Si-Cu cast alloys.

| Experiment Number | Gas Flow Rate, L/min. A | Current Ampere B | Filler Rods C | Gas Nozzle Cap Number D |
|---|---|---|---|---|
| 1 | 9 | 110 | ER4043 | No.6 |
| 2 | 9 | 140 | ER5356 | No.7 |
| 3 | 9 | 170 | ER4043& ER5356 | No.8 |
| 4 | 12 | 110 | ER5356 | No.8 |
| 5 | 12 | 140 | ER4043& ER5356 | No.6 |
| 6 | 12 | 170 | ER4043 | No.7 |
| 7 | 15 | 110 | ER4043& ER5356 | No.7 |
| 8 | 15 | 140 | ER4043 | No.8 |
| 9 | 15 | 170 | ER5356 | No.6 |

## III. RESULTS AND DISCUSSION

### A. Analysis of Signal/Noise Ratio for Impact Energy

The impact energy (CV) is treated as quality response using the large is the best and can be calculated according to equation 1:

$$\boldsymbol{CV^{*} = -10log\left(\frac{1}{r}\sum_{i=1}^{r}\frac{1}{CV_i^2}\right)} \qquad (1)$$

where CV* is the calculated signal-to-noise (S/N) ratios for charpy impact energy and $(CV)_i$ is the experimental values of the i$^{th}$ in the row. Table 3 and Figure 2 are indicated that the higher obtained result for impact energy is given by running experiments No.1 and No.2 among all other experiments with average value of 5.18 and 5.31 Joule respectively. This may attribute to higher heat input and slower cooling rate that coarsen the precipitating phases of the fusion zone.

The main effects CV* and average CV for welded Al-Si-Cu cast alloys are given in Table 4 and Figure 3. The optimal welding factors are 9L/min for gas flow rate, 140A for current, ER4043 for filler rod, and No.6 for gas nozzle cap or A1B2C1D1. The gas flow rate and filler rod are the most affected factors; followed by gas nozzle cap and current.

TABLE 3. Impact energy and calculated CV* ratio of welded Al-Si-Cu cast alloys

| Experiment number | CV, Impact Energy (J) | | | | $CV^*$ Ratios |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | Average | |
| 1 | 5.10 | 5.10 | 5.34 | 5.18 | 14.28 |
| 2 | 5.46 | 4.98 | 5.50 | 5.31 | 14.48 |
| 3 | 4.42 | 3.90 | 4.52 | 4.28 | 12.58 |
| 4 | 3.58 | 4.62 | 5.50 | 4.57 | 12.79 |
| 5 | 4.38 | 4.14 | 5.18 | 4.57 | 13.08 |
| 6 | 4.42 | 5.14 | 4.42 | 4.66 | 13.31 |
| 7 | 4.10 | 4.10 | 4.02 | 4.07 | 12.20 |
| 8 | 4.83 | 4.06 | 4.57 | 4.49 | 12.97. |
| 9 | 5.01 | 4.18 | 4.62 | 4.60 | 13.19 |

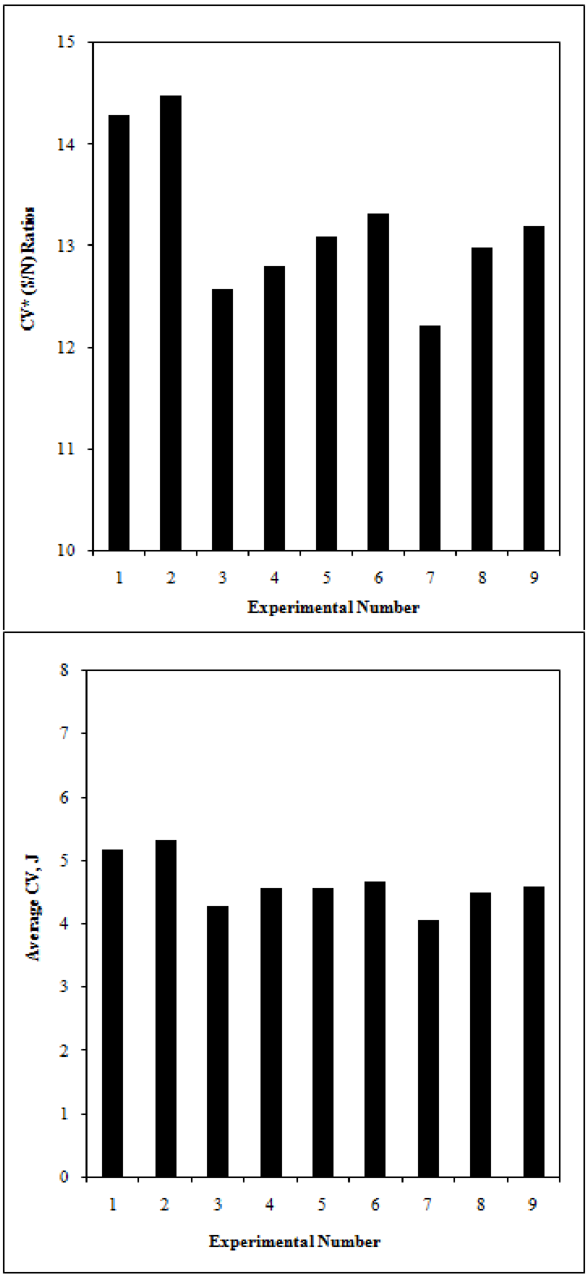


Fig.2. CV*(S/N) ratios and Average impact energy (CV) of welded Al-Si-Cu cast alloys.

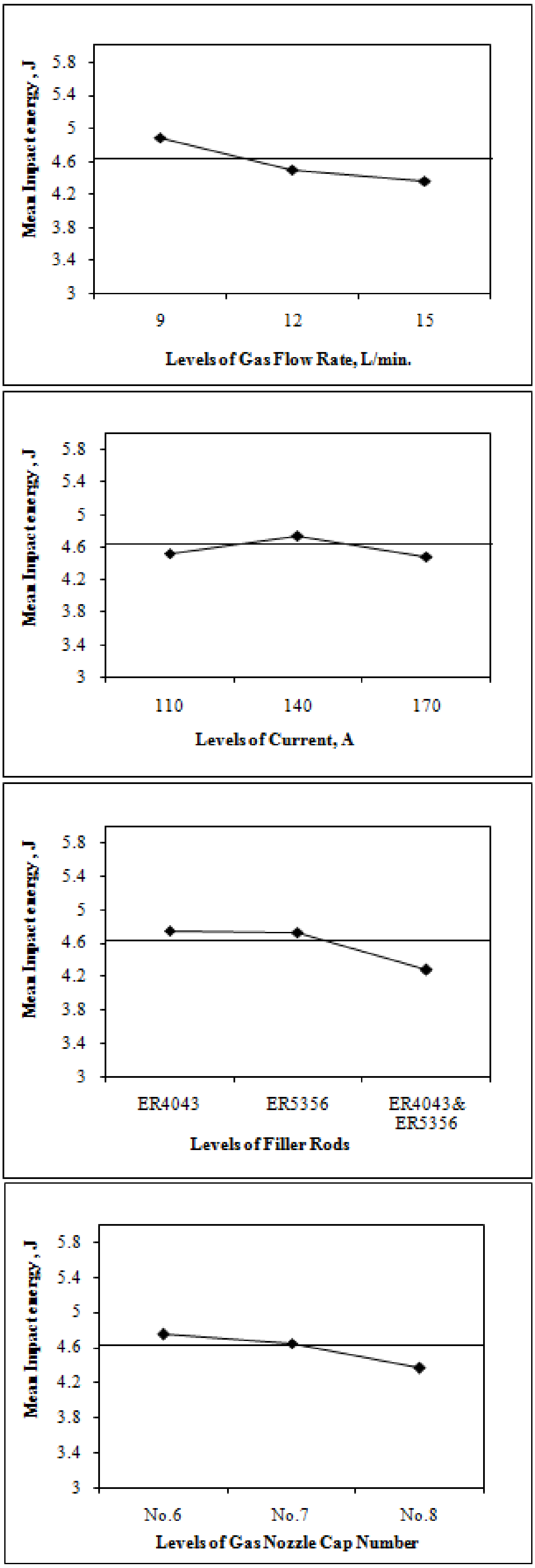


Fig.3. Main effects of impact energy of welded Al-Si-Cu cast alloys.

TABLE 4. Main effects CV* (S/N) for impact energy of welded Al-Si-Cu cast alloys

| Factors | Level 1 | Level 2 | Level 3 | Max. - Min. | Rank |
|---|---|---|---|---|---|
| A-Gas flow rate | 13.785 | 13.066 | 12.795 | 0.990 | 1 |
| B- Current | 13.098 | 13.518 | 13.031 | 0.487 | 4 |
| C- Filler rods | 13.526 | 13.495 | 12.626 | 0.900 | 2 |
| D- Gas nozzle cap | 13.524 | 13.336 | 12.787 | 0.737 | 3 |

*B. Analysis of the Variance for Impact Energy*

The obtained ANOVA results are given in Table 5 for the impact energy, indicating that the contribution factors to impact energy are gas flow rate with 35.45%, followed by filler rods with 35.28%, gas nozzle cap number with 19.86%, and the current with 9.41%. This is consistent with the analysis of the CV* ratios.

*C. Experiment Confirmation for Impact Energy*

The final step in Taguchi method is running confirmation test, which is conducted to verify the improvement of the quality characteristic using the optimal levels of factors. If the confirmation test equation does not predict results of various combinations of control factors, then a new Taguchi DOE is required. The predicted CV* ratio using the optimal levels of the welding factors can be given by equation (2):

$$(\boldsymbol{CV}^{*})_{\boldsymbol{predict}} = (\boldsymbol{CV}^{*})_{\boldsymbol{mean}} + \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} [((\boldsymbol{CV}^{*})_{\boldsymbol{opt}})_{\boldsymbol{i}} - (\boldsymbol{CV}^{*})_{\boldsymbol{mean}}] \quad (\mathbf{2})$$

The mathematical model for the specific set of experiments is given by equation (3):

$$\mathbf{CV^* = 13.216 + (\bar{A}_i - 13.216) + (\bar{B}_i - 13.216) + (\bar{C}_i - 13.216) + (\bar{D}_i - 13.216)} \quad \mathbf{(3)}$$

Where $A_i$, $B_i$, $C_i$, and $D_i$ are average levels of signal/noise and are given Table 4.

TABLE 5. Results of ANOVA for impact energy of welded Al-Si-Cu cast alloys

| Factors | DF | SS | V | P (%) |
|---|---|---|---|---|
| A- Gas Flow rate | 2 | 1.5735 | 0.78675 | 35.45 |
| B- Current | 2 | 0.4179 | 0.20895 | 9.41 |
| C- Filler rods | 2 | 1.5661 | 0.78305 | 35.28 |
| D- Gas Nozzle Cap | 2 | 0.8814 | 0.44070 | 19.86 |
| Total | 8 | 4.4391 | | 100 |

DF: degrees of freedom; SS: sum of squares; V: variance; P: percent contribution

The impact energy values of running confirmation of experiments No. 1 & 2 are in good agreement with the predicted equation as shown in Table 6. The optimal welding factors are 9L/min for gas flow rate, 140A for current, ER4043 for filler rod, and No.6 for gas nozzle cap or A1B2C1D1gives 5.43 Joule as calculate by equation 2. The higher impacts values can be related to slow cooling rate (high heat input) produces coarsen microstructure.

TABLE 6. Confirmation test of impact energy of welded Al-Si-Cu cast alloys

| Welding Factors | Prediction Experiment A1B2C1D1 | Experiment No.1 A1B1C1D1 | Experiment No.2 A1B2C2D2 |
|---|---|---|---|
| Flow rate<br>Current<br>Filler rod<br>Gas Nozzle Cap | 9 L/min<br>140 A<br>ER4043<br>No.6 | 9 L/min<br>110 A<br>ER4043<br>No.6 | 9 L/min<br>140 A<br>ER5356<br>No.7 |
| Impact Energy(CV) | 5.43 Joule | 5.18 Joule | 5.31 Joule |
| Reference<br>Improvement | Experiment No.8 (A3B2C1D3)<br>1.2 higher (optimal/Reference) | | |

*D. Microstructures*

Figure 4 shows the coarse silicon particles and round irregular particles assumed to be $Al_2Cu$ (gray) in an aluminum matrix (light) of Al-Si-Cu cast alloy. The dark feature may be assumed to be shrinkage or porosities, a casting defect. The microstructure of experiment No.1 at fusion boundary of welded Al-Si-Cu cast alloy is given in Figure 5. It is clearly that the microstructure is tend to be coarsen in fusion boundary (equiaxed grains) which is attributed to the slower cooling rate (high heat input). The coarsen microstructure can be related to higher charpy impact of experiment number 1.

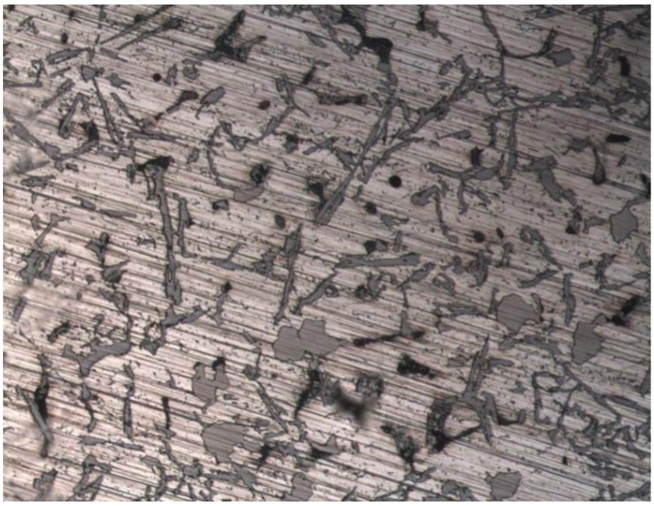

Fig. 4. The microstructure of the Al-Si-Cu cast alloy, etchant 5%HF, 100x.

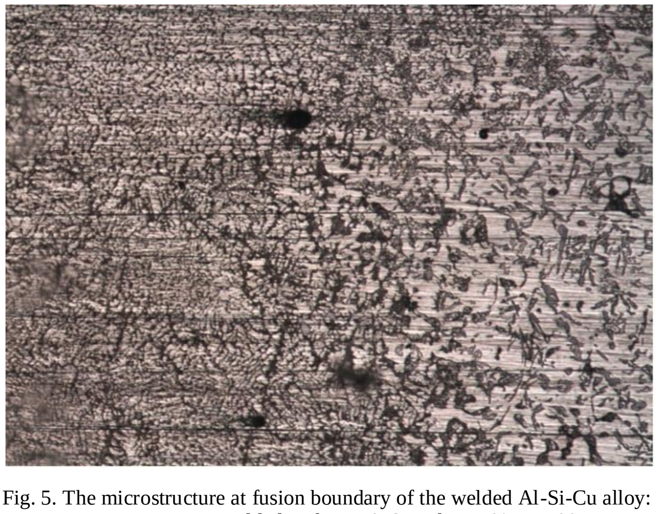

Fig. 5. The microstructure at fusion boundary of the welded Al-Si-Cu alloy: experiment No. 1, welded with ER4043, etchant 5%HF, 100x.

## IV. CONCLUSION

The research work is demonstrated the application of Taguchi method employing charpy impact as quality response to efficiently establishing optimal welding factors of welded Al-Si-Cu cast alloys by TIG. The obtained results of experiment No.1 (A1B1C1D1) and experiment No.2 (A1B2C2D2) give the higher impact energy (5.18 and 5.31 Joule). The optimal welding factors (A1B2C1D1) are 9L/min for gas flow rate, 140A current, ER4043 for filler rod, and No. 6 for gas nozzle cap, give 5.43 Joule. The most influence factors are gas flow rate with contribution of 35.45%, 35.28 for filler rod, 19.86% for gas nozzle cap and 9.41% for current. The microstructure of welded alloy shows coarse grains at fusion boundary.

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