Horia Dascau[1], Snežana Kirin[2], Aleksandar Sedmak[3], Abdsalam Eramah[4], Srđan Tadić[2]

CRACK RESISTANCE OF ALUMINIUM ALLOY FRICTION STIR WELDED JOINT

OTPORNOST PREMA PRSLINAMA SPOJEVA LEGURA ALUMINIJUMA ZAVARENIH TRENJEM SA MEŠANJEM

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Adresa autora / Author's address:
1) ISIM, Timisoara, Romania, email: dascau@isim.ro
2) University of Belgrade, Innovation centre of the Faculty of Mechanical Engineering, Belgrade, Serbia
3) University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia
4) University of Tripoli, Libya

Keywords

- friction stir welding
- Taguchi method
- Charpy instrumented testing
- fracture toughness

Ključne reči

- zavarivanje trenjem sa mešanjem
- Taguči metoda
- Šarpi instrumentirano ispitivanje
- žilavost loma

Abstract

Charpy testing is conducted on a high-speed data acquisition instrument, using instrumented pendulum to separate energies for crack initiation and propagation. The J-R curves are used to determine J_{Ic}, as the measure of fracture toughness. The Taguchi method with a special design of orthogonal matrices to reduce the number of experiments to a reasonable level has been applied.

Izvod

Šarpi ispitivanje instrumentiranim klatnom je sprovedeno sa opremom za brzu akviziciju podataka, sa mogućnošću razdvajanja energija za inicijaciju i rast prsline. J-R krive su korišćene za određivanje J_{Ic}, kao mere žilavosti loma. Taguči metoda sa posebnim oblikom ortogonalnih matrica je korišćena u ovom istraživanju da bi se broj eksperimenata sveo na razumnu meru.

INTRODUCTION

The process of friction stir welding (FSW), as a very efficient way of welding both homogeneous and heterogeneous metals, has found application in many branches of industry. This process is especially important for welding of some aluminium alloys, since it takes place in a solid state, causing no significant changes in the welded material. Anyhow, problems related to crack initiation and propagation still remain to be considered. Therefore, the instrumented Charpy testing is conducted on a high-speed data acquisition instrument to separate energies for crack initiation and propagation, as well as the standard testing of J-R curves to determine J_{Ic}, as a measure of fracture toughness. The Taguchi method with a special design of orthogonal matrices to reduce the number of experiments to a reasonable level has been applied for all experiments.

TAGUCHI METHOD

A large number of experiments have to be carried out when the number of input and output parameters increases. To solve this task, the Taguchi method uses a special design of orthogonal matrices to reduce the number of experiments to a reasonable level.

Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio, i.e. lower-the-better, higher-the-better and nominal-the-better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a larger S/N ratio corresponds to a better quality characteristic. Therefore, the optimal level of the process parameters is the level with a higher S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which parameters are statistically significant.

There are three forms of signal to noise (S/N) ratio that are of common interest for optimization of statistical problems. Here we consider 'Larger-the-better', when the loss function of the higher-the-better quality characteristic can be expressed as:

$$L_{ij} = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{1}{y_{ijk}^2}$$

where L_{ij} is the loss function of the i-th quality characteristic in the j-th experiment; n is the number of tests; and y_{ijk} is the experimental value of the ij-th quality characteristic in the j-th experiment at k-th test, being equal to:

$-10\log_{10}$[mean sum of squares of reciprocal of measured data]

The purpose of ANOVA is to investigate which process parameters significantly affect the quality characteristics. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of squared deviations from the total mean of the S/N ratio, into contribution by each of the welding process parameters and the error. The percentage contribution by each of the welding process parameters in the total sum of squared deviations can be used to evaluate the importance of the process parameter change on the quality characteristic.

The mean sum of main characteristic (y_{ijk}) is given by the following formula:

$$m = \sum(y_{ijk1} + y_{ijk2} + \ldots + y_{ijkn})$$

Average values of the mean sum are given as follows, for a 3×3 scheme:

$$m_{A1} = (y_{ijk1} + y_{ijk2} + y_{ijk3})/3 ,$$
$$m_{A2} = (y_{ijk4} + y_{ijk5} + y_{ijk6})/3 ,$$
$$m_{A3} = (y_{ijk7} + y_{ijk8} + y_{ijk9})/3 ,$$
$$m_{B1} = (y_{ijk1} + y_{ijk4} + y_{ijk7})/3 ,$$
$$m_{B2} = (y_{ijk2} + y_{ijk5} + y_{ijk8})/3 ,$$
$$m_{B3} = (y_{ijk3} + y_{ijk6} + y_{ijk9})/3 ,$$
$$m_{C1} = (y_{ijk1} + y_{ijk6} + y_{ijk8})/3 ,$$
$$m_{C2} = (y_{ijk2} + y_{ijk4} + y_{ijk9})/3 ,$$
$$m_{C3} = (y_{ijk3} + y_{ijk5} + y_{ijk7})/3 .$$

Other formulas used for Taguchi method are as follows: Grand total sum of squares:

$$\sum_{i=1}^{4} n_j^2$$

Sum of squares due to mean:

$$\sum_{i=1}^{4} m^2$$

Total sum of squares:

$$\sum_{i=1}^{4} (n_j - m)^2$$

Sum of squares due to A:

$$\sum_{i=1}^{4} (m_{Ai} - m)^2$$

Sum of squares due to error:

$$\sum_{i=1}^{4} e_i^2$$

The optimization of process parameters is the key step in Taguchi's method to achieve high quality without increasing cost. This is because the optimization of process parameters can improve quality characteristic and optimal process parameters obtained from Taguchi method are insensitive to the variation of environment conditions and other noise factors. In the problem analysed here, 9 trials are used, as defined in Table 1, to replace 27 experiments (3 parameters, 3 values, $27 = 3^3$).

Table 1. The experiment scheme.

trial	1	2	3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

EXPERIMENT

In the scope of experimental investigation, hot rolled AA5083 plates, 6 mm thick, cut into a 500 × 100 mm sections have been welded. The experimental plan was as follows: rotational speed (ω) was in the range 500–700 rpm, welding speed 75–125 mm/sec, and advancing tilt angle of the tool 1–3 deg.

Charpy testing is conducted with a high-speed data acquisition instrument, using instrumented pendulum to separate energies for crack initiation and propagation. The standard testing of J-R curves is applied to determine J_{Ic}, as the measure of fracture toughness.

Figure 1, as an example, shows the relationship between load and displacement for one pair of specimens. The load rises rapidly to maximal value and drops suddenly. This drop in load marks the boundary line of two distinct phases, i.e. fracture initiation and fracture propagation phase of the total fracture event. In fact, the specimen having the largest area under the curve has also the highest toughness. Other diagrams are given in /1/.

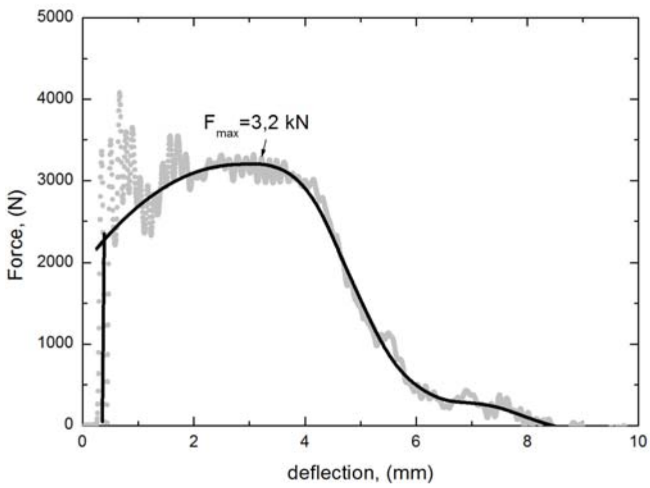

Figure 1a. Force vs. deflection for sample 1a (1 1 1)

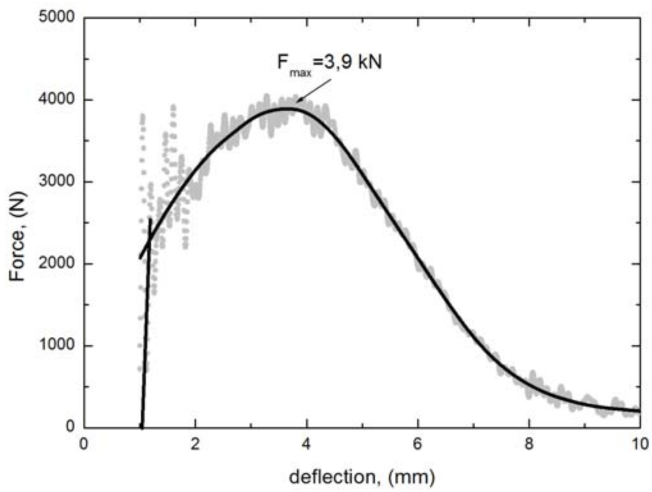

Figure 1b. Force vs. deflection for sample 2a (1 2 2)

The J–Δa diagram for specimen with a crack in the weld metal (WM-NZ) is shown in Fig. 2, as an example of fracture toughness testing performed in the scope of this investigation (trial 1). Other diagrams are given in /1/.

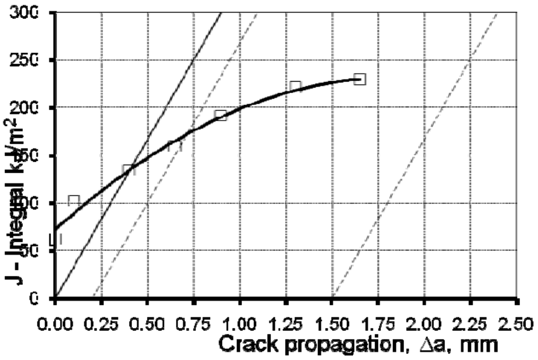

Figure 2. The J-Δa curve for sample 1a (1 1 1).

Results for the impact energy and fracture toughness are given (two specimens and their average value) in Tables 2 and 3, respectively. Some of the results for impact toughness (first three rows) are presented also in /2/. Statistical analysis of results for the impact energy, including separated values for initiation and propagation, are given in Tables 4-6, in respect. Only average values are given, since the difference between individual values is small.

Results for the fracture mechanics testing are given in Table 7. The same procedure for statistical analysis is applied in the case of fracture toughness, as shown in Table 8, also using only average values, for the same reason.

Table 2. Total Charpy energy.

No. of sample	Rotat. speed (rpm)	Welding speed (mm/min)	Tilted angle (deg.)	Average energy (J)	1st measur. (J)	2nd measur. (J)
1 1 1	500	75	1	15.05	14.9	15.2
1 2 2	500	100	2	19.25	19.0	19.5
1 3 3	500	125	3	22.9	22.7	23.1
2 3 2	600	125	2	21.5	21.5	21.5
2 2 1	600	100	1	16.4	16.1	16.7
2 1 3	600	75	3	17.3	17.0	17.6
3 2 3	700	100	3	21.9	21.4	22.4
3 1 2	700	75	2	21.65	21.5	21.8
3 3 1	700	125	1	23.75	23.6	23.9

Table 3. Average separated Charpy energy.

No. of sample	Rotat. speed (rpm)	Welding speed (mm/min)	Tilted angle (deg.)	Average energy (J)	Initiat. energy (J)	Propag. energy (J)
1 1 1	500	75	1	15.05	7.05	8.0
1 2 2	500	100	2	19.25	8.8	9.45
1 3 3	500	125	3	22.9	10.8	12.1
2 3 2	600	125	2	21.5	9.5	12.0
2 2 1	600	100	1	16.4	5.8	10.6
2 1 3	600	75	3	17.3	6.5	10.8
3 2 3	700	100	3	21.9	9.7	12.2
3 1 2	700	75	2	21.65	9.25	12.4
3 3 1	700	125	1	23.75	10.15	13.6

Table 4. Statistical analysis of the impact energy.

m	1	2	3	Σdiff^2	%
m_A	19.1	18.4	22.4	27.4	27.4/63.7 = 43
m_B	18.0	19.2	22.7	35.7	35.7/63.7 = 56
m_C	19.5	20.1	20.0	0.6	0.6/63.7 = 1

Table 5. Statistical analysis of the initiation energy.

m	1	2	3	Σdiff^2	%
m_A	8.9	7.3	9.7	8.96	8.96/21.14 = 42
m_B	8.7	7.9	9.1	4.04	35.7/63.7 = 19
m_C	7.6	9.5	8.8	8.14	0.6/63.7 = 39

Table 6. Statistical analysis of the propagation energy.

m	1	2	3	Σdiff^2	%
m_A	9.8	11.1	12.7	12.66	12.66/20 = 63
m_B	10.7	10.8	12.2	4.23	4.23/20 = 21
m_C	10.4	11.7	11.6	3.14	3.14/20 = 16

Table 7. Average values for fracture toughness.

No. of sample	Rotat. speed (rpm)	Welding speed (mm/min)	Tilted angle (deg.)	Average K_{Ic} (MPa·m$^{1/2}$)	1st measur. (MPa·m$^{1/2}$)	2nd measur. (MPa·m$^{1/2}$)
1 1 1	500	75	1	55	53	57
1 2 2	500	100	2	60	58	62
1 3 3	500	125	3	70	69	71
2 3 2	600	125	2	72	71	72
2 2 1	600	100	1	66	64	67
2 1 3	600	75	3	72	70	73
3 2 3	700	100	3	75	74	77
3 1 2	700	75	2	76	75	77
3 3 1	700	125	1	67	66	69

Table 8. Statistical analysis of the fracture toughness.

m	1	2	3	Σdiff^2	%
m_A	60.2	70.0	72.7	259.58	259.58/295.82=88
m_B	67.3	67.3	69.7	11.52	11.52/295.82=4
m_C	67.7	66.3	69.7	24.72	24.72/295.82=8

DISCUSSION

Average values of the total impact energy, as obtained for the 9 experiments, chosen according to the orthogonal matrix, indicate that the travel (welding) speed has the largest effect (56%), followed by significant effect of the rotational speed (43%), whereas the tool angle has a very small effect (1%).

Different effects are obtained when separated energies are considered. In the case of initiation energy, the rotation speed is the most influential (42%), closely followed by the tool angle (39%), whereas the effect of the welding speed if smaller (19%), but not negligible. In the case of the propagation energy, the rotation speed is still the most influential, even more pronounced (63%), whereas both the tool angle and welding speed effects are significantly lower (21% and 16%, respectively).

The effects of tool angle on individual energies cancel each other, so the effect on the total energy is negligible.

Another crack resistant property, fracture toughness, has shown similar behaviour, as in the case of the propagation energy, which is reasonable to expect, since in both cases it is the crack dominated behaviour, whereas the influence of loading type is obviously small (also reasonable for material which is not exactly brittle). Anyhow, one should notice more pronounced effects, since the rotation speed is rated at 88%, whereas the welding speed and tool angle are rated only at 4% and 8%, respectively. One can conclude that the rotation speed has almost an exclusive effect for the crack resistance under static loading, keeping its dominance in the case of crack resistance under impact loading, but at a smaller scale.

CONCLUSION

Based on experimental results presented here, one can conclude the following:

- Welding and rotational speed are two dominant effects on the total Charpy impact energy, whereas the tilt angle has negligible effect.
- Similar effects are noticeable for separated impact energies, except that the tilt angle effect is not negligible any more, but it seems that even this small effect is cancelled out when energies are combined.
- In the case of fracture toughness, rotational speed has a dominant effect, whereas both the welding speed and the tool angle have negligible effects.

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