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Investigation of machining parameters on corner accuracies for slant type taper triangle shaped profiles using WEDM on Hastelloy X

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Abstract: Wire electro-discharge machining (WEDM) is a widely used machining process for machining of difficult to cut materials, which are used in precision profile applications like dies, metal stampings, and gas turbine parts. In the present research work, a new slant type taper fixture was used to obtain angular machining of triangular shape slots of sides 1mm, 3mm and 5mm machined both in 0° and 30° as slant angles on Hastelloy X. The corner radius and corner errors were investigated for different machining parameters like corner dwell time (CDT), offset distance (WO), wire guide distance (WGD) and cutting speed override (CSO) using L_{16} orthogonal array for both the slant angles. SEM micrographs indicated that corners were with lower radii at 30° than in 0° slant profiles, at lowest and highest cutting speeds. The main effects plot showed that the corner radius increases with the increase in wire offset and wire guide distance parameters. The increase in corner dwell time has an adverse effect on the corner radius. The triangles were machined at different cutting speeds from 0.47 to 1.51 mm/min with various parameters; it was observed that as the corner radius decreases the corner error also reduces. However, the corner radius and corner error can be minimized by selecting an optimized cutting parameter.

1. Introduction

The superalloys are heat resistant alloys, which are used in operating temperatures of 1050°C. However, occasionally the temperatures reach up to 1200°C [1, 2]. These alloys have superior and exceptional properties like high fatigue strength, corrosion and oxidation resistance even at elevated temperatures. Hastelloy X is nickel-based superalloys used in jet engines, tailpipes, afterburner components, cabin heaters to dies, stamping and tooling. The presence of nickel makes the superalloy to have high toughness, reactive to tool materials and low thermal diffusivity that makes the machining operation more difficult and challenging [3]. WEDM is a non-conventional machining technique, which is the most preferred for machining of such conductive, difficult to cut superalloys for required geometrical shape. It is also used in precision machining of complicated and tapered profiles especially in die, stamping, aerospace and defence industries [4]. In profiling complex shapes, the sharp or curved shapes lead to corner inaccuracies due to lag in wire and guide position. Sarkar et al. [5] have investigated the gap force and wire lag that controlled the corner accuracies and proposed an analytical model to measure these characteristics. Based on the analytical model wire compensation

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was calculated and then machined to improve corner accuracies. Firouzabadi et al. [6] have reported that processing forces on the wire and low rigidity of the wire are the main reasons for wire deflection causing corner inaccuracies during machining. Successive cuts were adopted in order to improve the accuracy of small-radius concave corners. Selvakumar et al. [7] concluded that multi-pass cutting or wire path modification was essential to be adopted to improve corner accuracies in their study on the influence of process parameters on corner error.

Taper machining has many applications, such as forming cutters, plastic and rubber extrusion die, wortle, splicing mould, spray bars, flame holders and rocket skirts etc. In WEDM, the taper is attained moving the guide and tilting the wire in the angular manner to machine the workpiece. The main disadvantages of taper machining in WEDM are; insufficient flushing leading to surface flaws, wire breakage, angular inaccuracies, and wire guide wear [8, 9]. Sanchez et al. [10] have reported on angular inaccuracies considering the mechanical behaviour of soft wires during tapering in WEDM using FEM model. A quadratic equation considering the electrical parameters and part geometry was formulated to improve taper accuracy [10]. Selvakumar et al. [11] have reported that the cutting speed was independent of the taper angle and wire tension was a major factor that influenced taper accuracy during the investigation of machining parameters on cutting speed, surface roughness and taper error in taper machining. Martowibowo et al. [12] have performed taper motion in WEDM using Taguchi method for achieving taper surface and observed that the taper angle also influences the surface roughness in the machining process.

In the present research work, a unique tapering machining method was designed with the aid of slant fixture in order to eliminate the disadvantages of the tapering process. The slant type fixture of aluminium H9 series was fabricated and used as a tilting mechanism during machining to achieve the required tapered surface. In this paper, an attempt was made to study the corner inaccuracies like corner error and corner radius during profiling of triangular shaped geometry on the workpiece at 0° and 30° slant angles.

2. Experimental details

The experiments were performed in Electronica ecocut of model ‘ELPLUS 15’ WEDM. The machine uses deionized water as a dielectric medium. The as-received alloy was heat treated at 1175°C for 1h to ensure minimal residual stress. The workpiece was Hastelloy X machined by zinc coated brass wire of diameter 250 µm. The workpiece was fixed on the slant type fixture having tilting mechanism as shown in figure 1. The Taguchi’s L16 orthogonal array design was used in machining of triangle shaped profiles. The figure 2 indicates the programed profile of sides 1mm, 3mm and 5mm. The figure 3 indicates different profiles machined on the workpiece with the aid of slant type fixture. Based on the initial experiments a favourable cutting parameter was selected and retained constant throughout the experiment as shown in table 1. Table 2 indicates the different machining parameter range considered for the investigation of corner inaccuracies.

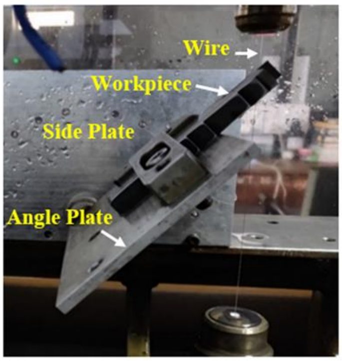

Figure 1. Slant type fixture in WEDM.

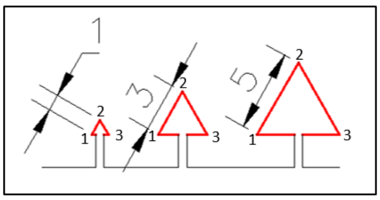

Figure 2. Programmed Profile.

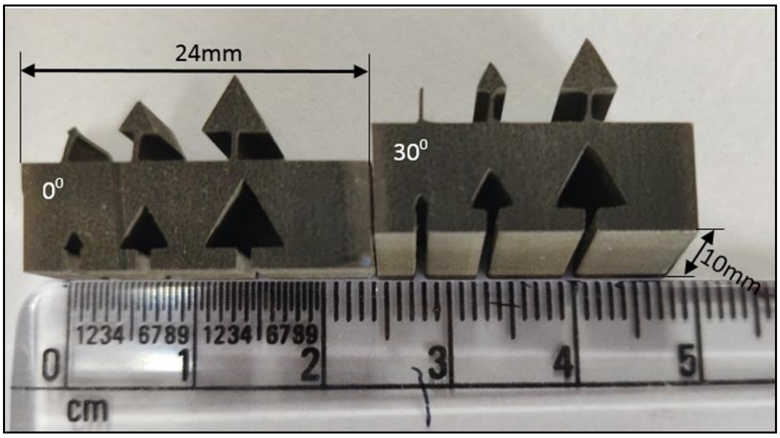

Figure 3. Workpiece machined at 0° and 30° slant angles.

Table 1. Constant Cutting Parameters.

Sl. No.	WEDM Parameters	Settings
1	Pulse off time (T_{off}) (µs)	44
2	Servo Feed (SF) (mm/min)	20
3	Wire Feed (WF) (m/min)	6
4	Pulse on time (T_{on}) (µs)	115
5	Servo voltage (SV) (V)	40

Table 2. Machining Parameters and levels.

Sl. No.	EDM Parameters		Settings (Levels)			
1	Wire Guide Distance (mm)	0°	40	50	60	70
2	Wire Guide Distance (mm)	30°	100	110	120	130
3	Cutting Speed Override (%)		31	54	77	100
4	Wire Offset (µm)		0	40	80	120
5	Corner Dwell Time (s)		0	33	66	99

3. Results and discussion

3.1. Cutting speed variation for different angles

The profile was machined on the workpiece and the cutting speeds were observed and recorded at both the slant angles as shown in table 3 and 4. It can be observed that in both the slant angles the cutting speed was highest at 100% and least at 31% of cutting speed override parameter. The highest cutting speed was 1.51 mm/min at 0° and 1.45mm/min at 30°. The lowest cutting speed was 0.62mm/min at 0° and 0.47mm/min for 30°. Figure 4 shows the variation of cutting speed at each trial of the experiment for both 0° and 30° slant angles. For the constant cutting parameters, it can be inferred that the cutting speeds at 0° are greater than the cutting speeds at 30°. This increase was observed due to

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increase in the slant angle during profiling. As the angle of cut increases the cutting thickness also increases, this increases the amount of material near the wire. Since the discharge for a cutting parameter is constant, it takes more time to melt due to the increase in surface area of cut thus decreasing the cutting speed [13]. Figure 5(a) and (b) shows the main effect plots of cutting speed at 0° and 30° slant angles during profiling for the input parameters. It can be concluded from main effects plot that only the cutting speed override parameter mainly influenced the cutting speed and other parameters can be considered insignificant on cutting speed at both the slant angles, similar conclusions were reported by Roy et al. [14]. Although the machining was carried out in constant cutting parameters, the cutting speeds were observed to vary at both 0° and 30° slant angle. The cutting speed override parameter controls the discharge energy that melts the workpiece during machining. This leads to variation in the cutting speed based on the different levels of cutting speed override parameter.

Table 3. Cutting speed for different parameters at 0° slant angle.

Trial No.	**WDG (mm)**	**CDT (s)**	**WO (μm)**	**CSO (%)**	**CS (mm/min)**
1	100	0	0	31	0.48
2	100	33	40	54	0.57
3	100	66	80	77	1.00
4	100	99	120	100	1.38
5	110	0	40	77	0.98
6	110	33	0	100	1.36
7	110	66	120	31	0.49
8	110	99	80	54	0.57
9	120	0	80	100	1.38
10	120	33	120	77	1.05
11	120	66	0	54	0.59
12	**120**	**99**	**40**	**31**	**0.47**
13	130	0	120	54	0.59
14	130	33	80	31	0.50
15	**130**	**66**	**40**	**100**	**1.45**
16	130	99	0	77	1.01

Table 4. Cutting speed for different parameters at 30° slant angle.

Trial No.	**WDG (mm)**	**CDT (s)**	**WO (μm)**	**CSO (%)**	**CS (mm/min)**
1	40	0	0	31	0.74
2	40	33	40	54	0.95
3	40	66	80	77	1.26
4	40	99	120	100	1.43
5	50	0	40	77	1.27
6	50	33	0	100	1.41
7	50	66	120	31	0.66
8	50	99	80	54	0.80
9	60	0	80	100	1.40
10	60	33	120	77	1.37
11	60	66	0	54	0.81
12	**60**	**99**	**40**	**31**	**0.62**
13	70	0	120	54	0.75
14	70	33	80	31	0.68
15	**70**	**66**	**40**	**100**	**1.51**
16	70	99	0	77	1.33

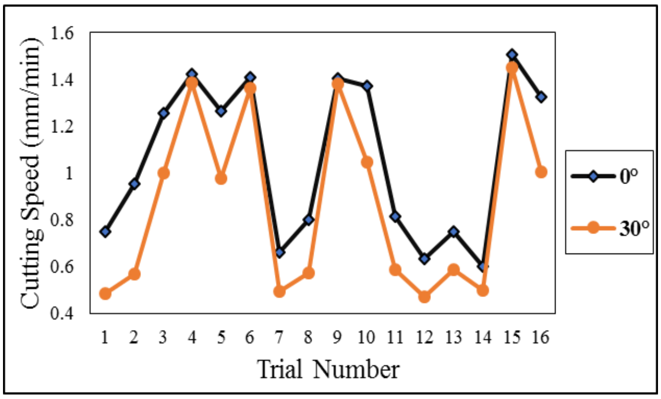
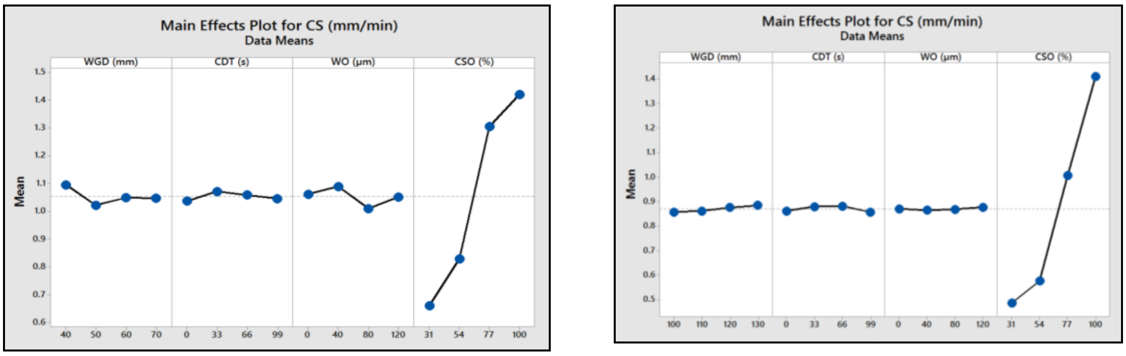


Figure 4. Cutting speed variation at different slant angles 0° and 30°.



(a) (b)

Figure 5. Main effect plots for cutting speeds at (a) 0° (b) 30° angles.

3.2. Variation of corner radius for different angles

3.2.1. Effect of wire guide distance (WGD) on corner radius. The SEM 'JEOLJSM 6380LA' micrographs of the 2nd corners of side 1mm, 3mm and 5mm were used to measure the corner radius using image J software. Table 5 and 6 show the different corner radii that were measured at slant angles 0° and 30°. Figure 6 and 7 indicate the different main effects plots for corner radius at both 0° and 30° slant angles. From the main effects plots, it can be observed that as the WGD and WO increases, the corner radius also increases. As WGD increases the length of the wire also increases which increases the wire deflection. Due to increase in wire deflection, there is a greater lag in the wire position and CNC position. This leads to an increase in the corner radius at both the slant angles [15]. It can be noticed from the table 4 and 5 that the higher WGD parameter yielded the highest corner radii. It can be observed that there was a sharp increase in the corner radii at 50mm and 60mm of WDG at figure 6(a) and 40mm, 50mm of WDG at figure 7(c). Figure 7(a) there is a slight increase of corner radius from 40mm to 50mm of WGD. This phenomenon is due to the chaotic wire vibration caused by uneven forces, flushing, sparking and discharging [16]. The range of corner radius was higher at 30° slant angles due to the increase in cutting thickness. As the cutting thickness increases the wire, deflection also increases. This increase in wire deflection leads to higher wire lag causing a larger range of corner radius.

3.2.2. Effect of wire offset (WO) on corner radius. In the case of the WO parameter, as the offset distance increases corner radius also increases because of the increase in the dimensional shift of the profile [17]. The lowest corner radii were observed at 0mm of WO parameter in trial 1 as measured in table 5 and 6 for both the slant angles as it has a minimal dimensional shift. From the figure 6 (b) and (c) it was witnessed that as WO decreases the corner radius also decreases at 0µm to 40µm. A similar decreasing trend was noticed at 0µm to 40µm and 80µm to 120µm from figure 6(b) and (c) respectively. This decrease in corner radius was due to a slight decrease in cutting speed due to profile geometry [18]. There was a sharp increase in 80µm to 120µm in figure 6(a) and 0µm to 40µm in figure 7(c) due to the vibration of the wire and this is due to uneven forces created during sparking and discharging, flushing etc. [16].

Table 5. Corner radius for different parameters at 0° slant angle.

Trial No.	WDG (mm)	CDT (s)	WO (µm)	CSO (%)	Corner Radius		
					∆ 1mm 2nd (µm)	∆ 3mm 2nd (µm)	∆ 5mm 2nd(µm)
1	40	0	0	31	**153.51**	**157.56**	**162.54**
2	40	33	40	54	161.66	169.50	164.50
3	40	66	80	77	172.89	175.20	159.43
4	40	99	120	100	**205.00**	189.00	173.08
5	50	0	40	77	180.83	187.16	169.83
6	50	33	0	100	182.22	173.33	174.00
7	50	66	120	31	177.29	170.94	180.86

8	50	99	80	54	170.09	175.08	165.94
9	60	0	80	100	184.86	184.45	195.23
10	60	33	120	77	168.25	182.75	179.35
11	60	66	0	54	177.54	188.81	177.94
12	60	99	40	31	184.73	170.98	178.71
13	70	0	120	54	188.71	189.92	182.16
14	70	33	80	31	180.00	180.00	179.30
15	70	66	40	100	177.97	**210.52**	182.73
16	70	99	0	77	187.49	197.00	**197.73**

3.2.3. Effect of corner dwell time (CDT) on corner radius. With regard to the CDT parameter, the figure 6 and 7 showed that as the CDT parameter increases the corner radius decreases initially and then it increases at 33s of CDT for 0° slant angle. But in 30° slant angle the corner radius increases as CDT increases and at 66s of CDT there was a decrease in corner radius. This contrasting behaviour was observed due to the increase in cutting thickness of the material at higher slant angles. At higher cutting thickness, the lower corner radius can be achieved at higher CDT due to the fact that the wire has to cut more material. From table 5 it can be observed that among all the profiles, the highest corner radius of 210.52µm, was obtained at highest CDT for 99s of 0° angle, and in case of 30° slant angle the highest corner radius of 235.42µm was observed in 66s of CDT as indicated in table 6. It can be observed that at higher CDT corner radius increases because of the overcut, this can be inferred that the CDT parameter has to be optimized as higher CDT can cause an increase or decrease in the corner radius. [19]

3.2.4. Effect of cutting speed override (CSO) on corner radius. For CSO parameter, from table 5 the highest corner radius for triangle profiles 1mm, 3mm and 5mm were measured to be 205µm, 210.52µm and 197.73µm respectively at higher cutting speeds obtained at 100, 100, 77 of CSO% parameter for 0°. For 30° it was observed to be 235.42µm, 208.68µm and 196.36µm at 100, 77, and 77 of CSO% respectively having greater cutting speeds as inferred from table 6. However, it can be concluded from table 4 and 5 that the lowest corner radius was observed at CSO parameter 31% for trial 1, which yields the lowest cutting speeds. From all the main effects plot it can be clearly noticed that as the CSO% increases the corner radius also increases. It can be observed that as the cutting speed increases the corner radius also increases. Figure 6(b) and (c) shows a sudden increase in corner radii at 77% and 31% CSO respectively, this is due to increase in cutting speed and wire vibration caused by uneven forces during sparking and discharging [16]. At higher levels of CSO% the wire vibration is stabilized so there might be a slight decrease in corner radius as observed in figure 6 (b).

Table 6. Corner radius for different parameters at 30° slant angle.

Trial No.	WDG (mm)	CDT (s)	WO (µm)	CSO (%)	Corner Radius		
					Δ 1mm 2nd µm	Δ 3mm 2nd µm	Δ 5mm 2nd µm
1	100	0	0	31	**163.51**	**167.56**	**165.94**
2	100	33	40	54	171.00	177.33	175.33
3	100	66	80	77	197.67	193.68	**196.36**
4	100	99	120	100	207.50	196.01	182.66
5	110	0	40	77	159.50	186.50	181.75
6	110	33	0	100	193.33	193.66	180.00
7	110	66	120	31	187.08	177.00	179.66
8	110	99	80	54	201.67	187.78	193.17
9	120	0	80	100	208.34	204.00	188.10
10	120	33	120	77	230.68	**208.68**	190.00
11	120	66	0	54	165.54	183.81	170.94
12	120	99	40	31	185.33	169.35	187.77
13	130	0	120	54	222.92	197.00	187.70
14	130	33	80	31	180.85	181.25	186.00
15	130	66	40	100	**235.42**	192.69	190.76
16	130	99	0	77	184.44	201.00	174.00

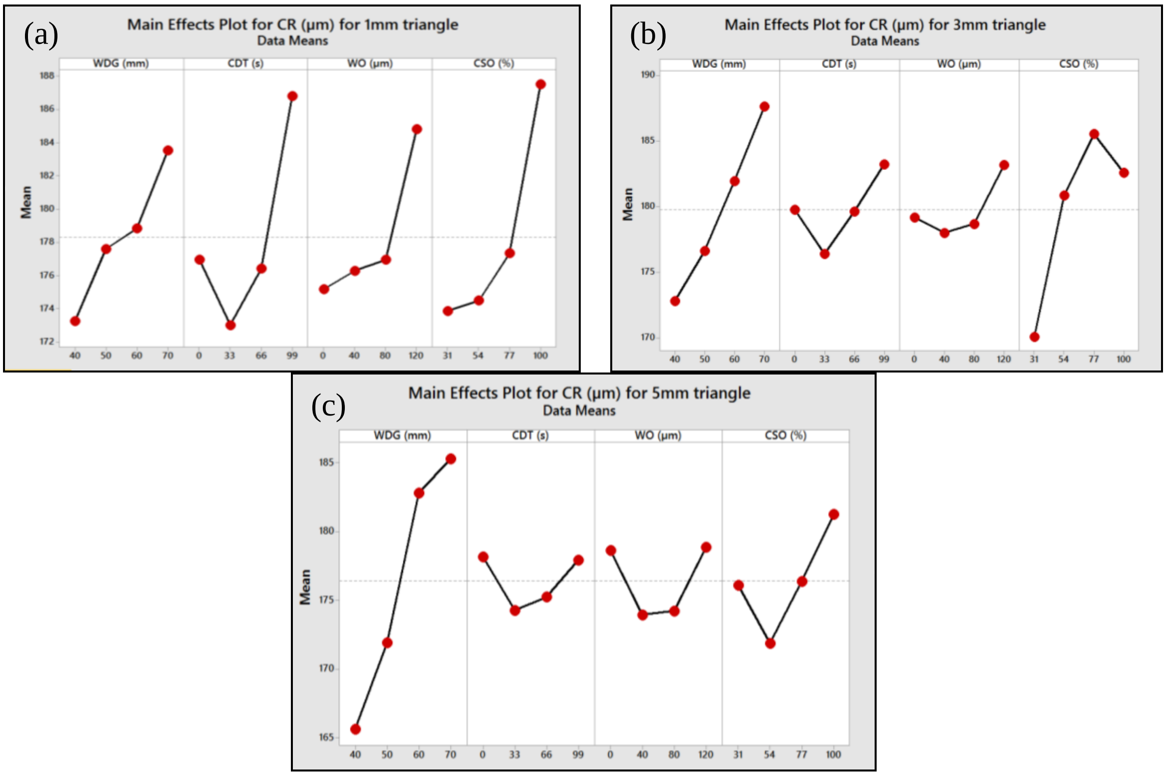


Figure 6. Main effect plots of (a) Δ 1mm (b) Δ 3mm (c) Δ 5mm at 0° slant angle.

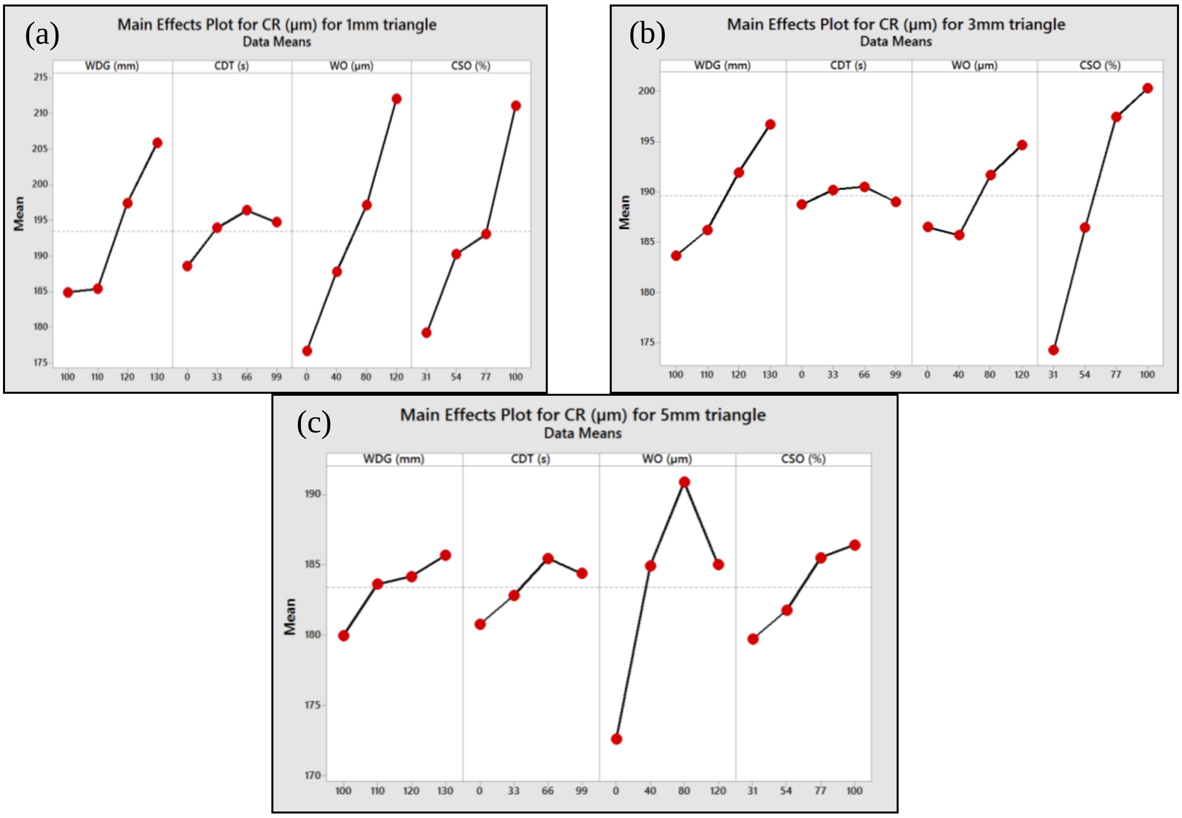


Figure 7. Main effect plots of (a) Δ 1mm (b) Δ 3mm (c) Δ 5mm at 30° slant angle.

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3.3. Corner accuracies at the highest and lowest cutting speed

Figure 8 shows the SEM images of second corner of the 3mm triangle machined at highest and lowest cutting speeds (CS) for both slant angles. The SEM images were used to measure corner radius (CR) and corner error (CE) using Image J software. The corner radius measured 176.82µm at lowest cutting speed of 0.62mm/min and 210.52µm for highest cutting speed of 1.51mm/min for 0° as shown in figure 8(a) and (b) respectively. At 30° the lowest cutting speed of 0.47mm/min generated corner radius of 169.35µm as in figure 8(c) and figure 8(d) indicates the corner radius to be 190.76µm at highest cutting speed of 1.45mm/min. It can be observed that at higher cutting speeds the corner radius was also higher as shown in main effect plots in figure 6(b) and figure 7(b) for both the angles. The corner errors were 15835.1µm^2 for lowest cutting speed and 25297.6µm^2 for highest cutting speed at 0°. At 30°, it was 22996µm^2 and 27138µm^2 for lowest and highest cutting speed respectively. From the corner radius and corner error, it can be concluded that as the corner radius increases, the corner error also increases. The corner errors were higher for higher cutting speeds when compared to the corner errors at lower cutting speeds for both the angles. Similar kind of corner inaccuracies were noticed and they reported this accuracies was due to wire lag and wire deflection [18].

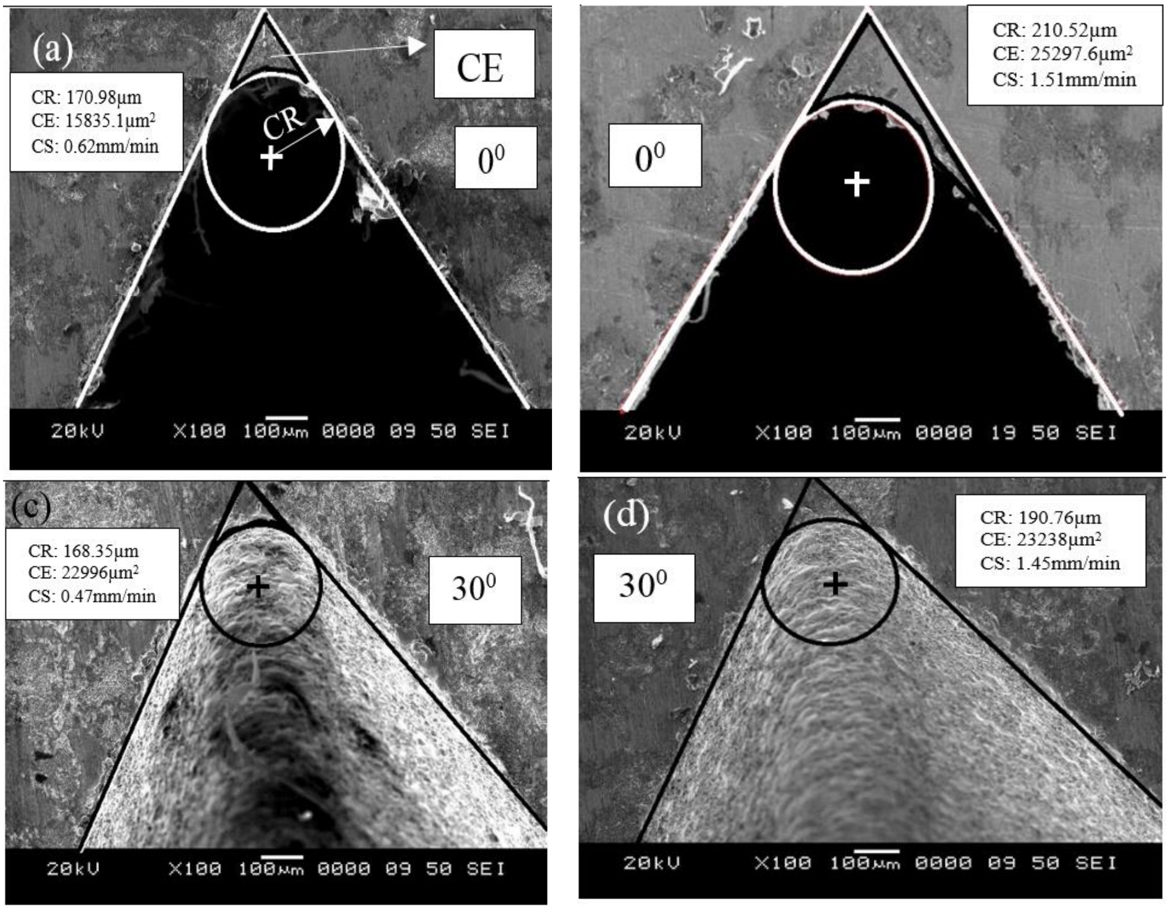

Figure 8. SEM micrographs of corners for (a) lowest and (b) highest cutting speeds at 0°, (c) lowest and (d) highest cutting speeds at 30°.

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4. Conclusions
The triangular profiling was machined on Hastelloy X using slant fixture at 0° and 30° slant angle. Cutting speed, corner radius and corner error was investigated for different machining parameters like WGD, WO, CDT and CSO and the following conclusions were drawn

The CSO parameter was the most influential parameter that affected the cutting speed for both at 0° and 30° slant angles, although machining was performed at cutting parameter T_{on}=115, T_{off} =44, SV=40, SF=20 and WF=6. There was 3.97%, 24.193% decrease in cutting speed for the lowest and highest cutting speed parameters respectively at different slant angles of 0° and 30°,this is due to increase in cutting thickness during machining at different slant angles.

The corner radius increased with increase in WGD, WO and CSO parameters. CDT parameter was observed to have contrasting behaviour at 0° and 30° slant angles due to the change in cutting thickness. It was observed that for an optimal CSO and CDT parameters i.e. 31% of CSO and 33s CDT at 0° and 31% of CSO and 0s CDT at 30° the corner radius was reduced.

Based on the main effects plots, the optimised parameters are considered to be WDG=40, CDT=33, WO=0, CSO=31 measures the lowest corner radius of 153.51µm, 157.56µm and 162.54µm for 1mm, 3mm and 5mm triangle shape slots respectively at 0° and WDG=100, CDT=0, WO=0, CSO=31 was optimal at 30° slant angle, as it measured lowest of 163.51µm, 167.56µm and 165.94 µm corner radius for 1mm, 3mm and 5mm triangle slots respectively. It was observed that the 30° corners were measured with lower corner radii having 169.35 µm, 190.76 µm at the highest and lowest cutting speed parameters respectively, than the corners at 0° slant profiles which measured 170.98µm, 210.52 µm at the highest and lowest cutting speed parameters respectively.

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