PROCESS CAPABILITY EVALUATION OF SHAPED METAL DEPOSITION INTEGRATED SYSTEM THROUGH CONTROLLING THE DIMENSIONS OF FABRICATED PARTS OF AUSTENITIC STAINLESS STEEL

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ABSTRACT

The aim of this work is to investigate the process capability of the shaped metal deposition processes to be able to fabricate products with geometries meet the required specifications of the designed parts. The intent of the present paper is to highlight the using of the statistical techniques and process capability for the continuous current and pulsed current TIG-based shaped metal deposition processes in order to achieve the suitable performance. Two experiments with different sets of deposition process parameters were carried out in order to study the capability of the SMD processes at different conditions. The results showed that all the experiments were performed under statistical control state. The parts produced by PC-SMD method are very close and consistent with the target specification comparing to the CC-SMD method. However, the CC-SMD produces wall with lower side wall machined layer less than that of PC-SMD process. As results the CC-SMD method is recommended for future usage sine it give more saving in the metal removal during further machining processes.

Keywords: Process capability, Statistical quality control, Shaped metal deposition, Pulse frequency, Austenitic stainless steel

INTRODUCTION

The process can be defined as a combination of materials, methods, equipments, and people engaged in producing a measurable output (Senvar and Tozan, 2010). Process capability refers to the uniformity of the process (Montgomery, 2009a). Process capability compares inherent variability in a process with the specifications that are determined according to the customer requirements. Thus, process capability represents the proportion of actual process spread to the allowable process spread, which measured by six process standard deviation units (Senvar and Tozan, 2010). Process capability compares the output of a process that is an in-control state to the specification limits by using process capability indices (Kane, 1986). The specification can be defined as an explicit set of requirements to be satisfied by a material, product or service. Specifications must be respected to avoid sanctions (Kurekovă, 2001).

Process capability index C_p it is a simple and quantitate way to express process capability. It represents the process capability ratio. Juran (1974) defined the process capability index as:

$$Cp = \frac{UTL - LTL}{6\sigma} \qquad (1)$$

UTL (USL) and LTL (LSL) are the upper and lower tolerance (specification) limits respectively

C_p measures potential capability in the process, but it cannot reflect the condition of the center shift. The measurement of the actual process capability was done using C_{pk}since it takes process centering ratio into account (Montgomery, 2009b) Cpk can defined as:

$$Cpk = \min.\left[\frac{UTL-\mu}{3\sigma} \text{ or } \frac{\mu-LTL}{3\sigma}\right] \qquad (2)$$

where μ is the process mean, σ is the standard deviation.

Another capability index is part per million (PPM). This index indicates the ratio between the number of pieces exceeding the specification limits and a million produced units (Kurekovă, 2001). The identification of the main characteristics to analysis is the first step in the process capability analysis. So that the most important features such as product dimensions are identified. The process should be in statistical control during selecting the data for process capability analysis. In case of this research paper, the important characteristics selected were the part dimensions and the machined layer thickness during finishing processes to final part dimensions.

One of the main goals of the present study is to investigate the reliability of the manufacturing system and the process parameters during continuous production for the important parts, especially for aerospace components which are usually fabricated from an expensive materials and so the removal material during further finishing processes should be as minimum as possible. Which is the main advantage of the additive manufacturing technologies over the traditional methods. This paper investigates the process capability of the shaped metal deposition (SMD) integrated system through manufacturing selected parts, which are straight walls of austenitic stainless steel. The choice of straight wall geometry is too essential since it mimics the type of built-up that would be required to manufacture thin walled, pocketed sections commonly found in structural aerospace applications (Hoye et al., 2013). This investigation aimed to characterize the important geometries of manufactured parts from two SMD processes namely continuous current SMD (CC-SMD) and pulsed current SMD (PC-SMD).

EXPERIMENTAL PROCEDURE

SMD experimental set-up and Materials

The experiments were conducted using a SMD machine which was designed and developed for only deposition processes as shown in Fig. 1. The developed SMD machine is computer controlled with 3-axes positioning actuated by three steeper motors. Melting source used for the SMD process is water cooled LINCOLN V320-T AC/DC TIG welding machine which is capable of supplying both continuous and pulsed TIG arc current. TIG torch is LincTorch (LT18W) water cooled duty cycle 100%, 1.8 cm cup size with 2% throated tungsten. Schematic form of pulsed current and the main parameters used in the pulsed current shaped metal deposition (PCSMD) process are shown in Fig. 2. More details about this integrated system are reported in the literature (Oguzhan et al., 2015).

AISI 304 substrates were used in the form of plate with the dimensions of 150 mm x 250 mm x 6 mm. The filler metal used for depositing was a solid stainless steel wire with diameter of 1 mm. Its grade was chosen according to AWS A5.9-95 specification, so that the wire grade is ER316L (Afrox website).The suggested shielding gas which is Argon with 99.90 % purity with 12 l/min flow rate was used in this work.

The paper aims to characterizing the important geometries of the selected sample feature manufactured by SMD process with view the comparing the continuous current SMD (CC-SMD) and pulsed current SMD (PC-SMD) processes. The designed dimensions of the

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manufactured parts were calculated based on the previous study on the same current SMD system and according to the required part specifications (see Fig.3).

The designed combination set of process parameters listed in Table 1. Which were used for building up the samples with planned wall width, height and wall side roughness, for both CC-SMD and PC-SMD. Two sets of process parameters were used in this research as listed in Table2. In conducting the comparison, a measurable test components, straight wall samples measuring 100 mm length with measured height and width were built on AISI 304 austenitic stainless steel substrate of 6 mm thickness as shown in Fig. 3. The tests sample were used to check the performance of the SMD processes under same trail conditions of the two processes. The experiments consisted of fabricating 13 test samples for each method. After the deposition processes were completed the test samples were characterized and the results were given in graphical forms for each method.

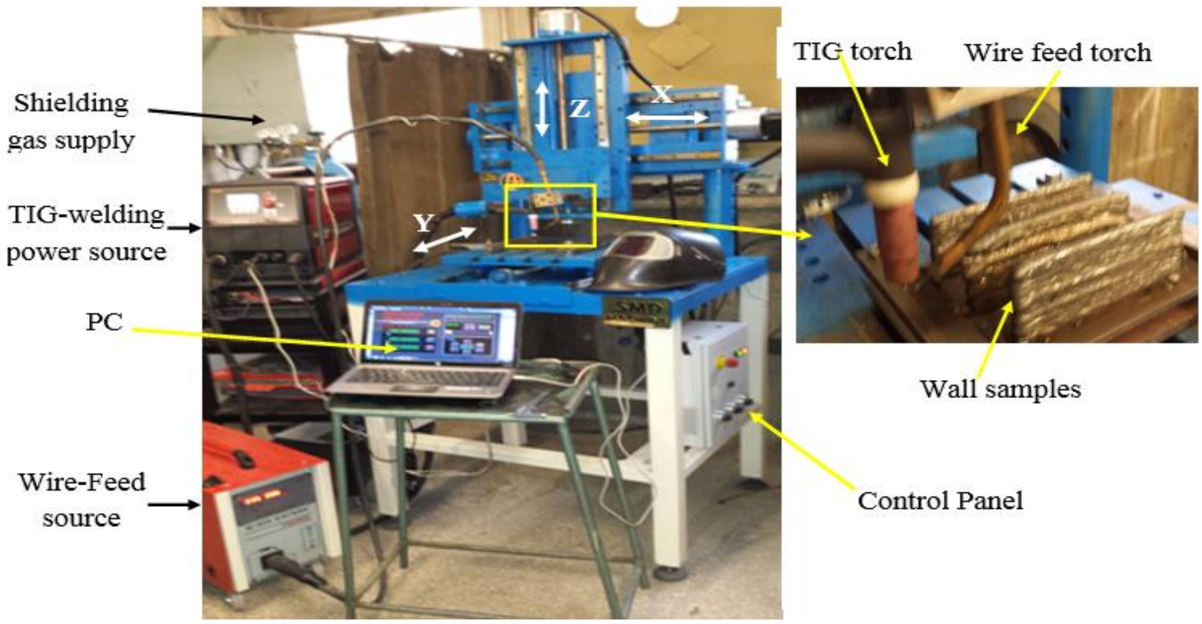

Fig. 1. Experimental set-up for SMD process

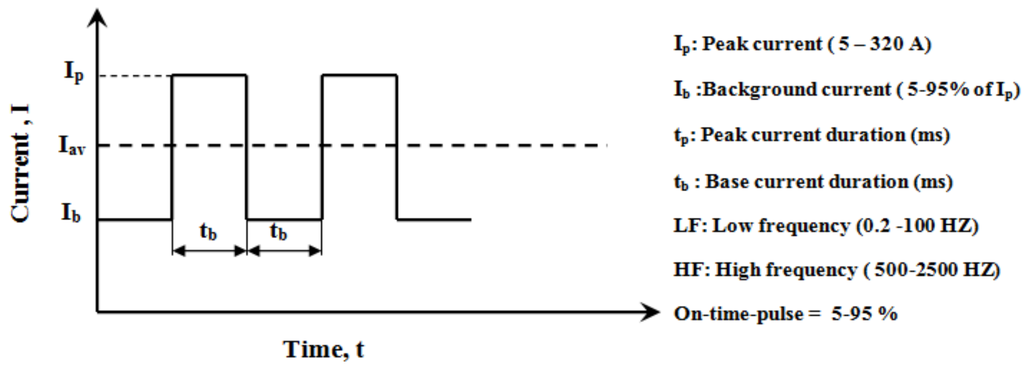

Fig. 2. Schematic diagram of a standard pulse current-time square waveform

CC-SMD Process

Using the process parameters listed in Table 1, thirteen wall samples were deposited to the required dimension for both experiments.In order to increase the reliability, the experiments were replicated. The required dimensions and assigned tolerances (specifications) for each dimension were summarized in Table 2.

Table 1. Process parameters used for deposition experiments

Parameter/ Condition	*Symbol*	*CC-SMD*		*PC-SMD*	
		1st experiment	*2nd experiment*	*1st experiment*	*2nd experiment*
Welding current (A)	I	160	180	160	180
Travel speed (mm/s)	TS	3	4	3	4
Wire feed speed (m/min)	WFS	2.5	3	2.5	3
Frequency (Hz)	F	0	0	5	30
Length of arc (mm)	L	5	5	5	5
Interpass temperature (°C)	T_{sub}	300	300	300	300
Stick out (mm)	--	15	15	15	15
Feeding angle (°)	A	30	30	30	30
Number of layers	-	10	10	10	10
Step height (mm)	Hs	1	1	1	1
I_p/I_b ratio (A/A)	CR	1	1	2	2

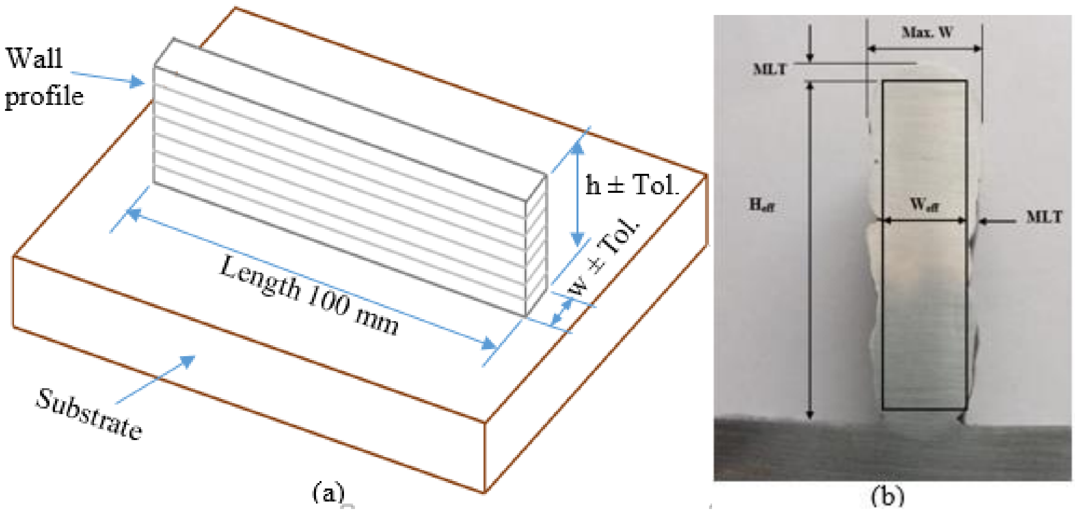

Fig. 3 (a). Schematic illustrates the test wall specimen, and (b) cross-section view of the wall sample illustrates the selected geometries

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Table 2. The assigned Dimensions, tolerances, and actual deposit dimensions of the CC-SMD

Dimension	*Experiment*	*After machining*	*Max. dimension as deposit*	*Tolerances*
Wall width (mm)	I	6	8.5	8.5^{+1}_{-1}
	II	6	8.5	8.5^{+1}_{-1}
Wall height (mm)	I	8	9	$9^{+1}_{-0.5}$
	II	7	8	$8^{+1}_{-0.5}$
Thickness of removed layer (mm)	I	0	0	$0^{+1.5}_{-0.0}$
	II	0	0	$0^{+1.5}_{-0.0}$

Table 3. The assigned Dimensions, tolerances, and actual deposit dimensions of the CP-SMD

Dimension	*Experiment trial*	*After machining (required)*	*Max. dimension as deposit*	*Tolerances*
Wall width (mm)	I	5	7	$7^{+1.5}_{-0.5}$
	II	5	7	$7^{+1.5}_{-1.0}$
Wall height (mm)	I	9	10.5	10.5^{+1}_{-1}
	II	8.5	10	10^{+1}_{-1}
Thickness of removed layer (mm)	I	0	0	$0^{+1.5}_{-0.0}$
	II	0	0	$0^{+1.5}_{-0.0}$

Table 4. The wall geometry measurements for the experiment I in the CCSMD process

Exp. No.	*Max. wall width as average (mm)*	*Max. wall height as average (mm)*	*MLT*
1	8.833	8.25	0.675
2	9.025	9.15	0.3
3	8.35	9.6	0.35
4	8.3	9.825	0.375
5	8.2	9.325	0.525
6	8.5	9.475	0.575
7	8.525	8.575	0.375
8	8	9.175	0.6
9	8.2	9.4	0.35
10	8.3	9.45	0.375
11	8.1	9.1	0.575
12	8.775	8.9	0.625
13	9.25	8	0.575

PC-SMD Process

Using the weldingconditions given in Table 1, thirteen wall samples were carried out. The part dimensions before and after finishing machining processes and the assigned allowances are listed in Table 3.

RESULTS AND DISCUSSIONS

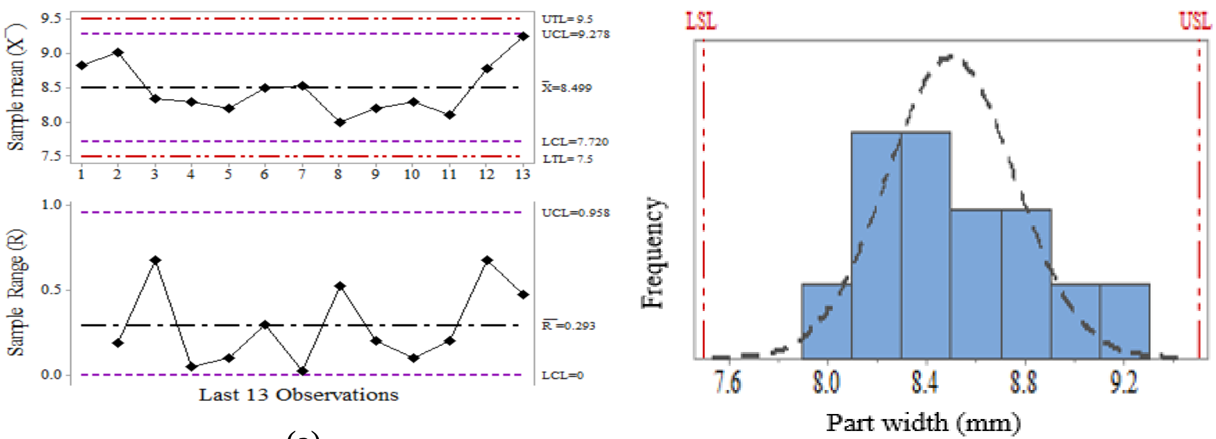
CC-SMD process.

First experiment (I)

The experiment results are listed in Table 4

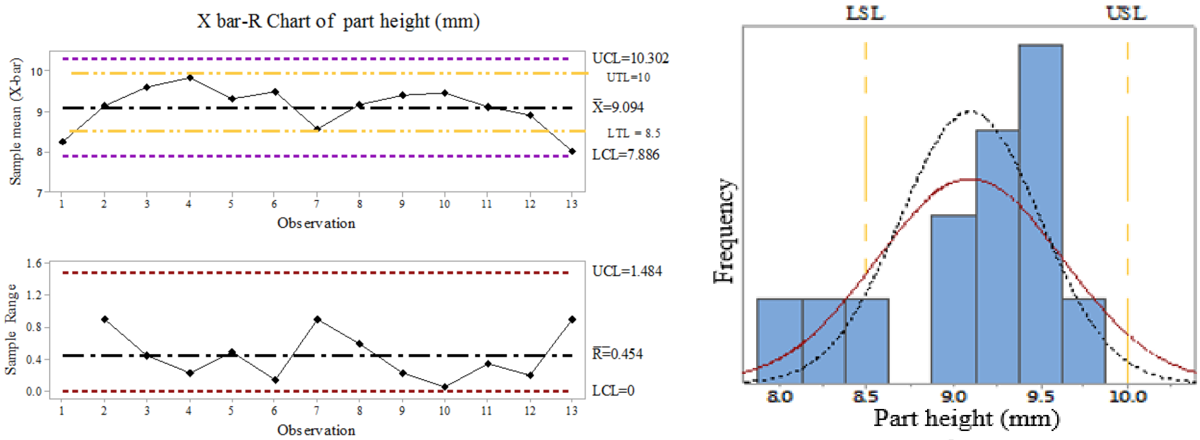
Wall width (W)

The statistical quality control (SQC) was performed through using the $\overline{X}$ -R charts. From the Fig. 4(a), it can be seen that the process is under statisticalcontrol since all the measured parts' width are within the control limits of the charts. From the process capability histogram shown in Fig.4 (b), it seems that the CC-SMD process is capable to produce and control on the bead width with non-confirmed PMP of 118.74. The process capability indices Cpk, Cp, and standard deviation (σ) are 1.28, 1.28 and 0.259826 respectively.



(a) (b)

Fig. 4 (a). $\overline{X}$ -R chart for the wall width, and (b) the capability histogram of the part width



(a) (b)

Fig. 5 (a) $\overline{X}$ -R charts for the wall height, (b) Capability Histogram

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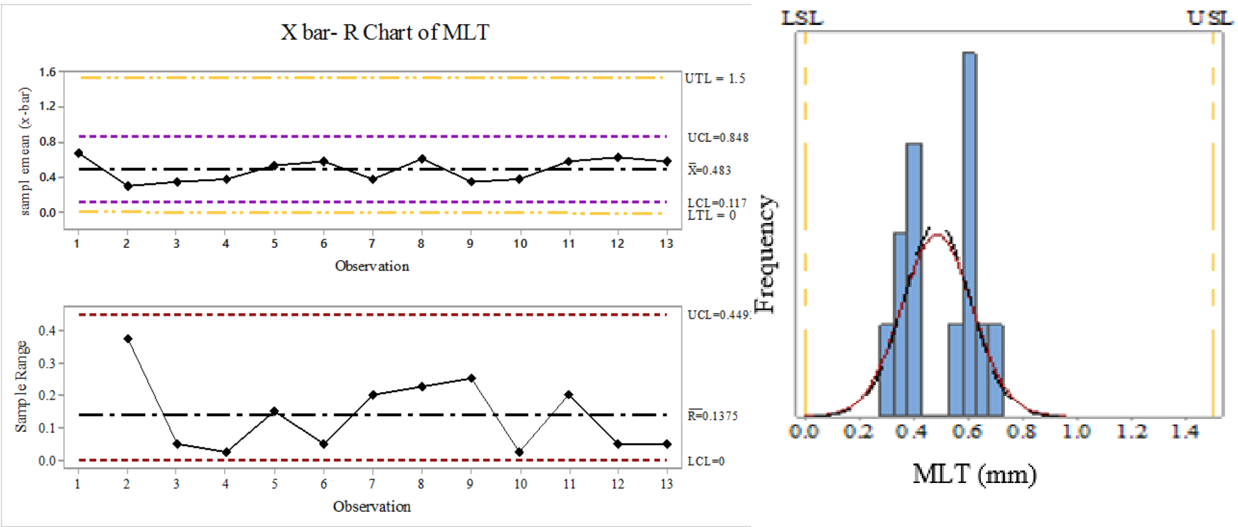
Wall height (H)

The statistical quality control (SQC) of the part height is summarized in the Fig. 5. From figure 5(a), it is obvious that although the process is under statistical control, but this process is unable to satisfy the designing tolerates relevant the wall height since the specifications limits are smaller than the control limits and hence the capability index (PC) is 0.62 and the Pck is 0.49 which are less than 1. This process will produce about 82283.95 non-confirming PPM with standard deviation of 0.40263 as illustrates in the process capability histogram shown in Fig. 5(b).

Machined layer thickness MLT

The SQC of the MLT is summarized in the Fig. 6(a) while the process capability histogram of the MLT is summarized in the Fig. 6(b). It is clear that the process is under statistical control and the process is centred and usually able to meet the designed specifications. The PC, Pck, σ, and PPM are 2.05, 1.32, 0.121897, and 37.11 respectively.



(a) (b)

Fig. 6(a). $\overline{X}$ -R charts for the MLT, (b) Capability Histogram

Table 5. The results of the experiment trial II in CC-SMD process

Exp. No.	*Max. wall width as average (mm)*	*Max. wall height as average (mm)*	*MLT*
1	8.52	8.075	0.475
2	8.775	7.2	0.5
3	8.925	7.85	0.475
4	9	7.825	0.575
5	8.675	8.05	0.65
6	9.025	7.95	0.45
7	9.475	7.6	0.9
8	8.25	8.3	0.425

9	8.75	7.975	0.325
10	8.957	7.7	0.55
11	8.625	8.12	0.375
12	8.35	8	0.6
13	8.925	7.925	0.5

Second experiments (II)

The results of the II experiment are shown in Table 5.

Part width

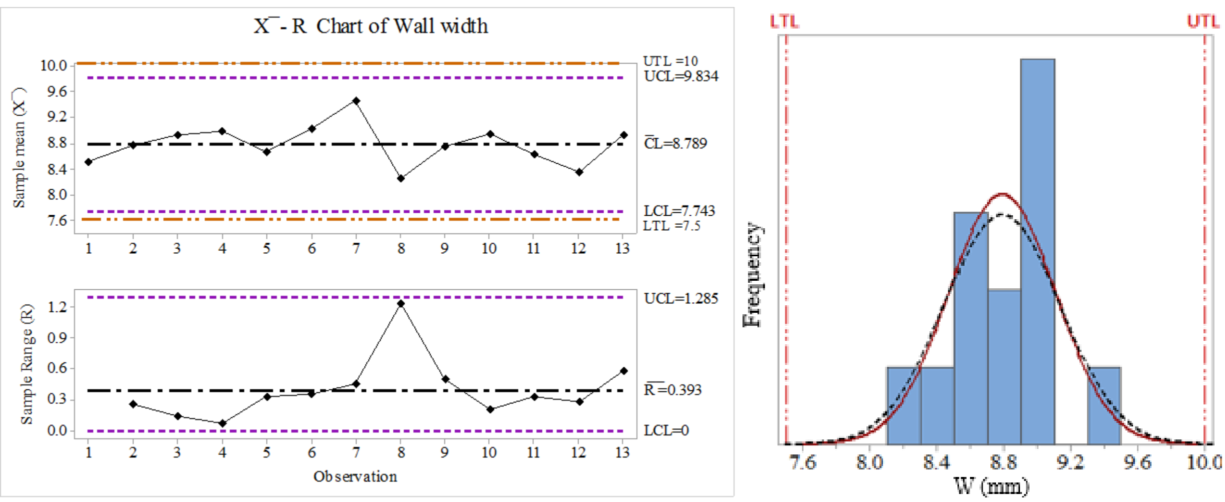
The SQC of the wall width is summarized using the $\overline{X}$ -R charts as shown in Fig. 7(a) while the process capability of the part width is summarized by the process capability report shown in Fig. 7(b). It is clearly appear the process is under statistical control and it is able to satisfy the product specifications since it has (Cp of 1.2 &Cpk of 1.16) >1, also the process has σ of 0.348626 and PPM of 365.65.

Part height

The SQC of this dimension is summarized in Fig. 8(a), while the process capability histogram of the part height is summarized in Fig. 8(b). The process is under statistical control but it is not capable since the lower tolerance limit is more than lower control limit and so the Pck becomes <1 (0.43) therefore, the process is not capable since the variation is too large and the process mean is not on the target, also the Cp is 0.82 (poor process) and hence the non-confirming PPM is about 101273.68.

Thickness of removal layer

The SQC of this dimension is summarized in Fig. 9(a), while the process capability histogram of the machined layer thickness is summarized in Fig. 9(b). It is clear that the process is under statistical control and also it is capable to meet the required specifications. Pc and Pck are >1 and the PPM are 567.2 with σ of 0.160683.



(a) (b)

Fig. 7 (a). $\overline{X}$ -R chart for the part width, and (b) Capability histogram

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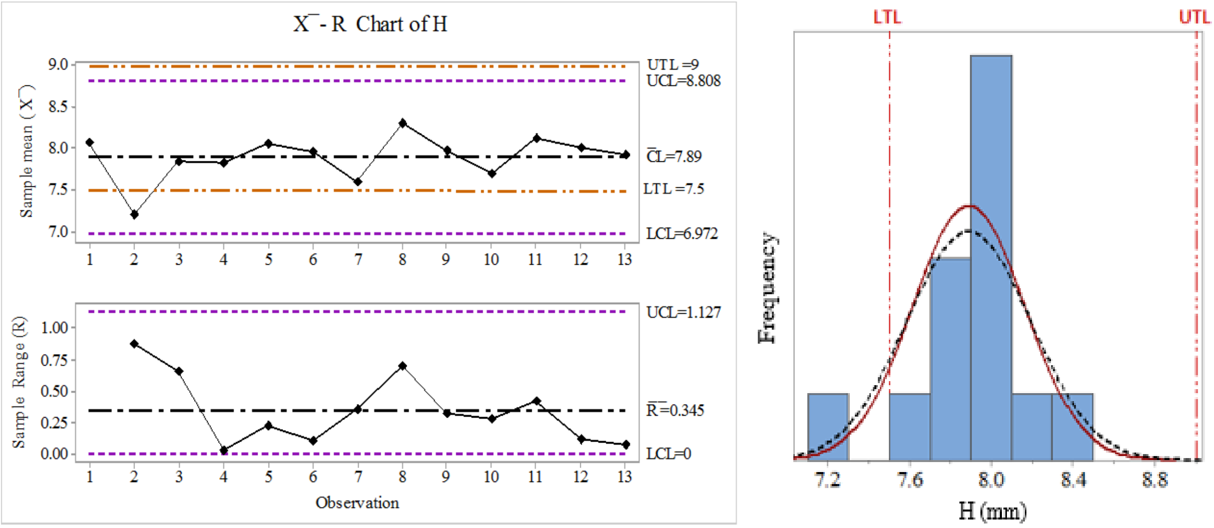
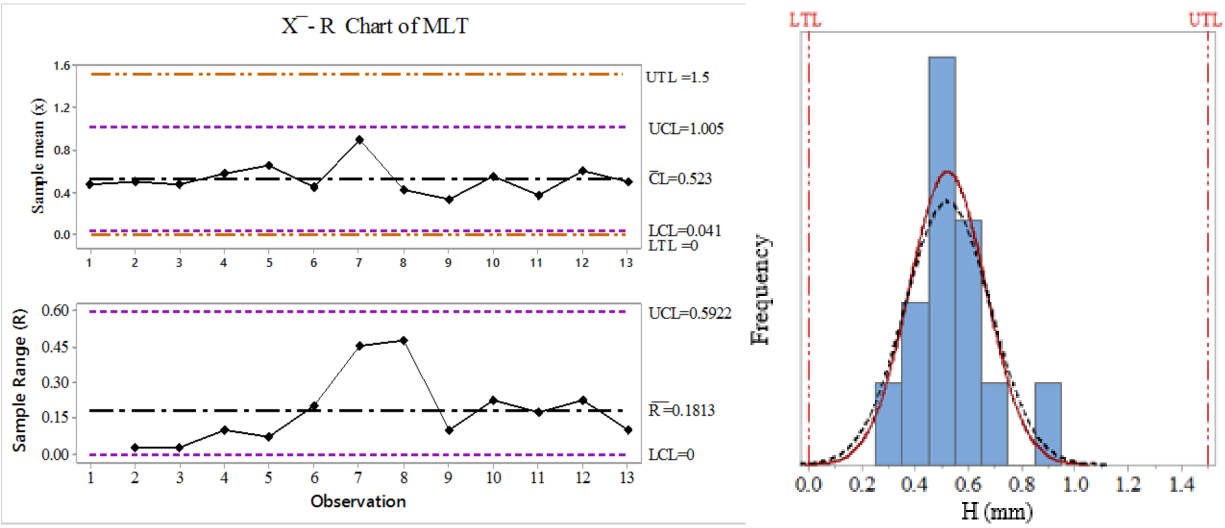


(a) (b)

Fig. 8 (a). $\overline{X}$ - R charts for the part height, and (b) Capability histogram



(a) (b)

Fig. 9 (a). $\overline{X}$ -R charts for the part height, and (b) Capability histogram

Table 6. The measurement results of the experiment I.

Exp. No.	*Max. wall width as average (mm)*	*Max. wall height as average (mm)*	*MLT*
1	7.275	9.525	0.575
2	6.55	10.05	0.6
3	6.825	9.875	0.35
4	6.475	9.625	0.35
5	6.9	11.35	0.35
6	6.525	10.575	0.75
7	8	9.625	0.55

8	6.625	9.575	0.45
9	6.625	9.3	0.525
10	6.7	10.3775	0.325
11	7.025	11.45	0.475
12	6.775	11.3	0.6
13	7.55	10.65	0.575

PC-SMD Process

First Experiment (I)

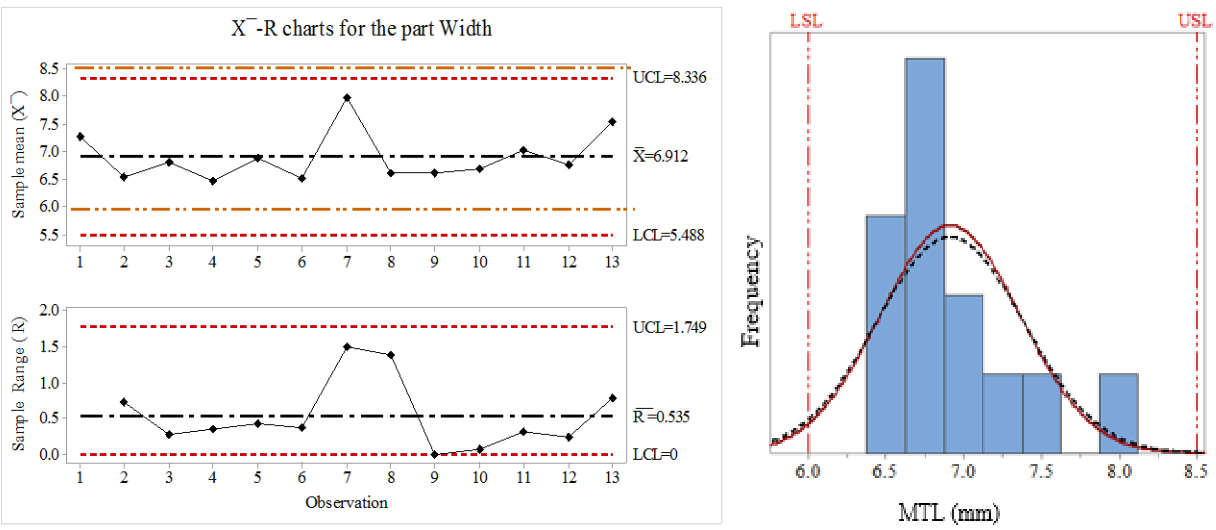
The geometry measurements for the test samples in the PCSMD process are listed in Table 6.

Wall Width (W)

The SQC was performed through using the X bar-R diagrams (see Fig. 10(a)) and the capability histogram shown in Fig.10 (b). From the Fig.10a, it is clear that the process within statistical control, but it is not capable since the lower specification limit is more than the lower control limit which means that the Cpk < 1 (0.64) and the Cp is 0.88 with standard deviation (σ) of 0.47466 and hence the non-confirm PPM of 27752.84.

Wall Height (H)

The SQC was performed through using the $\overline{X}$ - R charts (Fig. 11(a)). Process capability histogram shown in Fig.11 (b). The process seems under statistical control, but it is not capable since the lower and upper specification limits are more and lower than the lower and upper control limits respectively, and thereby Cpk is <1 (0.44) and also the Cp is 0.59. Thus, the non-confirming PPM becomes 106243.07.



(a) (b)

Fig. 10 (a). $\overline{X}$ -R charts for the part width, and (b) Capability histogram

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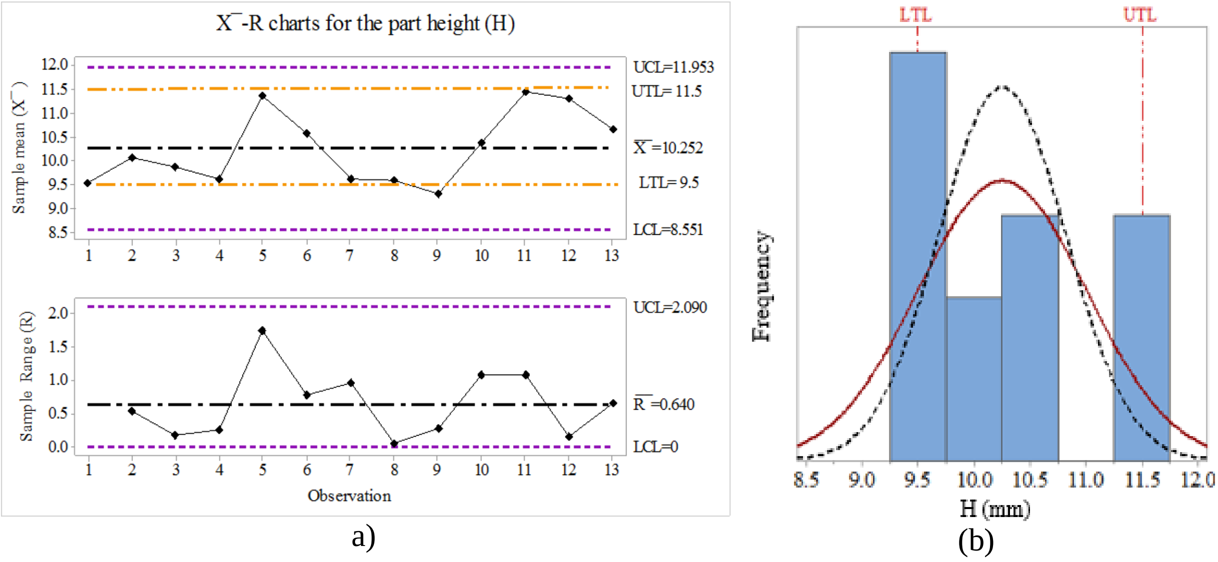

Fig. 11 (a). $\overline{X}$ -R charts for the part height, and (b) Capability histogram

Thickness of Removed Layer (MLT)

The SQC was performed through using the $\overline{X}$ -R charts as shown in Fig. 12(a).Process capability histogram shown in Fig.12 (b). The process is under statistical control and it is strongly capable to meet the required tolerances. So that the Cpk is 1.45 and the Cp is 2.18 with PPM of 6.81.

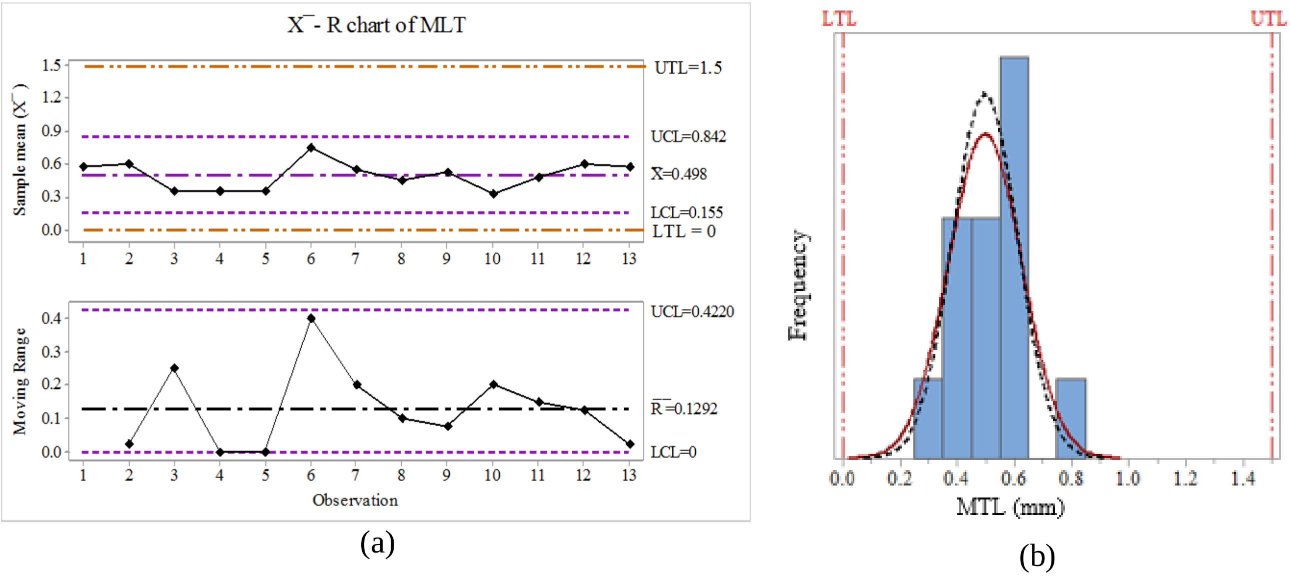

Fig. 12 (a) $\overline{X}$ -R charts for the MLT, and (b) Capability histogram

Table 7. The Measurement Results of the Experiment II

Sample No.	*Max. wall width as average (mm)*	*Max. wall height as average (mm)*	*MLT*
1	7.2	10.35	0.55
2	6.775	9.925	0.45
3	7.075	8.8	0.725
4	7.1	9	0.725
5	6.95	8.95	0.55
6	6.65	10.05	0.375
7	6.9	9	0.5
8	6.75	9.5	0.7
9	6.5	9.875	0.55
10	6.925	9.7	0.625
11	6.55	10.35	0.65
12	6.425	10.075	0.675
13	6.975	11.275	0.65

Second Experiment (II)

The geometry measurements for the test samples in the PCSMD process are listed in Table 7.

Wall Width (W)

The statistical quality control was performed through using the $\overline{X}$ - R charts (see Fig. 13(a)).Process capability histogram shown in Fig.13(b). This process is under statistical control and capable to meet the designed specifications of the product with Cpk of 1.12 and Cp of 1.7 and so the PPM is 369.29.

Wall Height (H)

The SQC was performed through using the $\overline{X}$ -R diagrams (Fig. 14(a)) and capability histogram shown in Fig.14(b). Although this process is under Statistical control, but it is not capable to meet the product specifications since, as shown in Fig. 14(a), the tolerance limits are the nearest to the central line (CL) of the process which causes the Cpk to be < 1 (0.48) and also the Pc of 0.63, and hence the non-confirming PPM of 84076-82.

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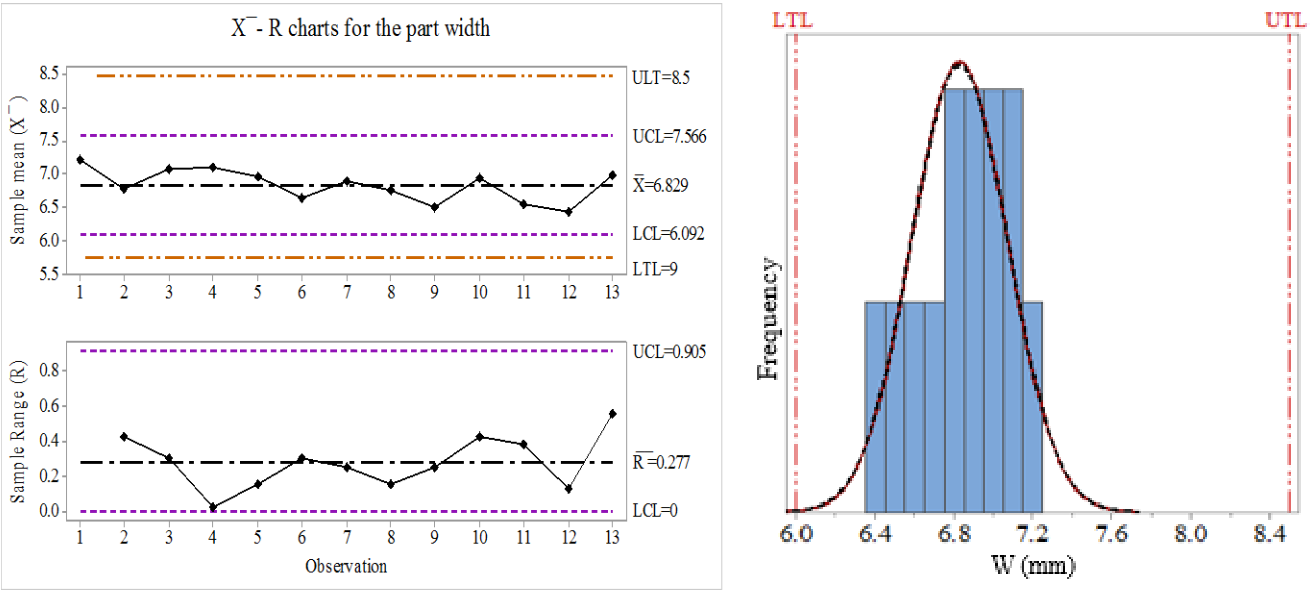
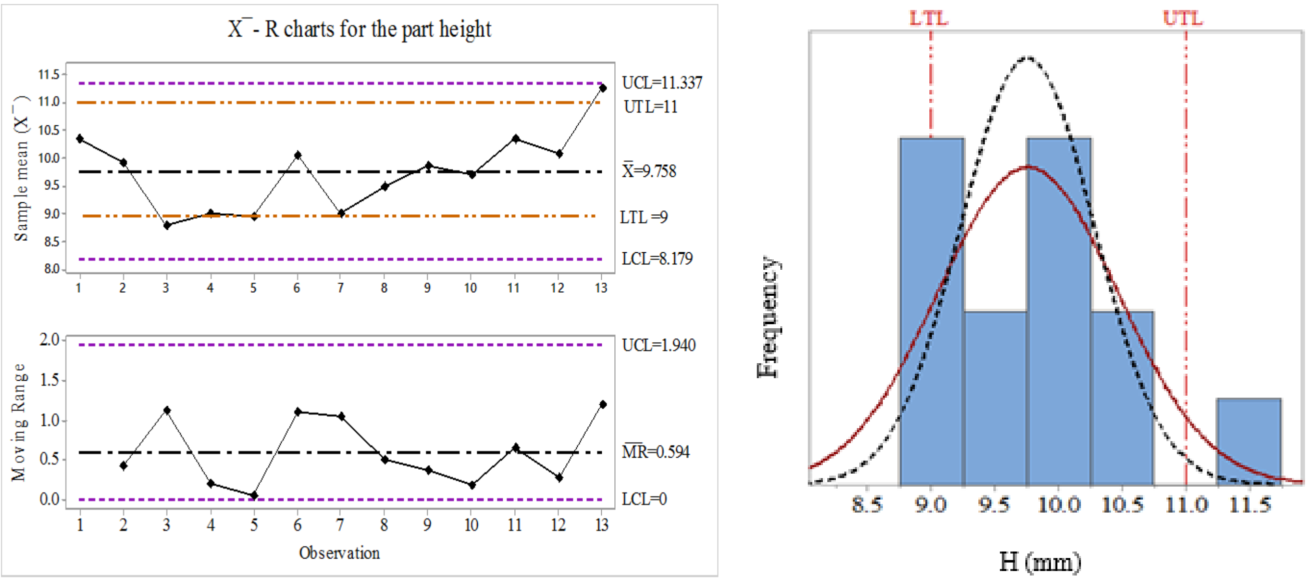


(a) (b)

Fig. 13 (a) $\overline{X}$ -R charts for the part width, and (b) Capability histogram



(a) (b)

Fig. 14 (a) $\overline{X}$ -R charts for the part height, and (b) Capability histogram

Thickness of Machined Layer (MLT)

The SQC was carried out using the $\overline{X}$ -R charts (Fig. 15(a)) and the capability histogram shown in Fig.15 (b). It obvious that this process is under statistical control and also is strongly capable to meet the requirements of the product specifications. The Pck is 1.99 and Cp is 2.51 with standard deviation of 0.09973, and hence there is no PPM.

Process Capability Analysis

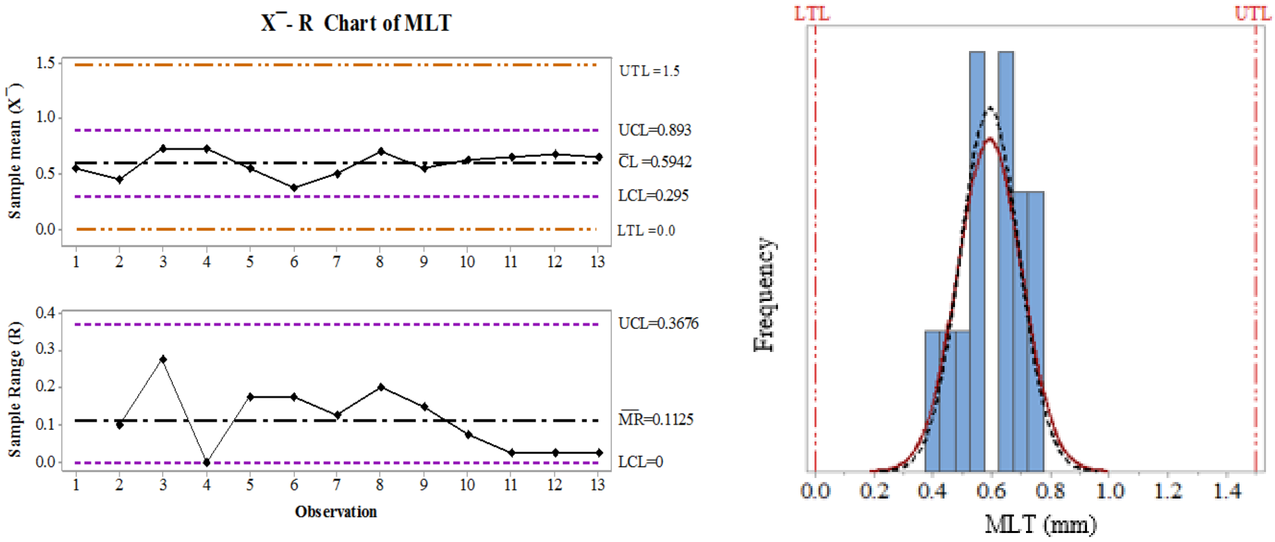
The analysis of the selected geometries were summarized individually for both SMD processes.

Wall Width

For the first experiment (I) and second experiment (II), the process capability indiceCP$_{k,}$ andthemean width are compared between the CC-SMD and PC-SMD process as shown in Figs. 16 and 17 respectively. The CC-SMD process is more capable to meet the specifications of the wall width in both experiments. Also this process produces parts with relatively large width than PC-SMD process (Fig. 17)

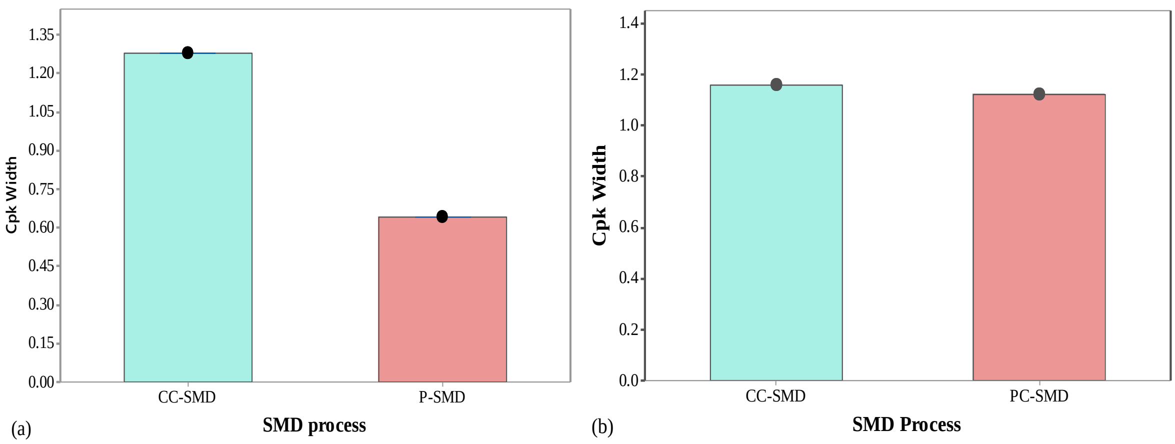
Wall Height

The results of the two experiments were compared in both CC-SMD and PC-SMD processes for the Cpk and the sample height as shown in Fig. 18 and Fig. 19. From Fig. 18, it is obvious that the Cpk is < 1 for both SMD processes and for both experiments. The Pc-SMD process is usually produces more height than CC-SMD process (Fig. 19)



(a) (b)

Fig. 15 (a) $\overline{X}$ - R charts for the part height, and (b) Capability histogram



(a) (b)

Figure 16. Comparison of Cpk of CCSMD and PCSMD of width W for (a) experiment I and (b) for experiment II

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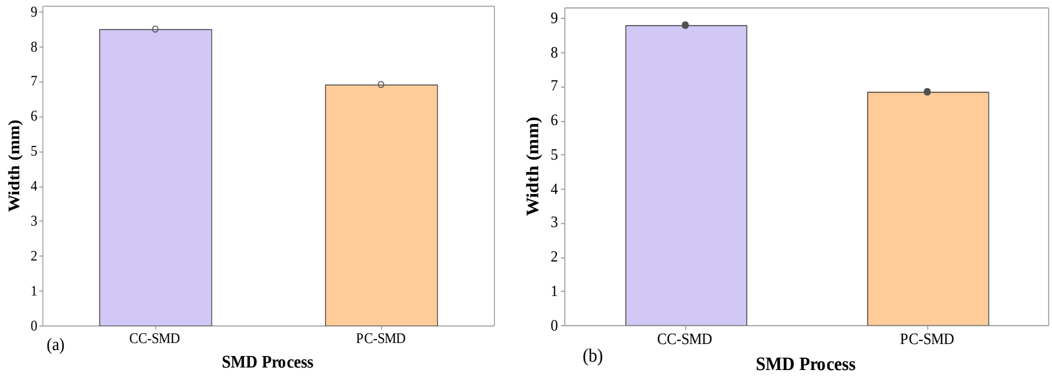

Figure 17. Comparison of sample width of CCSMD and PCSMD for (a) experiment I and (b) for experimentII.

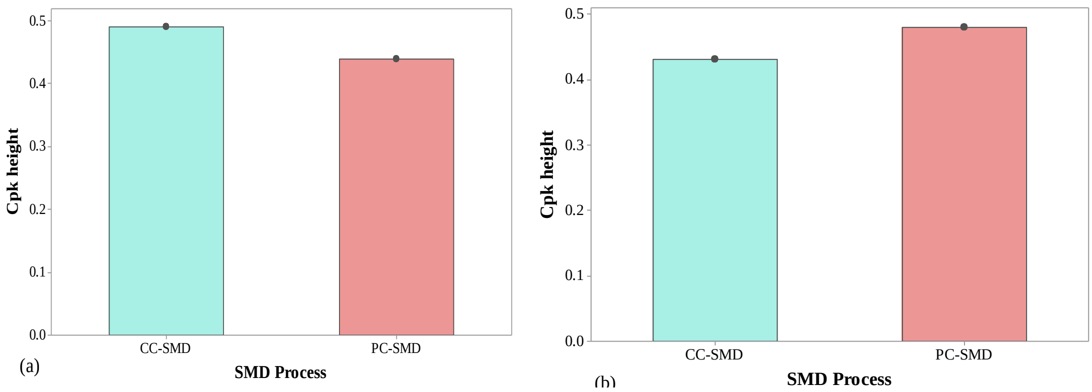

Figure 18. Comparison of Cpk of CCSMD and PCSMD of sample height for (a) experiment I and (b) for experiment II

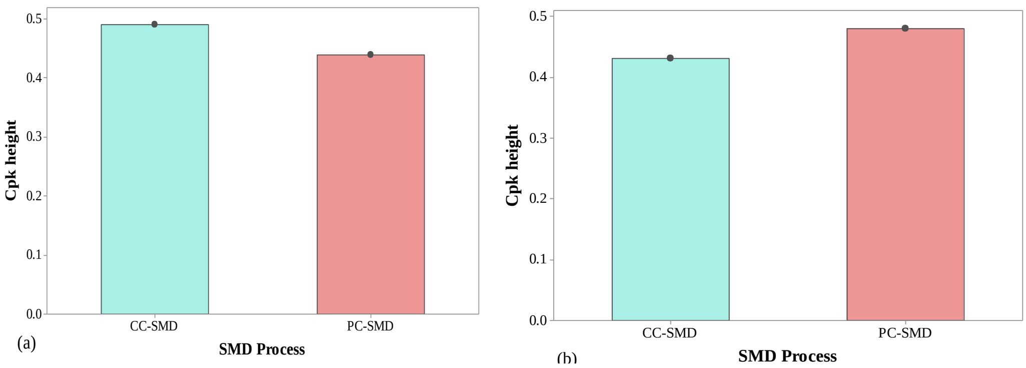

Figure 18. Comparison of Cpk of CCSMD and PCSMD of sample height for (a) experiment I and (b) for experiment II

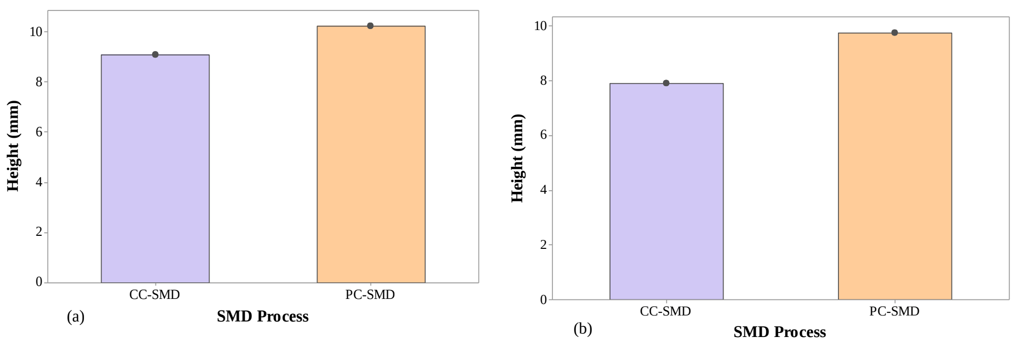

Figure 19. Comparison of sample height of CCSMD and PCSMD for (a) experiment I and (b) for experiment II.

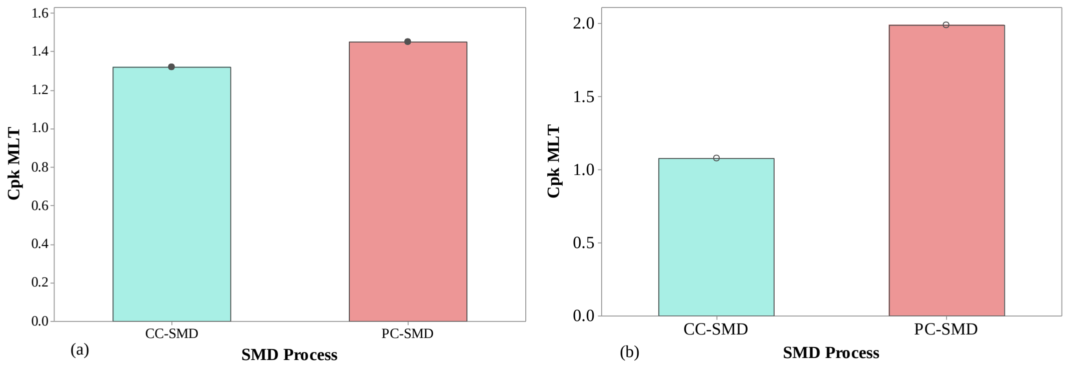

Figure20. Comparison of Cpk of CCSMD and PCSMD of the sample MLT for (a) experiment I and (b) for experiment II

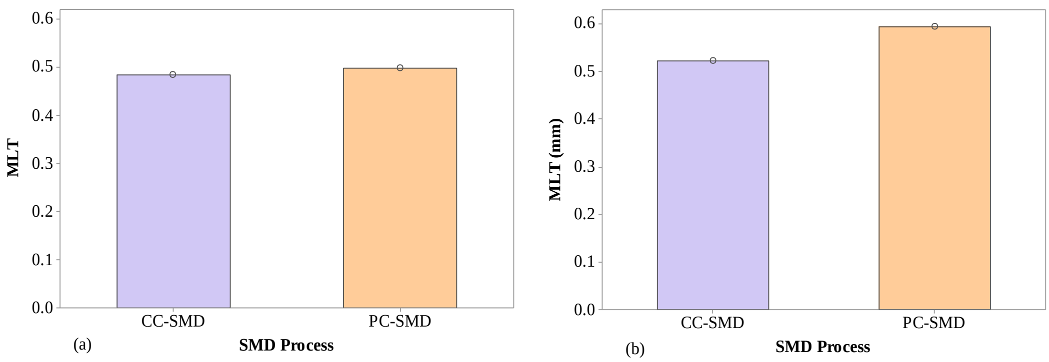

Figure 21. Comparison of sample MLT of CCSMD and PCSMD for (a) experiment I and (b) for experiment II.

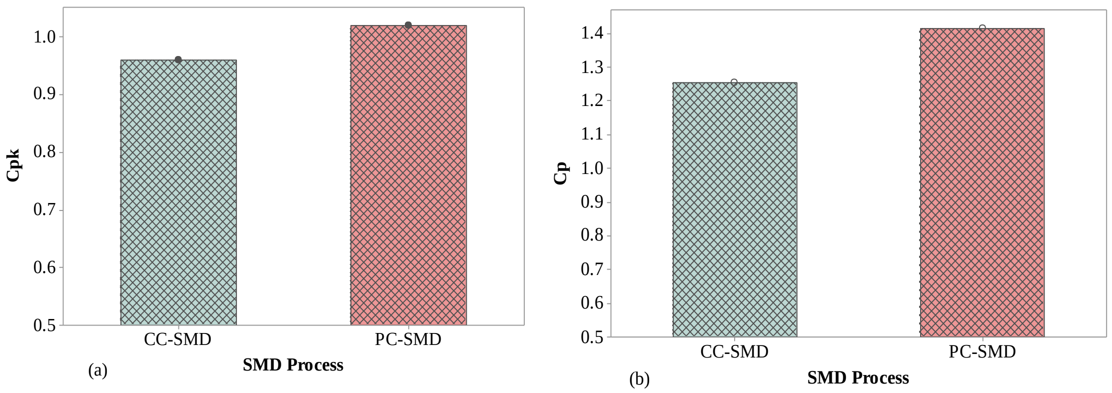

Figure 22. General comparison between CC-SMD and PC-SMD of (a) average of all the Cpk for the SMD process aspect, and (b) average of all the Cp for the SMD process aspect

Machined layer thickness

The results of the Cpk and MLT in the two experiments and for both CC-SMD and PC-SMD processes are shown in Fig. 20 and Fig.21 respectively. The PC-SMD process is more capable to meet the specifications of the MLT dimension and also produce higher MLT than in CC-SMD process

The overall Cpk and Cp values were achieved by averaging the Cpk and Cp values for all the geometries. The Fig. 22a presents the average of all the Cpk for the various geometries of the SMD processes. The PC-SMD manufacturing method has an average of 1.02 which is near to the goal since it is within the range (1 to 1.33) which means that the process is a barely capable process and must be closely monitored since this process has a spread just about

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equal to tolerances (specifications) limits [capab.1]. Cpk of the CC-SMD process is less than 1, which gives indicates that it is not capable process to produce the present product with current designed specifications.

The average of all the Cp for the various selected geometries is shown in Fig. 22b. It is obvious that both SMD processes have Cp more than 1. This means that the SMD manufacturing method is able to produce and control the fabricated part features since if Cpis greater than 1 then the process has the potential to meet specifications as long as the mean is centered. The CP-SMD manufacturing process has more capability than CC-SMD manufacturing process.

CONCLUSIONS

The present work concentrates on the comparison of two shaped metal deposition methods in terms of geometrical accuracy of the fabricated parts. A single strand straight metal wall sample was selected for investigating in order to give an in depth knowledge of the quality control and process capability of the manufactured parts using SMD methods. The manufacture of parts with features out of the specification limits leads to a huge amount of material to be removed to achieve the required dimensions within the designed tolerances. The most significant conclusions are summarized as follow:

1) The test samples produced from the CC-SMD method were with larger wall width than those of the PC-SMD method. CC-SMD process is more capable to meet the requirements of the product specifications than PC-SMD process.

2) The sample manufactured by PC-SMD process are generally more height than the CC-SMD process. Cpk results showed that the SMD process used in this study were not capable to meet the requirements of product tolerances of the wall height, which means that more effort should be done to correct the process capability through redesigning the specification limits to be more realistic.

3) The results showed that the PC-SMD method has more average Cpk than CC-SMD method. However, the set of parameters in experiment I produces wall with lower side wall machined layer less than that of experiment II especially for CC-SMD method. As a results the CC-SMD method is recommended for future usage sine it give more saving in the metal removal during further machining processes.

4) The Cpk analysis results showed that the parts produced by PC-SMD method are very close and consistent with the target specification comparing to the CC-SMD method.

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