

## CHAPTER 5

### **Multi-stage robot assisted Single point Incremental sheet hydroforming of Al alloy 6061 sheet**

#### **5.1 Introduction**

It was concluded from the work reported in the previous chapter that RAISHF is a more capable forming technique than RAISF, in terms of the quality of product formed and formability, at least holistically. In the current work, the multi stage robot assisted incremental sheet forming (MSISF) strategy was adopted in order to achieve larger wall angles.

Earlier researchers have used MSISF to attain steeper wall angles and better thickness distribution. Li et al. [144] used FEA analysis to analyze multi stage incremental sheet forming and found that more uniform thickness distribution can be obtained. Kumar et al. [130] performed multi stage ISHF for cone with high wall angles. Liu et al. [152] presented design strategies for multi stage ISF. Nirala et al. [153] used multi stage ISF and came up with a strategy to eliminate stepped features between intermediate stages during forming.

In the current work, two types of RAISHF have been done on AA6061; namely, single stage RAISHF and multi stage RAISHF. Thickness distribution along the length of the cone has been examined for the cones, formed by both single as well multi-stage RAISHF. Samples taken from the cones formed by single and multi-stage RAISHF have been examined for surface finish.

## 5.2 Experimental details for single and multi-stage RAISHF

Fixed wall angle conical frustum has been made by single stage RAISHF using strategy explained in Figure 2.4 and Figure 4.1. The maximum wall angle achieved is found to be  $64^\circ$ . The strategy for multi stage RAISHF is presented in Figure 5.1.

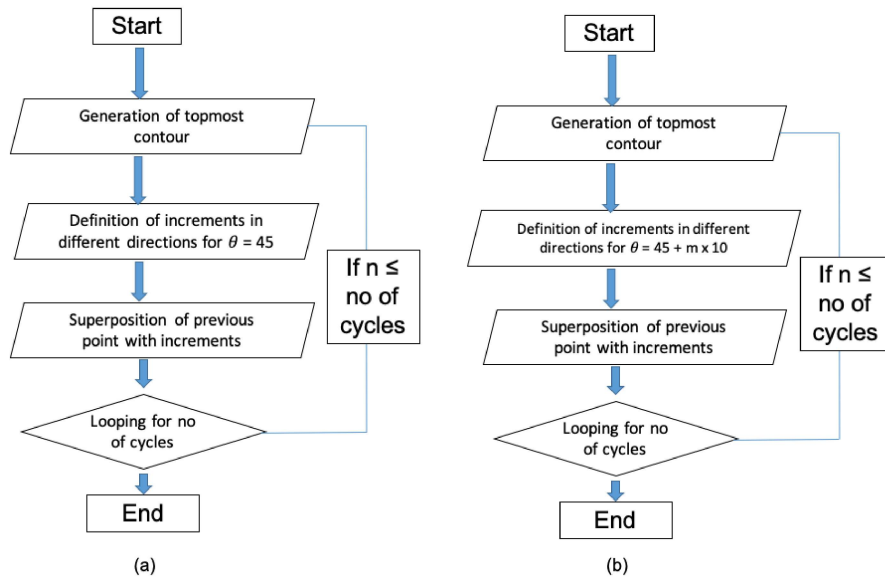


Figure 5.1: Strategy for multi stage RAISHF (a) 1<sup>st</sup> stage (b) n<sup>th</sup> stage


For multi stage RAISHF, the initial wall angle is  $45^\circ$  and has been increased by  $10^\circ$  for every subsequent stage. The parameters used are same as discussed in Chapter 4. The details of experimental parameters are given in Table 5.1.

Table 5.1: details of experimental parameters used for RAISHF

Parameters used	Optimized value
Type of tool used	Fixed ball tool
Tool Diameter	10 mm
Tool speed	74.75 mm/sec
Step depth	0.42 mm
Back hydraulic pressure	1.5 bar

The details of the specimens obtained from RAISHF are given in Table 5.2 and Figure 5.2(a). The maximum wall angle obtained from single stage RAISHF was found to be  $64^{\circ}$ . The experimental details of the sample made by single stage RAISHF are given in Table 5.2.

Table 5.2: Details of fixed wall angle Cone formed by single stage RAISHF

<b>Fixed wall angle Cone formed by single stage RAISHF</b>		
Tool used	Fixed ball tool	
Tool diameter	10 mm	
Initial circle radius	70 mm	
Constant Step size	$\Delta r = 0.21$ mm $\Delta z = 0.42$ mm	
Theoretical wall angle	$64^{\circ}$	
No of cycles run	161	
Anticipated depth	$161 * 0.42 = 67.62$ mm	
Actual depth reached	61.52 mm	
Spring back occurred	9.02 %	
No of stages performed	1	
Final status	Product Successfully formed	

Same wall angle cone was fabricated by multi stage RAISHF for comparison of output parameters. The experimental details of the sample made by multi stage RAISHF are given in Table 5.3.

Table 5.3: Details of fixed wall angle Cone formed by multi stage RAISHF

Fixed wall angle Cone formed by multistage RAISHF	
Tool used	Fixed ball tool
Tool diameter	10 mm
No of stages	2
Stage 1	
Initial circle radius	70 mm
Constant Step size	$\Delta r = 0.31$ mm $\Delta z = 0.42$ mm
Theoretical wall angle	$54^\circ$
No of cycles run	150
Anticipated depth	$150 * 0.42 = 63$ mm
Actual depth reached	57.75 mm
Spring back occurred	8.33 %
Final status	Product Successfully formed
Stage 2	
Constant Step size	$\Delta r = 0.21$ mm $\Delta z = 0.42$ mm
Theoretical wall angle	$64^\circ$
No of cycles run	150
Anticipated depth	$150 * 0.42 = 63$ mm
Actual depth reached	60.2 mm
Spring back occurred	4.44 %

Stepped marks



Final status	Product Successfully formed	
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Stepped marks are found to be left at the end of the formed cone as shown in Figure 5.2(b).

Proper forming strategy can be adopted to remove these stepped marks [153].



Varying wall angle stepped conical frustum (VWASCF) has been fabricated by increasing the wall angle initially by  $10^{\circ}$  for the first two stages and by  $5^{\circ}$  for the subsequent stages.

The experimental details of stepped cone fabricated by RAISHF are given in Table 3 and the detailed diagram of VWASCF is presented in diagram 5.2(e).

Table 5.4: Details of different stages for forming SCVWAF

VWASCF formed by Multistage RAISHF		
Tool used	Fixed ball tool	
Tool diameter	10 mm	
No of stages	2	
Stage 1		
Constant Step size	$\Delta r = 0.42 \text{ mm}$ $\Delta z = 0.42 \text{ mm}$	
Theoretical wall angle	$45^{\circ}$	
No of cycles run	180	
Anticipated depth	$180 * 0.42 = 75.6 \text{ mm}$	
Actual depth reached	70.3 mm	
Spring back occurred	7.01 %	
Stage 2		
Constant Step size	$\Delta r = 0.29 \text{ mm}$ $\Delta z = 0.42 \text{ mm}$	
Theoretical wall angle	$55^{\circ}$	



No of cycles run	160	
Anticipated depth	$150 * 0.42 = 63 \text{ mm}$	
Actual depth reached	63 mm	
Spring back occurred	6.25 %	
Stage 3		
Constant Step size	$\Delta r = 0.19 \text{ mm}$ $\Delta z = 0.42 \text{ mm}$	
Theoretical wall angle	$65^\circ$	
No of cycles run	70	
Anticipated depth	$120 * 0.42 = 50.4 \text{ mm}$	
Actual depth reached	47.8 mm	
Spring back occurred	5.15 %	
Stage 5		
Constant Step size	$\Delta r = 0.12 \text{ mm}$ $\Delta z = 0.42 \text{ mm}$	
Theoretical wall angle	$75^\circ$	
No of cycles run	60	
Anticipated depth	$60 * 0.42 = 25.2 \text{ mm}$	
Actual depth reached	24.3 mm	
Spring back occurred	3.57 %	

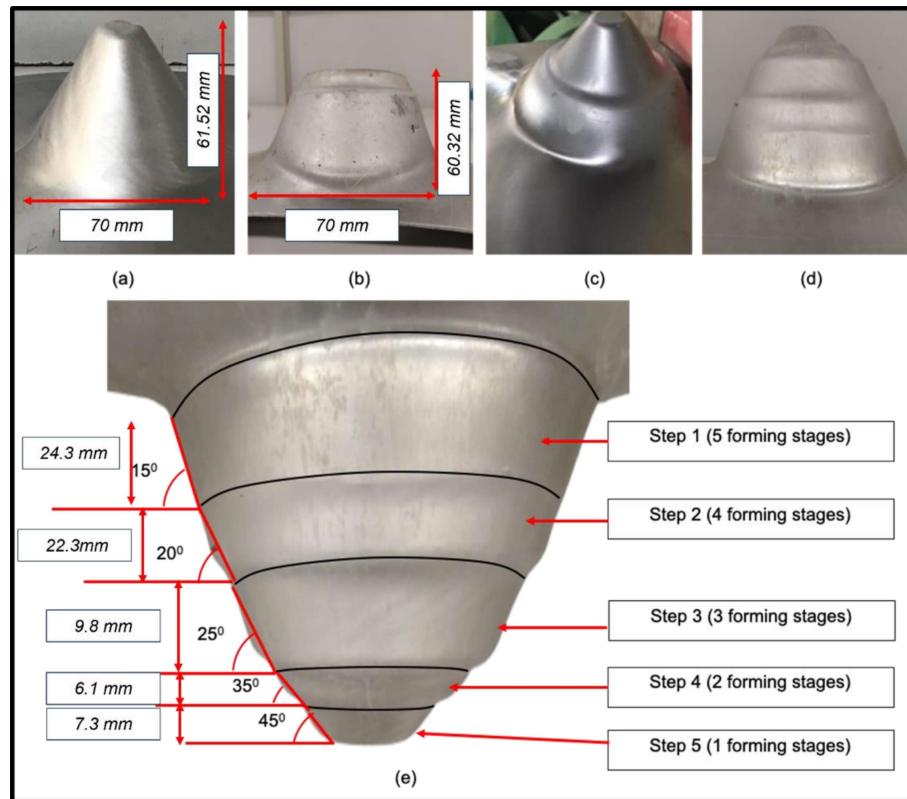


Figure 5.2: Different shapes made by RAISHF: (a) conical frustum made by single stage RAISHF, (b) conical frustum made by multi stage RAISHF, (c) conical frustum made by 3-stage RAISHF, (d) conical frustum made by 5- stage RAISHF, (e) SCVWAF made by multi-stage forming

This has been fabricated to examine the effect of no of stages in multistage RAISHF. As shown in Figure 5.2(e), the topmost section has undergone maximum no of forming stages (N). The section right below the topmost section has undergone (N-1) forming stages and so on.

### 5.2.1 Results and discussions

Once the samples had been made, they were tested for thickness distribution and surface finish which are discussed below.

Thickness distribution:

The thickness distribution of the sample made by single and multi-stage RAISHF has been examined. For this purpose, the cone has been cut meridionally using wire electric discharge machine and the length of the cone is divided in three regions.

**Region 1:** The region of upper undeformed blank and the region of deformation of initial contours of the wall.

**Region 2:** The middle region of the wall, where the sine law for thickness prediction is most accurate.

**Region 3:** The region of the lower undeformed region and the region of deformation of the last contours of the wall.

The plot of thickness distribution along the length of the cone formed by single stage and multistage RAISHF is shown in Figure 5.3(a) and 3(b) respectively.

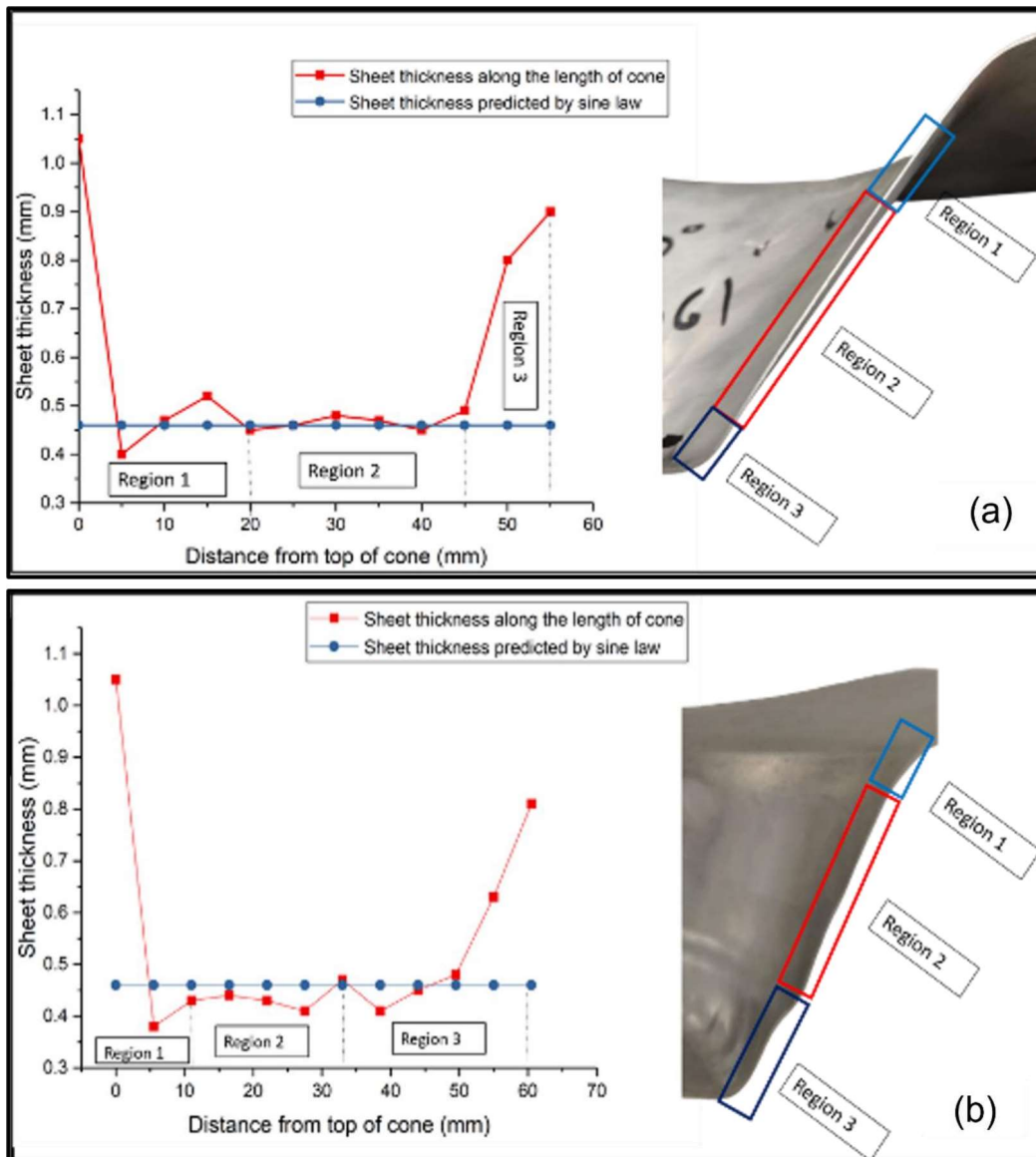


Figure 5.3: Thickness plot of the cone formed by Single stage RAISHF and representation of various regions along the length of cone.

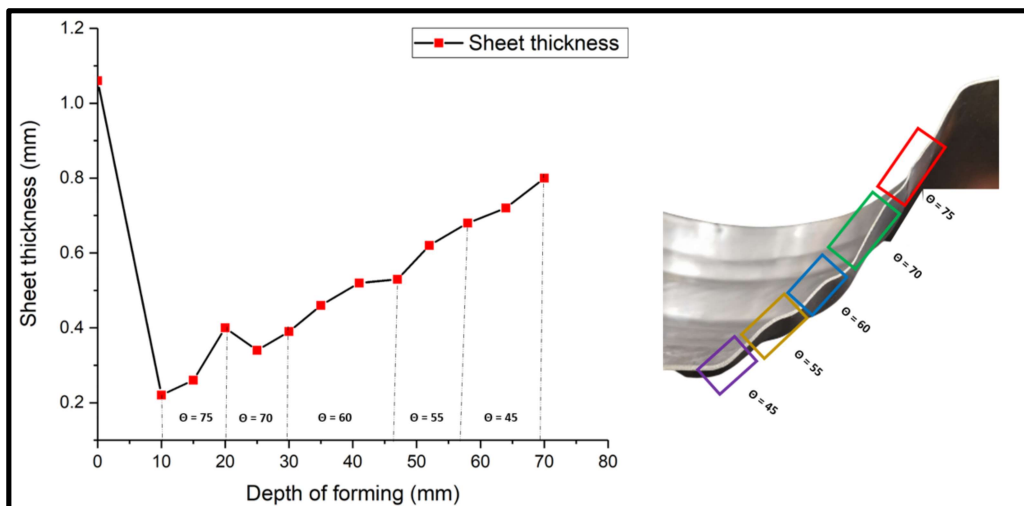
It may be observed from Figure 5.3(a) that for single stage RAISHF, excessive thinning happens in region 1. In region 2, the thickness was found to be uniform and can be approximated by sine law. Thickness again increases in region 3 due to the presence of undeformed sheet near the cone bottom. This trend is found to be in agreement with the trend obtained by Young and Jeswiet [139]. The minimum thickness is found in region 1

due to bending and stretching taking place in this region in the initial stage of forming. In region 2 the sheet thickness is found to be uniform due to shear mode of forming. In multi stage forming, the trend is almost similar; however, the sheet is found to be slightly thinner. The thickness values for both the cases are given in Table 5.5.

Table 5.5: Thickness values in single and multi-stage RAISHF

Forming method	Minimum thickness	Average thickness	Maximum deviation
Single stage RAISHF	0.4 mm	0.49 mm	24 %
Multistage RAISHF	0.38 mm	0.46 mm	16%

It may be observed from Table 5.5, that slightly more thinning is observed in case of multistage RAISHF; however, more uniform strain distribution is observed in case of multi stage RAISHF. Hence, multi-stage RAISHF can be helpful in getting steeper wall angle and additionally can be responsible for more uniform strain distribution. In order to investigate the effect of number of forming stages, the thickness distribution along the length of for VWASCF has been also examined and is given in Figure 5.4.



*Figure 5.4: Thickness distribution in regions of different wall angles in VWASCF*

It can be observed from Figure 5.4 that in the top region of the cone the sheet underwent maximum thinning, and hence the thickness in this region is minimum. This is because this region of VWASCF underwent maximum stages of forming. As the depth of cone increases, the wall angle decreases and hence sheet thickness naturally increases. It can be said that as the number of stages in multi-stage forming increases, the sheet thickness decreases. The limiting wall angle can be evaluated for thinning limits, depending upon the application in which the process is deployed.

### **5.2.2 Surface finish**

In order to compare single and multi-stage RAISHF, their surface qualities have been examined. For this purpose, three samples have been examined: (a) undeformed sample, (b) Sample taken from region 4 of cone formed by single Stage RAISHF (SS), (c) Sample taken from region 4 of cone formed by single Stage RAISHF (MS). The surface topography and surface roughness of these samples have been examined for surface characterization of the formed product. For surface topography, scanning probe microscope (SPM) has been used. Surface roughness of the samples has been measured by  $R_a$  and  $R_q$  values, which is captured by moving the stylus knob over the sample. This test has been carried out on the Mitutoyo Surftest SV-2100 machine. The sample length was 0.8 mm, the number of samples was 5, and the travel length was 8.8 mm. The topographic micrographs of 2D and three-dimensional 3D view of UD is presented in Figure 5.5.

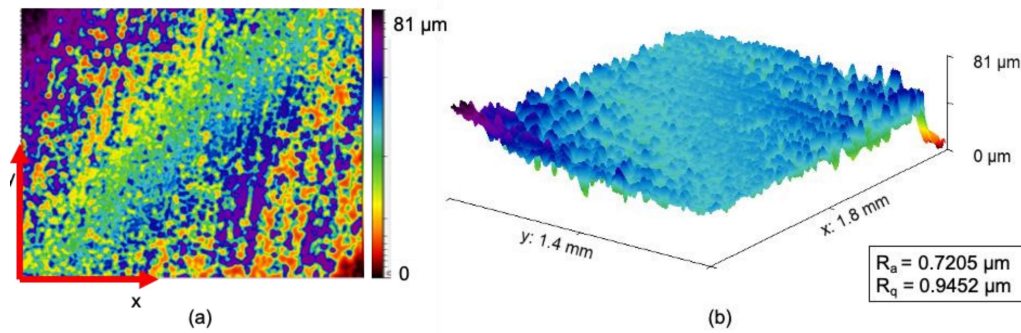


Figure 5.5: Topographic micrograph of undeformed sample in (a) 2D and (b) 3D.

Surface characterization of either surfaces of the samples formed by single and multi-stage RAISHF has been also carried out. The 2D and 3D topographical micrographs of different surfaces of samples are displayed in Figure 5.6(a) - (g). It can be observed from Figure 5.6 that forming can affect the surface quality of the formed product. The surface quality of the inner surface, which is in direct contact with the tool, gets deteriorated when the cone is formed.

It can be seen from the 3D surface micrograph of the inner surface (Figure 5.6(b)), that the surface quality is more uneven as compared to that of the undeformed sample. However, the surface quality improved significantly on performing multi stage RAISHF. As the surface after first stage of forming has waviness due to tool motion on it, in subsequent stages the tool motion suppressed this waviness accounting for better surface finish of the formed cone. The surface had very few non-uniformities, as seen in Figure 5.6(c). In terms of  $R_a$  value also, the surface roughness has significantly improved on performing multistage RAISHF. The  $R_a$  value in case of multi-stage RAISHF reduced to  $0.325\mu\text{m}$  from  $0.925\mu\text{m}$ ; thus, there is a significant improvement of 64.86% in surface quality of the formed product. So far outer surface is concerned, the surface quality in case of multistage RAISHF is found to be better, seen that  $R_a$  value reduced to  $1.192\mu\text{m}$  from  $1.751\mu\text{m}$ .

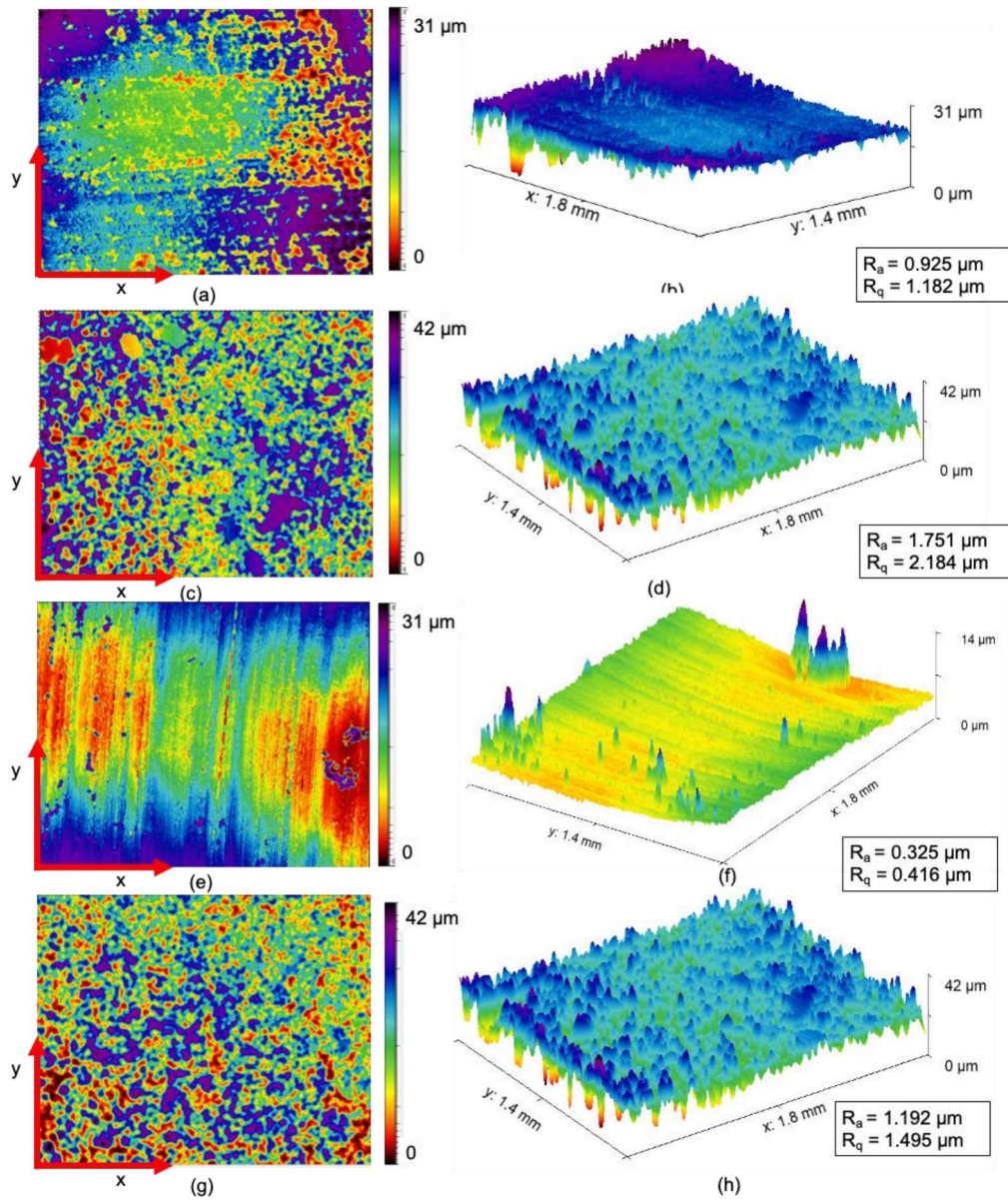


Figure 5.6: 2D and 3D micrographs of different surfaces: (a) 2D topographical micrograph of inner surface of single stage (SS), (b) 3D topographical micrograph of inner surface of SS, (c) 2D topographical micrograph of outer surface of SS, (d) 3D topographical micrograph of outer surface of SS, (e) 2D topographical micrograph of inner surface of multistage (MS), (f) 3D topographical micrograph of inner surface of MS, (g) 2D topographical micrograph of outer surface of MS, and (h) 3D topographical micrograph of outer surface of SS.

Surface quality of outer surface is also found to be superior in case of multistage RAISHF than that of single stage RAISHF. It can be said that better surface quality product can be obtained in multistage RAISHF than in single stage RAISHF. It has been also confirmed by measuring the surface waviness of the three samples. It has been observed that the surface formed after single stage RAISHF had high waviness, which can be due to combined bending and stretching occurring during the forming operation. However, the surface finish became better after subsequent stages. The measure of waviness is given in Figure 5.7.

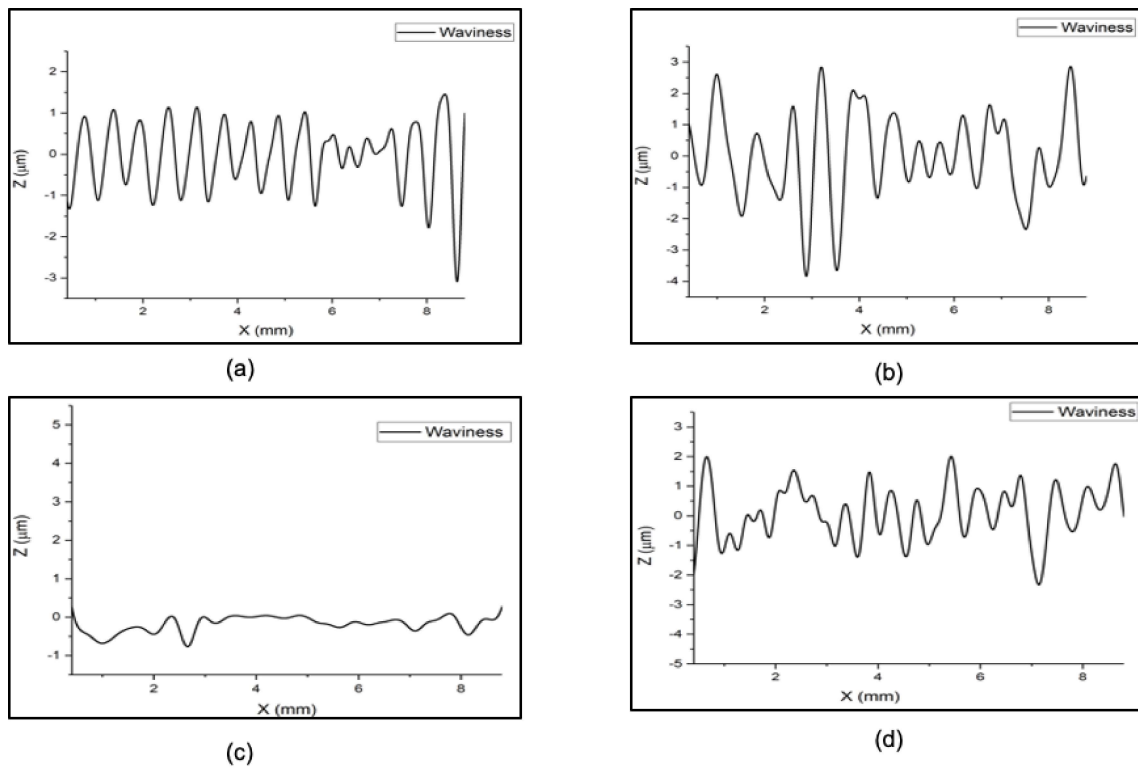


Figure 5.7: waviness plot of different surfaces: (a) inner surface of SS, (b) outer surface of SS, (c) inner surface of MS, and (d) outer surface of MS.

It may be observed from Figure 5.7 that waviness of the surface formed by multi stage RAISHF has significantly reduced waviness as compared to that formed by single stage RAISHF. The inner surface of cone formed by RAISHF has least waviness. The valley

height of the multi stage RAISHF formed surface varied between  $-0.73\mu\text{m}$  to  $0.26\mu\text{m}$ , whereas for the single stage RAISHF, it varied from  $3.07\mu\text{m}$  to  $1.46\mu\text{m}$ . The outer surface of the cone formed by both the processes has more surface atrocities in form of waviness than the inner surface. However, out of the two outer surfaces, the cone formed by multi stage RAISHF has less waviness as can be seen from Figure 5.7(b) and 7(d).

Thus, it can be concluded that performing multi stage RAISHF can improve surface quality significantly. It does not only ensure less surface roughness than single stage RAISHF, but waviness is also be significantly reduced which is a major problem in incremental sheet forming.

In order to further examine the effect of multi stage forming on surface quality of the formed product, the surface finish and topographical micrograph of different regions of VWASCF has been studied. Samples have been taken from regions of different wall angles in VWASCF and surface finish test has been carried out. The 2D and 3D topographic micrographs are shown in Figure 5.8.

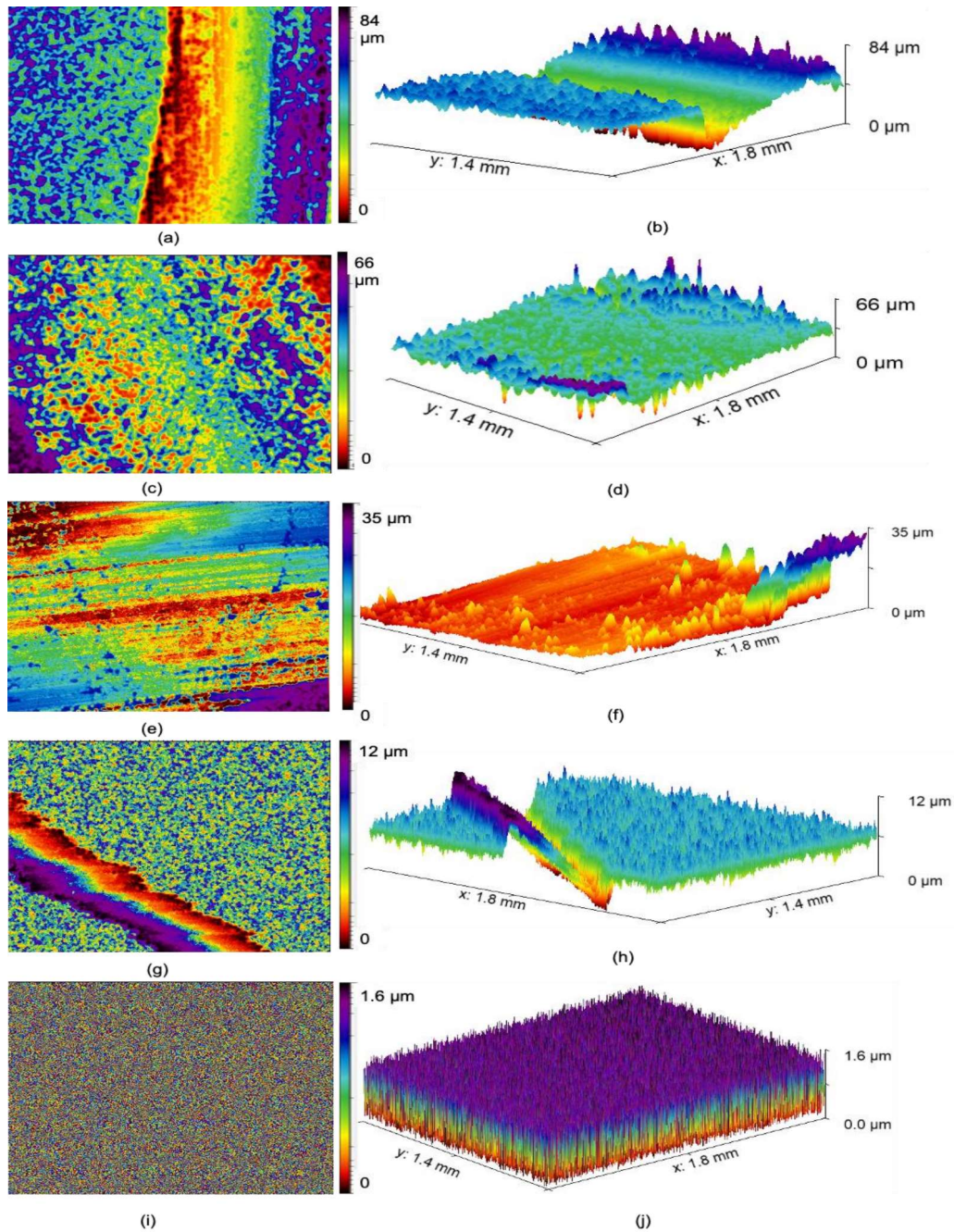


Figure 5.8: Topographic micrographs of various regions of VWASCF: (a) 2D topography of  $45^{\circ}$  cone, (b) 3D topography of  $45^{\circ}$  cone, (c) 2D topography of  $55^{\circ}$  cone, (d) 3D topography of  $55^{\circ}$  cone, (e) 2D topography of  $65^{\circ}$  cone, (f) 3D topography of  $55^{\circ}$  cone, (g) 2D topography of  $70^{\circ}$  cone, (h) 3D topography of  $70^{\circ}$  cone, (i) 2D topography of  $75^{\circ}$  cone, and (j) 3D topography of  $75^{\circ}$  cone.

It is quite evident from Figure 8(a) – 8(j) that valley height decreased continuously on increasing wall angles, and thus increasing number of steps. It is evident that surface became more homogeneous as the cone was formed in more RAISHF stages. To confirm the same, surface finish test has been carried out. The graph of average roughness in terms of  $R_a$  value with number of forming stages is shown in Figure 5.9.

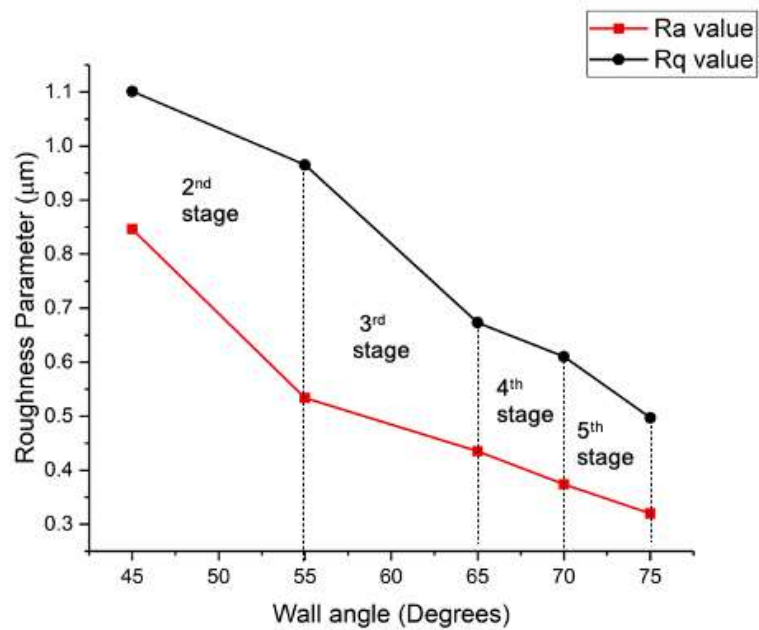


Figure 5.9: Variation of  $R_a$  and  $R_q$  value in regions of different wall angles in VWASCF.

It is quite evident from Figure 5.9 that both  $R_a$  and  $R_q$  values decreased with increasing number of forming stages, and hence the formed surface became better with increasing number of forming stages. After 2<sup>nd</sup> forming stage, the  $R_a$  value decreased almost linearly from  $0.534\mu\text{m}$  to  $0.32\mu\text{m}$  as the wall angle increased from  $55^\circ$  after 2<sup>nd</sup> stage, to  $75^\circ$  after 5<sup>th</sup> stage.

It can be concluded that surface finish of the product formed by multi stage RAISHF is significantly better than that formed by single stage RAISHF. It is recommended that the

product should be formed in a double stage manner in RAISHF, as it can lead to suppression of waviness which appears in single stage RAISHF.

### 5.3 Conclusions

In the current work, a comparison has been made between single and multi-stage RAISHF in terms of formability, thickness distribution and surface finish of the formed product. In addition to this, a sample named VWASCF has been proposed to study the effect of the number of forming stages in RAISHF. Following conclusions are drawn based on experiments and analysis.

- (1) Multi-stage RAISHF can be helpful in getting steeper wall angle and additionally can ensure more uniform strain distribution than that observed in single stage RAISHF. The maximum deviation from average thickness went down to 16% in multi stage RAISHF to 24% in single stage RAISHF.
- (2) A significant increase in the surface quality of both sides of the formed cone has been observed in multi stage RAISHF than in single stage RAISHF. It has been further observed that inner side of the cone formed by multi stage RAISHF had 64.86% better surface finish than that formed by the single stage RAISHF.
- (3) The waviness of the formed surface can be significantly reduced by performing multi stage RAISHF.
- (4) As the number of forming stage increased to form VWASCF, the surface finish became better and a linear decrease from  $0.534\mu\text{m}$  to  $0.32\mu\text{m}$  has been recorded as wall angle varied from  $55^\circ$  after 2<sup>nd</sup> stage to  $75^\circ$  after 5<sup>th</sup> stage.