Chapter 6
Conclusions

6.1 INTRODUCTION

In the present industrial scenario, every process is optimized for optimal process parameters and optimal performances. In this work, the process parameters of single point incremental sheet metal forming of AA5052, AA6061 and AA8011 alloy sheets were optimized to achieve optimal performances. The optimal value of process parameters namely thickness of the sheet metal, type of tool, diameter of the tool, sheet thickness, vertical step down, feed rate, speed and lubricant which were optimized using multi-objective optimization technique are summarized and presented for three different AA sheets considered for the study. These parameters have been achieved in order to get the maximum formability in terms of total sum of strain and minimum surface roughness. The effects of these input parameters on the performance measures are also summarized here. The user can use these optimum parameters and get the maximum benefits.

6.2 CONCLUSIONS ON GROOVE TEST

In this chapter, the conclusions derived from the various studies carried out are presented. Based on the experiments, the multi objective optimization of the SPIF process parameters using TM based GRA coupled with PCA was carried out for AA5052, AA6061 and AA8011 sheet metals and ANOVA was also carried out. The results are presented in the following table:

Table 6.1. Consolidated experimental results of multi objective optimization

<table>
<thead>
<tr>
<th>Optimized parameters</th>
<th>AA5052 sheets</th>
<th>AA6061 sheets</th>
<th>AA8011 sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2, B3, C3, D2, E2, F2 and G2</td>
<td>A2, B2, C3, D1, E2, F2 and G3</td>
<td>A2, B1, C3, D2, E2, F2 and G3</td>
<td></td>
</tr>
<tr>
<td>lubricant, tool diameter and tool type</td>
<td>lubricant, vertical step-down, feed rate, tool diameter, spindle speed and sheet thickness</td>
<td>lubricant, feed rate, tool diameter and spindle speed, sheet thickness and tool end type</td>
<td></td>
</tr>
</tbody>
</table>

Order of (most)Influencing parameters
<table>
<thead>
<tr>
<th>Order of non (least) Influencing parameters</th>
<th>vertical step down, feed rate, spindle speed and thickness</th>
<th>tool end type</th>
<th>the vertical step down</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Improvement at RD, TD and DD</td>
<td>Sum of strain</td>
<td>74.79%, 49.71% and 44.62%</td>
<td>14.45%, 17.61% and 9.97%</td>
</tr>
<tr>
<td></td>
<td>Surface roughness</td>
<td>92.41%, 93.99% and 94.65%</td>
<td>90.15%, 89.88% and 79.88%</td>
</tr>
</tbody>
</table>

The main effect plots were plotted using MINITAB and the effect of the each process parameter on the each performance measure have been studied and summarized as follows.

6.2.1 EFFECT OF TOOL TYPE
- In the case of AA5052, AA6061 and AA8011 alloy sheets sheets, The H type tool produces higher formability for all the directions namely rolling, transverse, and angular. The B- type tool produces less formability due to momentary sticking.
- The average surface roughness is less when B- type tool is used for all the directions. The surface roughness of tool end used as positive effects on the surface of the work material.

6.2.2 EFFECT OF SHEET THICKNESS
- In the case of AA5052, AA6061, as the sheet thickness increases, the sum of strain value increases. However, the sum of strain increases at lower rate in the case of AA5052 and higher in case of AA6061.
- In the case of AA8011, with lesser sheet thickness, increase in sheet thickness decreases the sum of strain values due to lower strength, lower strain hardening index value and effect of bending. At higher sheet thickness, the sum of strain value increases as in the conventional sheet metal forming.
- As the sheet thickness increases from 0.8 mm to 1mm the surface roughness increases in the case of AA5052 and AA8011 alloy sheets and the roughness value decreases when sheet thickness is increased from 1 to 1.2 mm due to the coefficient of friction between the sheet and forming tool. In the case of AA6061 alloy the trend is different due to its high strength and early failure.
6.2.3 EFFECT OF FEED RATE

- Increasing feed increases the sum of strain in the case of AA5052 and AA8011 due to low strength and low strain hardening index. The trend is reverse for AA6061 because of its high strength and high strain hardening index value.
- High feed resulted lower surface roughness value because the higher feed rate overcomes the original roughness of the sheet and reduces coefficient of friction.

6.2.4 EFFECT OF VERTICAL STEP DOWN

- In AA5052 alloy sheet, the effect of vertical step down on the sum of strain is less and at higher vertical step down the sum of strain value is less.
- Due to very less strain hardening and more spring back, the sum of strain is low when the vertical step down is less and it increases up to a critical value of vertical step down. After that the severity of forming increases and the sum of strain value decreases.
- As the vertical step down increases, squeezing effect increases on the soft materials AA5052 & AA8011 and the surface roughness value decreases. On contrast, the trend is reverse in case of AA6061 alloy sheets due to its high strength and high strain hardening index value.

6.2.5 EFFECT OF TOOL DIAMETER

- The tool diameter 10 mm produces high sum of strain because of optimum area of contact that avoids crack along groove compared to more pointed contact as in 8 mm tool and more area of contact as in 12 mm tool for AA5052 alloy sheets.
- In the case of greater strength AA6061 alloy sheets, even the tool having largest diameter 12 mm is not producing detrimental effect on the formability.
- Due to its low strength and low strain hardening exponent value, in the AA8011 alloys sheets, the largest diameter tool 12 mm produces highest formability.
- In all sheets considered, the surface roughness is low for 10 mm tool having optimum blunt radius.
6.2.6 EFFECT OF SPEED

- In case of AA5052 alloy, as the speed increases the formability decreases due to the high dynamic friction. In other two sheet metals, the trend is reverse.
- As the speed increases, initially the surface roughness is reduced and after critical value of speed the roughness is increased due to the more momentary sticking the higher speeds.

6.2.7 EFFECT OF LUBRICANT

- For aluminium AA5052 and AA8011, the forming force is less and the best lubricant is coconut oil as it has the ability to make optimum film of lubricant between tool and work material under less forming load. In case of AA6061, since the forming force required is higher, only grease can be best lubricant to maintain a thin layer of lubricant between the tool and work material.

6.3 CONCLUSION ON FORMABILITY

In incremental forming of sheet metal, plane strain condition and biaxial tension strain conditions are present. Under these conditions, the formability and surface roughness of the sheets are varied. The formability and surface roughness measured under these strain conditions for the sheets considered for the study are summarized here. Another measure of formability, the limiting wall angle, beyond which the sheet metals cannot be formed successfully by incremental forming also found for each sheet metal considered and concluded here. The conclusion on fractography result which gives idea and history about forming and fracture is also presented here.

6.3.1 CONCLUSIONS ON FORMABILITY IN PLANE STRAIN CONDITION

- All the sheet metals considered for the study possess a higher formability compared to conventional die and punch forming under favourable operating conditions, in plane strain region.
- The AA5052 alloy sheet with 0.8, 1.0 and 1.2 mm thickness exhibit a maximum limiting strain of 1.784, 1.430 and 1.566 respectively which are 12 to 15 times greater than for the sheets having equivalent strain hardening exponent values and formed by the conventional sheet forming.
• The AA6061 alloy sheets with 0.8, 1.0 and 1.2 mm thickness exhibit a maximum limiting strain of 1.175, 1.037 and 0.973 respectively which are 7 to 10 times greater than for the sheets having equivalent strain hardening exponent values and formed by the conventional sheet forming.

• The AA8011 alloy with 0.8, 1 and 1.2 mm thickness exhibits the maximum limiting strain of 1.316, 1.147 and 1.364 respectively which are very high comparing to the conventional sheet forming. These limiting strains in incremental forming under plane strain condition are roughly 11 to 17 times greater than that in conventional forming.

6.3.2 CONCLUSIONS ON FORMABILITY IN BIAXIAL TENSION STRAIN CONDITION

• All the sheet metals considered for the study possess a fairly higher formability compared to conventional die and punch forming under favourable operating conditions, in biaxial tension strain region also.

• The AA5052 with 0.8, 1.0 and 1.2 mm thicknesses exhibit a maximum limiting sum of strain of 0.1354, 0.98 and 1.08 respectively which are 5 to 7 times greater than that in conventional die and punch forming.

• The AA6061 with 0.8, 1.0 and 1.2 mm thicknesses exhibit a maximum limiting sum of strain of 0.66, 0.64 and 0.58 respectively which are 2.6 to 4 times greater than that in conventional die and punch forming.

• The AA8011 alloy sheet with 0.8, 1 and 1.2 mm thickness possesses a limiting major true strain values of 0.9, 0.68 and 0.82 which is 4.4 to 6.9 times higher than that of the conventional sheet forming.

6.4 CONCLUSIONS ON LIMITING WALL ANGLE

• The maximum wall angle that can be formed is decreasing with the increasing thickness of the sheet.

• For AA5052 alloy sheets having 0.8, 1.0 and 1.2 mm thicknesses, the wall angles are 74°38’35", 74°18’33" and 72°33’35” respectively.

• For AA6061 alloy sheets having 0.8, 1.0 and 1.2 mm thicknesses, the wall angles are 55°50’47", 53°35’40" and 47°53’59" respectively.
• For AA8011 alloy sheets having 0.8, 1.0 and 1.2 mm thicknesses, the wall angles are 73°32'57", 72°48'43" and 70°35'43" respectively.

6.5 CONCLUSIONS ON SHEET METAL CHEMICAL COMPOSITION, MICROSTRUCTURE AND TENSILE PROPERTIES.

The qualities of the sheet metals that affect the formability and surface roughness in incremental forming are the chemical composition of the sheet metal, the original microstructure and the original tensile properties namely strain hardening index and yield strength. The constituents that are formed from the chemical composition, in the material are seen in the microstructure. Apart from these constituents, the grain size is measured from microstructure. These results and results from standard tensile test for sheet metals and their effects on the formability and surface roughness are summarized here.

6.5.1 CONCLUSIONS ON CHEMICAL COMPOSITION

The following were concluded from the chemical composition, microstructure, tensile properties, fractography and surface texture for the sheet metals considered for this study.

• In AA5052, the presence of Mg, Fe and Si increases the strength and formability of AA5052 sheet without unduly decreasing the ductility. In Al-Mg-Si AA6061 Magnesium is followed by Silicon to increases the strength and ductility of the alloy. In Al–Fe–Si based AA 8011, more than 1 wt% total alloying element present to give correspondingly higher strengths. The properties are due to the fine grain size stabilized by the finely dispersed iron-rich second phase.

6.5.1.1 MICROSTRUCTURES OF SHEETS WITH THICKNESS 1.2 mm

• The microstructures of i) AA5052 ii) AA6061 and AA8011 sheets taken for the consideration show i) cold worked and elongated grains ii) cold worked and slightly elongated grains and iii) cold worked and slightly elongated grains respectively without any amount of recrystallization.
The microstructure of AA5052, evident less reduction, larger grain size, favourable grain orientation and less amount of intermetallics which lead to a good formability.

The microstructure of AA6061 shows evenly distributed congruent phase, Mg$_2$Si and evident less reduction, smaller grain size, and favourable grain orientation which lead to a moderate formability.

The microstructure of AA8011 shows evenly distributed intermetallics namely CaAl$_4$ and CaSi$_2$ evident smaller grain size, favourable grain orientation and randomly oriented intermetallics CaAl$_4$ and CaSi$_2$ lead to a moderate formability.

6.5.1.2 MICROSTRUCTURES OF SHEETS WITH THICKNESS 1.0 mm

- The microstructure of AA5052 alloy sheet shows medium reduction, medium sized grains, favourable grain orientation and fewer amounts of intermetallics lead to a moderate formability.
- The microstructure of AA6061 alloy shows cold worked and elongated grains slightly larger grains to medium sized grains, favourable grain orientation and congruent phase, Mg$_2$Si, lead to a good formability.
- The microstructure of AA8011 alloy sheet shows segregated intermetallics namely CaAl$_4$ and CaSi$_2$ and larger grains to medium sized grains and segregated intermetallics, lead to a good formability.

6.5.1.3 MICROSTRUCTURES OF SHEETS WITH THICKNESS 0.8 mm

- The microstructure of AA5052 alloy sheets show fewer amounts of intermetallics and even though there is highest reduction and small sized grains, the highly favourable grain orientation which lead to a highest formability.
- The microstructure of AA6061 alloy sheet shows segregated congruent phase, Mg$_2$Si. This sheet gives good formability in straight groove test due to segregated congruent phase, Mg$_2$Si.
- The microstructure of AA8011 alloy sheet more elongated than the other two sheets. Though there is highest reduction and the unfavourable grain orientation, this sheet gives good formability in straight groove test due to
larger grain size and evenly distributed intermetallics $\text{CaAl}_4$ and $\text{CaSi}_2$ of smaller size.

6.5.2 CONCLUSIONS ON TENSILE PROPERTIES

- The formability of the sheet metal in incremental forming is proportional to the average strain hardening exponent value of the sheet metal.
- The AA5052 with thickness 0.8, 1.0 and 1.2 mm are having a highest average strain hardening exponent value 0.1354, 0.08945 and 0.1243 respectively and they possess a sum of strain value of highest, low and higher respectively.
- The AA6061 with thickness 1.2, 1.0 and 0.8 mm have an average strain hardening exponent value of 0.1472, 0.12369, and 0.1122 and therefore they possess highest, higher and lowest sum of strain values respectively.
- The AA8011 with thickness 1.0, 0.8 and 1.2 mm thickness is showing an average strain hardening exponent value of 0.1022 with the highest sum of strain values, 0.0817 with higher sum of strain values & 0.0815 with the lowest sum of strain values respectively.

6.5.3 CONCLUSIONS ON FRACTOGRAPHY

- The SEM images of the fractured surface of AA5052 alloy sheet show the evidences for large plastic deformation for the sheets formed under optimum and near optimum process parameters. The elongated shear dimples and voids shown are the proof for plastic deformation. The SEM images show transcrysalline fracture, the crack crossed cleavages and widely spaced shallow dimples and voids when the sheets are formed with worst operating conditions with dry lubrications.
- AA6061 sheet formed under favourable conditions and with proper grease lubrication, show combination of voids, microvoids, dimples and little amount of serrations which is the indication of ductile mode of fracture. The SEM images of the fractured surface when the sheet is formed under unfavourable conditions with dry lubrication, show dimples with voids with trans-crysalline serrations and micro voids. The sharp edges or ends of the brittle particles are possible crack initiation sites.
- The sheet AA8011 formed under favourable conditions and with proper lubrication, show dimples, good amount of shear fracture with little cleavages.
Under favourable conditions, there is evidence for large plastic deformation in the form of elongated shear dimples and bigger size voids which represents the void growth coalescence upto fracture is comparatively large. Under unfavourable conditions with dry lubrication, the SEM images show smooth surface with widely spaced shear dimples but in less number.

6.5.4 CONCLUSIONS ON TEXTURE

- The pole figure for AA5052 alloy sheet with 0.8 mm thickness shows a more random structure than the other two. Therefore its formability is higher as 1.784, compared to the other two sheets.
- The pole figure for AA6061 alloy sheet with 0.8 mm thickness shows a more random structure than the other two thicknesses. Therefore, its formability is higher as 1.175 compared to the other two sheets.
- The pole figure for AA8011 alloy sheet with 1.2 mm thickness shows a more random structure than the other two and this possesses a higher formability as 1.364.

6.5.5 CONCLUSIONS ON SURFACE ROUGHNESS

- For all the sheets considered, the surface roughness is higher when the hemispherical end type tool is used when compared to the ball end type tool.

6.6 RECOMMENDATIONS AND SCOPE FOR FUTURE WORKS

The present dissertation research works constitute a multi objective optimization of SPIF on AA5052, AA6061 and AA8011. Its potential benefits are ensured by its enhanced formability, fractography and wall angle test. Some of the recommendations for future works are listed below:

- Productivity of incremental sheet metal forming can be increased by designing multi point forming tool and its formability can be studied
- The incremental forming can be employed for metal matrix composite material and portability of same can be analyzed
- Process modeling through ANN can be employed for the present work
- This study can be extended to perforated sheets
- Forming angle about 90° through SPIF can be studied