Chapter 2

Literature Review

2.1. INTRODUCTION

The first chapter explains the basics of sheet metal forming; draw backs in sheet metal forming, the need of an alternative process like incremental forming, basics of incremental sheet metal forming and its types. Before defining the exact problem statement for this research work, it is necessary to survey the works that have been already carried out in the area related to the incremental sheet metal forming. In incremental sheet metal forming, there are two important varieties namely single point incremental sheet forming and two point incremental sheets forming. Therefore, in this chapter, the literatures available in these topics are detailed. Apart from the above said fundamental types, there are more to analyse on ISF like the effect of the forming tool used and the tool path etc., on the incremental sheet forming.

The prime draw back in conventional sheet metal forming is very minimum limit of forming due to the effect of high strain and strain hardening. To prove that the forming limit is high in incremental sheet forming and to study by what percentage the limiting is higher than that in conventional forming; the literatures are presented in this chapter. Many of the researchers studied the effect of parameters on incremental forming. Also the literatures related to simulation and optimization to predict the forming limit in incremental sheet forming is presented here.

2.2 SINGLE POINT INCREMENTAL SHEET FORMING

Dai et al. (2000) reported about the axially symmetrical forming of SPIF was examined theoretically and experimentally and the technique to attain more even metal flow deformation was discussed. The authors proved that point by point movement of tool can control flowing of metal and different strain distribution can be produced by different forming locus. By loading the low stiffness and low deformation area first and decrease the time of loading on the boundary area where the splitting occurs easily can be optimized the forming locus.
Schafer and Schraft (2005) introduced a new incremental sheet metal-forming process by moving a hammering tool over a sheet metal using industrial robot. At the time of research it was revealed that complex geometries can be produced without any die plate. In addition, a special tool path was generated for the incremental forming process and several robot tools with different drives build up for the incremental forming process.

Ambrogio et al. (2005) presented a novel technique (ie SPIF) to produce a customized ankle support. In this paper, a highly-customized ankle support was manufactured with a measured difference, from the designed surface of lower than 1 mm. This study explained its simple integration with other reverse engineering techniques and its high flexibility in single point of incremental forming, allowed to produce a medical device in an easy, quick and efficient way.

Ji and Park (2008) attempted about the feasibility of incremental forming technique to magnesium alloys at warm temperature. Finite element method also carried out to realize the deformation characteristics. Hemispherical ended tool was used to form incrementally using CNC machines. The sheet formability were analysed by plane-strain and by axi-symmetric stretching tests at 200°C, 1000°C, 1500°C, 2000°C and 2500°C temperatures. It was found that increase in temperature increases the formability. The results show that forming limit curve for different temperatures is more or less straight line and parallel to one another. The authors reported that for a higher inclination angle circular cup which exceeds the forming limit can be formed by progressive forming concept of the incremental forming.

Hussain et al. (2008) made a experimental study in order to examine the appropriate tool and lubricant, which can be used to form a commercially pure titanium sheet (CP Ti) by the method of negative incremental forming. By measuring surface roughness and investigating through the scanning electron microscope (SEM) the effect of each combination of tool and lubricant was reported. The HSS tool with surface-hardened was found to be appropriate to form the commercially pure titanium sheet by negative incremental forming. The paste of molybdenum disulphide powder and white petroleum jelly mixed which was used as lubricant gives appropriate
surface quality. Small diameter to pitch ratio should be preferred to avoid sticking of the titanium sheet metal to the forming tool.

Franzen et al. (2009) reported that the possibility of employing the single point incremental forming technology for commercial PVC sheets and formability limits were evaluated for this process as function of major operating parameters. The authors conducted this test under normal room temperature with 2mm, 3mm as sheet thickness and the tool diameters about 10 mm and 15 mm with above said two process parameter the formability of the sheets were investigated. Thinner sheet sizes are more sensitive to wrinkles and twisting of the sheet al.ong the tool path direction and lead to failure due to thinning. Observed Results explain that SPIF is competent process of producing successful and high depth parts of commercially PVC sheets at room temperature.

Emmens et al. (2009) explained how in incremental sheet forming (ISF) strains can be attained well above the forming limit curve (FLC) with enhanced formability that is appropriate to common sheet forming methods like deep drawing and stretching. The distinction between fracture limit and necking limit in sheet metal forming was discussed. The necking limit represents a localized geometrical instability. Localized deformation is an essential characteristic of ISF and proposed mechanisms should stabilize the localization before it leads to fracture. There were six mechanisms mentioned in relation to ISF: contact stress, bending under tension, shear, cyclic straining, geometrical inability to grow and hydrostatic stress. Among those, contact stress, bending-under-tension, shear were able to localize deformation and all but the last, are found to be able to postpone unstable growth of a neck. Hydrostatic pressure may lead to the final failure, but cannot give details about stability above the FLC.

Petek et al. (2009) developed online system to identify the fracture of the material at the time of incremental forming. The proposed online system was is based on investigation of the shape of the forming force time series using skewness and statistical predictors and also verified with many tests using different work material, shapes, thicknesses and various process parameters. It was concluded that it was the quick and reliable fracture identification and localization.
Zhang et al. (2010) reported about the lubrication and their methods of applying in warm negative incremental forming for AZ31 sheet. For this study AZ sheet material of 0.8 mm thickness was used. Tool material of HSS, hemispherical ended tool head with 6mm diameter, vertical step down of 0.2 mm/revolution, feed rate of 2000 mm/min, forming angle of 55°, and sheet temperature 200°C was used. For lubrication purpose five different lubricants and three different methods to apply those lubricants were followed. Based on the experiment two new lubricating methods of applying the K_2Ti_4O_9 whisker and applying pulsed anodic oxidation to the surface of the sheet for insight warm SPIF have been recommended for good surface finish.

Ziran et al. (2010) reported about performance of hemispherical and flat ended tool on profile accuracy and formability in single point incremental forming. Author invested with aluminium AA 3003-O sheets of thickness 1mm.and five different end radius HSS tool were used in this study. The forming speed 2250 mm/min and step size 0.2 mm/rev were used as process parameters for this study. flat end tools provide better accuracy, required lower forming force when compared to hemispherical end. Tool radius does not affect the formability of the material.

Gottmann et al. (2011) proposed new setup for laser assisted incremental forming. The setup was successfully integrated the laser assisted heating unit and CNC controlled tool. In this research work two limitations of asymmetric incremental sheet forming namely low geometrical accuracy and low formability at room temperature were studied by conducting wall angle test. Investigational results showed that the formability and geometrical accuracy of the alloy Ti Grade 5 (TiAl6V4) can be increased.

Ambrogio et al. (2012) proposed a successful system based on the Joule’s effect. The workability of incremental forming based on supplied heating energy were drawn for three light alloys material like AA2024-T3, AZ31 and Ti6Al4V for this study wall angle of material was considered as responses. Different grain structures were obtained due to both electrical heating and induced strain directly dependent on the material properties. They observed that the surface roughness was getting poor by increasing the wall angle and the supplied energy.
2.3 TWO POINT INCREMENTAL SHEET FORMING

Attanasio et al. (2006) investigated different tool path, step down and scallop height in TPIF by taking an automobile part profile as reference. The experiments were conducted with metal sheets made of Fe P04 steel of thickness 0.7 mm. It was reported that use variable step depth, low values for step depth and low scallop height will give good results in part geometry accuracy, thickness of final part and surface quality of sheet.

Katjarinne et al. (2008) focused a study about the applicability of the colour coated sheet in incremental forming. Based on stretch forming tests and incremental sheet forming test the performance of colour-coated sheets was studied. The strong industrial robot was used for ISF test and hydraulic press with a hemispheric forming tool of diameter 100 mm was used for stretching test. Truncated pyramid was used as target geometry. The results showed that the colour-coated (polyurethane based) sheets were suitable for ISF. Visual examination of sheet metal in both sides did not showing any harmful effect from the forming tool. By comparing two methods of forming it was concluded that crack of the sheet limits the formability in traditional forming but the colour coating limits the formability in incremental forming.

Obikawa et al. (2009) presented about the dieless incremental forming process which was carried out in a desk top type milling machine. The two types of aluminium incremental forming 12 μm, and 50 μm thickness sheets formed using single point tool with a tip of radius 0.5 mm used. The results shows that forming limit was enhanced by tool rotation up to 20,000 rpm, and in-plane forces were reduced by 50 % approximately. Hydro dynamic lubrication between tool and aluminium foil sheet interface positive influence on the forming process, another observation made on axial feed was optimum step size for axial feed about thickness of the foil. Then, forming of miniature pyramids, car and letters was executed effectively in incremental fashion.

Jackson and Allwood (2009) aimed to evaluate the deformation mechanism of the two variables of ISF (SPIF and TPIF), and to estimate the accuracy of the sine
law for forecast of wall thickness. These experiments were conducted for an annealed copper plate shaped of truncated cone with wall angle of 30°. The results shows that the deformation mechanisms of both SPIF and TPIF were growing stretching and shearing in the direction of perpendicular to tool and shear in the direction of tool. The differences between the sine law and wall thickness measured for SPIF and TPIF was due to the increasing stretching and shearing perpendicular to the tool direction.

Kwiatkowski et al. (2010) made a study to overcome the disadvantage of the asymmetric incremental sheet forming. For this study they used four different tooling concept namely Twin Tool method, Multiple robot, Rotary Tool setup and Hedgehog Tool. Among the four methods Twin Tool method setup has proved most suitable process to speed up the process in simplest and cheapest way.

Obikawa et al. (2010) presented a study about SPIF of micro-forming thin shell products. The authors used three kids of material like AA8021, pure aluminium and pure gold foil. Micro grain cemented carbide tool of 10 μm, 20 μm and 100 μm were used. Results showed that optimum rotational spindle speed should be decreased for micro products. Grain size and surface roughness make an effect on the shapes of products to certain level not to expected high level.

Sekine and Obikawa (2010) studied single point micro incremental forming of miniature shell structures. Thin aluminium foils thickness of 12 μm and thin round tip too radius of 100 μm was used in specially made desk top type CNC forming machine for forming various fundamental and complex shell structures. Results of this study show that large contact area between tool and sheet was responsible for pinhole and crack nucleation. This also proved that single point micro incremental forming is compatible for forming miniature shell structures with various shapes.

Tisza et al. (2010) studied the issues concerning an innovative die less incremental forming. The experiments were performed with two different strategies like supporting tool moving back side of the sheet metal individually (A) and supporting tool moving along with the master tool (B). For this experiment the authors used AA 1050 sheet metal of thickness 0.6 mm, master tool diameter 10 mm
and supporting tool diameter 6 mm. The targeted shape of truncated cone of wall angle 45° was formed with the help of CATIA CAM software tool path. The results showed that when applying forming strategy A the sheet metal failed before reaching final depth but successful forming was done through strategy B. The minimum sheet thickness 0.329 mm was achieved and the simulation results confirmed a good agreement with the experimentally calculated strain components and thickness variation.

Fiorotto et al. (2010) presented a basic examination on adoptability of Single Point Incremental Forming techniques to hybrid composite laminates. Diaphragm of different shapes was used to improve the composite adhesion and to avoid wrinkling. The laminates, consists of alternating layers of composite and thin sheet metal were used for their excellent mechanical properties. Aluminum sheet diaphragm with a vacuum bag achieves wrinkle free parts formed in incremental forming fashion. The authors reported that non-uniform resin distribution would be resolved in future work.

Meier et al. (2011) worked with two moving tools and reported theoretically and experimentally with AlMn 99.81 that the maximum formability increases and geometric accuracy also increased. The inner surface quality was improved with smaller shifting angle and outer surface quality is improved with larger shifting angle. By this approach formability in terms of maximum draw angle is increased to 12.5% and the overall deviations spread evenly with higher deviations in the surfaces of higher draw angles and unformed bottom.

2.4 FORMING PATH IN INCREMENTAL SHEET FORMING

Hirt et al. (2004) focused their work on forming strategies to overcome two process limits namely maximum wall angle and geometrical deviations, including the processing of tailor rolled blanks. In addition, finite element modeling of the process was presented and discussed based on the forecasting of the forming limits in ISF. The material used for this study was Al 99.5 of initial sheet thickness 1.95 mm and the pyramidal shape with wall angle 45° and 63° were made using two forming strategies. Among that it was concluded that multistage forming strategy can be
produced steep flanges of up to $81^\circ$ and a correction algorithm helps to improve the geometric accuracy.

Kopac and Kampus (2005) studied about the five different tool path strategies and parameters like tool diameter, shape of the clamping frame. The experiments were tested with aluminium alloys in CNC milling machine. This paper presents that small ball tool with a diameter of 10mm, forming closest to the edge of the sheet metal, clamping frame which have the shape of the product required and forming first in the centre then from interior into exterior will gives the good results.

Duflou et al. (2008) studied experimentally about the multi step tool path. Sheet thickness and maximum wall angle of the sheet metal were compared theoretically by sine law, experimentally and by simulation method. The tests were conducted for AA3103 with thickness of 1.5 mm. To achieve maximum wall angle, the tests were done by multi stage by making step by step increment in the wall angle. This extended process window explained the straining of horizontal work piece areas that continue unaltered in conventional toolpath strategies. This permits manufacture of vertical walls without part failure. Multi step forming produces substantial tangential strains and due to this it can exceed maximum thickness reduction than single step forming. They found multi stage toolpath approach gives higher forming limits than single-step forming.

Skjoedt et al. (2008) studied about the five stage forming strategy to form a circular cylindrical cup with height to weight ratio one in Single Point Incremental Forming. Theoretical strains are calculated and geometrical relations were discussed. For this study 3-axis milling machine, 1 mm thickness sheets, hemi spherical end tool radius of 6mm, and forming speed is 1000 mm/min were used. This multi stage strategy method proved that a cup of $90^\circ$ drawing angle is possible in SPIF. It reveals that strains faraway from plane strain can be attained in SPIF and the strain distribution is depends on the geometry of the tool path and tool direction.

Verbert et al. (2008) addressed to overcome the maximum wall angle limitation of the SPIF. Multi stage forming method was proposed as one of the method to achieve maximum wall angle in SPIF. By this strategy vertical walls can be
formed without leading to part failure. The resulting sheet metal thinning during multi-step forming can go beyond the maximum thickness reductions experienced in single-step incremental forming.

Bambach et al. (2009) suggested multistage forming method to improve geometrical accuracy in asymmetric single point incremental forming. To conduct these study DC04 mild steel sheets of sheet thickness 1 mm were used. Four sided pyramidal frustum used as a benchmark part. At the time of forming, residual stresses were produced in AISF. The process chain of multi-stage forming, stress-relief annealing and trimming has been suggested to improve the accuracy of the final part. The above said process chain was verified with a case study of car fender section.

Rauch et al. (2009) studied the effects of tool path forming strategy and other programming parameters like feed rate, axial increment on produced part accuracy, forming force, maximum depth and flatness. Through results authors suggested that to build up dedicated tool paths to improve the efficiency and for the incremental sheet forming Intelligent CAM programmed tool paths was proposed. Some more results of this work shows that feed rate does not have considerable effect on the forming forces and above the feed rate value of 2 m/min sheet metal formability decreases with feed rate increases. Axial increment and forming strategy are major impact on final product geometry.

Duflou et al. (2010) presented Twist phenomena in incrementally formed parts by observing both in single and two point incremental forming. The material used for this study was AA 3103 with a thickness of 1.5 mm. the results showed that twist phenomenon was found to be independent of the tool diameter, the rotation speed of the tool, and the forming speed. The twisting direction occurred in the formed part corresponds to the tool path direction. The authors observed in-plane shear in opposite to toolpath direction when processing higher drawing angle parts.

Rajiv Malhotra et al. (2010) studied the tool path in incremental forming; the toolpath plays a noteworthy role on the dimensional accurateness, surface finish, and time for forming of the module. Present day toolpath generation techniques are
created on marketable CAM software packages and it does permit the construction of spiral 3D toolpaths for freeform modules having restraints on both dimensional accuracy and surface finish and as well as reducing forming time. The work done here deeds the resemblances between layered manufacturing and incremental forming for the development of a procedure to automatically generate spiral 3D single point incremental forming toolpaths to help in the formation symmetric as well as asymmetric modules, while bearing in mind some indicated restrictions on the anticipated geometric accuracy as well as maximum quantified scalloping height whereas decreasing the forming period. In order to check the established practice, the scalloping heights of modules shaped by means of the established practice are calculated and matched with the maximum acceptable scalloping heights quantified. Additionally, the dimensional correctness and developing time of the formed components by means of the established practice and by the generated tool paths by means of CAM software are equated. Here it is revealed that the tool paths generated by means of the established procedure form mechanisms has improved or comparable dimensional correctness as equated with that produced by commercial CAM software packages as well as with scalloping heights less than the maximum allowable scalloping height quantified by the operator. Simultaneously, the established procedure also decreases the forming time as matched with CAM toolpaths. This procedure can hold both symmetric in addition to asymmetric forms and it is a crucial step in the direction of mechanization of for incremental forming toolpath generation.

Vanhove et al. (2010) studied the twisting phenomena twist, convinced in the development of Single Point Incremental Forming (SPIF) in 3 axes CNC milling machine with Al 3103 of 1.5mm thickness is of significance for knowing asymmetric nature via unidirectional toolpath. With the purpose of appropriately point cut-outs and pre-formed topographies in the non-deformed sheets, understanding in the amount and path of the tempted twist in the course of incremental forming is necessary. The subsequent twist route, testified by diverse research groups in both single point incremental forming (SPIF) and two point incremental forming (TPIF), usually relates to the toolpath route as an outcome of the friction amongst tool and work piece via one directional toolpath. Nevertheless a twist in reverse direction is seen while processing portions having high drawing angles. Comprehensive
investigation of twist occurrences delivers understanding in the forming procedure of SPIF. The objective of this paper is to observe and learn the manifestation of twist by the process of measuring strain and note its effect on the thickness scattering in portions categorized by stiff semi vertical rib features.

Cui and Gao (2010) studied multi stage forming methods to form hole flanging through incremental forming. hole –flanging is used to make flanges around holes. The conventional sheet metal forming processes to produce hole flange requires punch and die. So the cost of the process will increase. In incremental forming the uses of dedicated punch and dies are avoided, It brings the processes cost to come down. In this study three different strategies were used. Aluminium 1060 were used with processes parameters like , tool diameter of 12 mm, part diameter of 65 mm. and feed rate of 2400 mm/min. The results proved that increasing part diameter in step by step during forming process gives optimum part geometry, higher neck height, and also gives uniform wall thickness.

Ambrogio and Luigino Filice (2011) presented methods to increase part accuracy by back drawing methods and multi stage forming of sheet metal. For this study Aluminium Alloy and DC04 Deep Drawing Steel are experimented with sheet thickness and tool step as varying parameter remaining parameters kept constant. Back drawing approach method reduced 15-25% dimensional deviation and incremental forming steps could increase accuracy.

2.5 FORMING TOOL IN INCREMENTAL SHEET FORMING

Jurisevic et al. (2006) initiated a preliminary research on die less forming with high speed water jet as a forming tool. From the knowledge of abrasive jet machining two technological windows are presented. One of these was water pressure and effective jet diameter while the other is water pressure and standoff distance between sheet metal and jet. But these technological windows are limited with high water pressure because it may lead to metal erosion. Besides to these results, an another result was presented as water jet sheet metal forming is appropriate forming process
for blank diameter less than 1 mm and it can be used for production of micro moulding tools.

Jurisevic et al. (2008) studied with aluminium alloy (AlMgSi) of thickness 0.23 mm as the work piece. This examination shows that the laminated supporting tool is comparatively simple to manufacture and does not considerably increase the total cost and time. This study evidently indicated that to obtain forming accuracy supporting tool plays vital role. Water jet incremental sheet metal forming is intended to be a rapid prototyping and small batch production process; with this point of view the forming time does not characterize such an significant process characteristic like forming accuracy.

Petek et al. (2008) studied about the comparison between rigid tool single point incremental forming (RTSPIF) and water jet incremental sheet metal forming (WJISMF). The material used for these investigations was aluminium alloy thickness of 0.23 mm. These studies were conducted by making various pyramidal shapes to identify the most significant parameters affecting the forming process through experimental comparison of the RTSPIF and WJISMF. From the experiments it was reported that RTSPIF is more suitable for larger wall angles and lesser horizontal steps, while WJISMF performs better at bigger horizontal steps and lesser wall angles. It was identified that in RTSPIF tool kinematics (load on the sheet metal) and in WJISMF water pressure were the controlling process parameters. Standoff distance has also influenced one in WJISMF. RTSPIF facilitates higher process accuracy and lesser machining time compared to WJISMF.

Sajn et al. (2011) reported a new technological window for incremental sheet forming with a flexible tool technology. This was used for small batch production and prototyping of sheet metal parts. This gift deals with new alternative of ISMF, where as a substitute of a rigid tool a Water Jet (WJ) is used as the main tool. it can be named as Water Jet Incremental Sheet Metal Forming (WJISMF). A Finite Element Analysis (FEA) simulation was developed and validated experimentally to simulate
the impact of WJ on rigid surface. The authors found strong agreement between calculated pressure distribution and with experimentally measured.

2.6 FORMING LIMITS IN INCREMENTAL SHEET FORMING

Kim and Yang (2000) studied about to increase the formability in incremental sheet forming process. The authors found that the uniformity in thickness is important key factor to increase formability and deformation takes place generally by shear deformation. To get the uniform thickness strain throughout the deformed area double pass forming method was found to be successful.

Shim and Park (2001) reported formability of incremental forming with freely rotated ball forming tool. The study was done in annealed aluminium AL 1050 sheet of thickness 0.3 mm. Al 1050 sheet incrementally formed; FLD was constructed as a straight line with a negative slope in positive region of forming limit diagram which is more distinct appearance than conventional forming processes.

Filice et al. (2002) was focused on formability of material in incremental forming. To study these three different types of tests were performed for achieving different straining condition. The results showed that incremental forming produced different forming limit curve than conventional one and it followed stretching deformation mechanics. Forming limit curves (FLC) which was drawn looks like a negative slope in the positive side and the attained FLC can be used to design industrial incremental forming processes.

Park and Kim (2003) studied formability of aluminium sheet of thickness 0.3 mm by single point incremental forming. The tool speed of 25 mm/s, vertical feed of 0.2 mm and the horizontal feed of 1 mm were chosen as the parameters. The results showed that positive forming method in incremental forming gives better formability than conventional ones. In negative forming, it is complicated to shape sharp corners or edges because cracks developed due to biaxial mode of deformation.
Strano (2005) reported about the formability of aluminium thin sheet of 0.6 mm thickness. The experiments were carried out using robotic cell to study the formability in terms of different wall angle. The following observations are made on formability to produce sound parts that increasing feed rate decrease the formability and increasing sheet thickness, probability of formability also increases.

Duflou et al. (2007) studied about the influences of local and dynamic heating on the forces required, formability, accuracy of the process and residual stresses in the formed. The experiments were conducted with new set up which has a rigid tool fixed in 6 axis robot to form from one side and a 500W Nd-YAG laser system to give local and dynamic heating to the tool and work piece interaction zone from the another side of the sheet metal. The sheet metal of AL 5182, thickness 1.25 mm was used and the tool of 10 mm diameter made of tungsten carbide was used. The initial test results shows that local and dynamic heating of tool work interface reduces the process forces in single point incremental forming. Due to Reduced stress level and reduced spring back effects an accuracy improvement can be realized. In addition it was verified that the formability of different materials can be considerably extended.

Hussain et al. (2007) presented a comparison of the forming limits which was tested by two different methods namely varying wall angle (slope varies along depth) and constant wall angle (fixed slope along depth) of an aluminum sheet-metal. To forecast the formability parameters like forming angle limit and thinning limit some mathematical formulation was carried out. The achieved results demonstrated that the formability of the sheet blank depends upon the slope distribution of the curve of part to be formed. With the constant wall angle test the maximum wall angle of the sheet metal can bear without fracturing was determined. Finally, concluded that the formability depends on the slope distribution of the curve along the part used in the test. Former group of the parts gives higher forming limits than the latter one.

Hussain and Gao (2007) presented a paper on focusing an novel and viable method to investigate the thinning limits and to verify the Cosine’s law of sheet metals in Negative Incremental Forming along with verification of the Cosine’s law of thickness distribution. For experimental work aluminium sheet metal was used and arc of circle was selected as generatrix. The thinning limits attained from the parts
produced at fixed slopes were found lower than those produced from the parts varying their slopes with its depths. The parts formed with fixed slopes were suggested to attain lowest possible thinning limit.

Hussain et al. (2007) proposed a new testing procedure to find out formability of the material. Two tests were carried out in order to estimate the formability of the sheet material. First one was constant wall angle test and another one was varying wall angle test. The results revealed that maximum wall angle obtained from constant wall angle test lower than varying wall angle test. To reduce number of test combination of both the tests can be used.

Minutolo et al. (2007) studied the estimation of the maximum slope angle of frustums of pyramid and cone was carried out by incremental forming and the validation was done by FE analysis. The testing material used for this study was aluminium alloy 7075T0 with thickness of 1 mm. For each test tool has speed of 1000 rpm and feed rate of 1000 mm/min was used. The test reveals that the maximum slope angle of frustums of pyramid and cone was 63° and 66° respectively.

Le et al. (2008) investigated preliminary study about the applicability of SPIF techniques to thermoplastic materials. Fractional factorial design was considered to study the formability. Tool size has a significant effect on formability of thermoplastic sheets. Formability of thermoplastic sheets increases with spindle speed and decreases with forming tool radius. The increase in feed rate and vertical step size decreases the formability of sheet which was measured in terms of wall angle.

Hussain et al. (2009) investigated formability of an aerospace grade material AA-2024 sheets in single point incremental forming. step size, forming speed and radius of the tool were considered as operating parameters and their the effects on formability was quantified through response surface methodology. Interaction of step size and tool radius is giving significant results in formability. Annealed AA-2024 sheet Formability does not affected by forming speed of Forming speed but it affects the formability of AA-2024 sheets and also annealed sheet confirms good formability than pre-aged sheet.
Park et al. (2009) reported formability of Magnesium alloy sheets of rotational incremental sheet forming. Due to hexagonal closed packed structure magnesium alloys provides less formability at room temperature. To overcome this issue, rotational incremental forming in which heat produced locally on the sheet was studied. In this study the effect of tool radius on formability also reported. Forming limit curve for 6mm tool radius predicts well the experimental results than compared to 50 mm tool radius. The results show 6mm tool radius curve good formability.

Martins et al. (2009) studied about the formability of five different thermoplastics materials by forming various cone shapes in incremental fashion. The experiments were conducted in conventional CNC milling machine. The results of experiment confirm that higher formability of thermoplastic materials can be achieved at cold forming. Initial sheet thickness gives positive sign on formability improvement. Maximum Initial drawing angle increases spring back and increasing initial thickness reduces spring back.

Hussain et al. (2009) studied the effect of various material properties like strain hardening exponent, percent elongation and strength co-efficient on the formability in SPIF for various materials. The results showed that conventional stretchability indicator namely hardening exponent did not showed any significant relationship with the spifability. Similar trend was applicable to formability indicators like percent elongation and strength co-efficient. Reduction in area at tensile fracture can be used as a formability indicator. An empirical formula describing the influence of newly proposed formability indicator on the suitability was also examined. The formula can be used to rank the materials in SPIF.

Guoqiang Fan et al. (2010) proposed a new electric hot incremental technique which can be controlled easily and hard to form. the present study was done on Ti-6Al-4V titanium sheet of thickness 1mm. The authors suggested self lubricating NiS$_2$ metal matrix composites is appropriate for hot incremental forming and titanium sheet formed accurately even it got oxidized at the temperature range between 500–600°C. The formability measured in this temperature range was 72°C.
Maria et al. (2011) reported about the failure mechanisms of incremental forming. The work was experimented with aluminium AA1050-H111 sheets of thickness 1 mm and forming limit was found out by tensile and hydraulic bulge tests. The experiments were conducted in single point incremental forming with five different tool radius to analyse the failure mechanism. The results shows that for large tool radius, the stabilizing effect of dynamic bending under tension seems to be competent of lift up the forming limit curve above what is normally found in stamping in order to ensure localization by necking. For small tool radius, the stabilizing effect is not enough to ensure localization, and as a result of this, failure mechanism was changed in order to support fracture with restraint of necking.

2.7 SIMULATION AND OPTIMIZATION OF INCREMENTAL SHEET FORMING

In a work, Ambrogio et al. (2010) found the factors which are severely affect the process performance based on the experiment conducted with the aim to investigate the process formability, the wall angle. The neural network approach was used to find “ready to use” procedure for complex shapes.

Essa and Hartley (2010) investigated the effect of supporting kinematic tool and backing plate and final stage tool path modification in incremental forming through finite element model. The results proved that the backing plate will decrease the sheet bending close to the initial tool contact location, the additional kinematic tool will decrease spring back, and the expansion of the tool path across the bottom of the sheet will eliminate the pillow effect.

Dejardin et al. (2010) analyzed the shape distortion and spring back effects occurred during SPIF through FE model based on shell elements simulation and the same was verified through experimentally also. A truncated cone was taken as targeted profile and aluminum 1050 material was taken for this study, in this paper it was demonstrated spring back can be predicted accurately from numerical simulations.
based on shell elements. It also revealed the geometrical profile accuracy of 3D finite elements simulation carefully accounted based on tool path strategy.

Bambach (2010) proposed an innovative idea for the process kinematics of ISF is offered that is further universal than the sine law. The idea indulgences ISF as an advancement of a surface from the unchanged sheet to the concluding shape. It calculates routes of surface points centered on flawless in-between profiles, supposing that the deformation amongst intermediary profiles continues by shifts along the surface perpendicular of the present profile. With the intention of using the innovative idea with uninformed portions, the idea was fed into a software package that analyzes membrane straining and the sheet thickness on a deltoid network. For benchmarking, the idea is related to the sine law in addition experimental outcomes. The consequence is that the new idea vintages improved thickness estimations than the sine law, particularly in non-flat portion zones where tensions parallel to the path of tool motion remain noteworthy.

Yuanxin Luo et al. (2010) proposed mechanical procedural idea is established to forecast the concluding profile established on the minimum energy principle. Here, a preliminary geometric surface is shaped by the punch; then on the basis of the information that the energy will make the sheet metal to achieve its lowest energy position, the geometry of the finishing form is acknowledged. Another idea is established to forecast the stress and strain circulations of the portion by means of the inverse finite element modeling (FEM) or the one-step FEM. The obtainable mechanical procedural idea can successfully forecast the resultant form of the portion, in addition to the stress and strain circulations of the portions. The forecasts of the ultimate form are usually precise, none the less a substantial miscalculation can befall around the boundaries nearby the blank holding locations.

Yuanxin Luo et al. (2010) proposed here the strategies in addition to construction of an incremental punching machine along with the experimental outcomes are discussed. The machine used is a three-axis computer numerical controlled (CNC) machine having a high-speed hydraulic punching head. In a certain portion, the punch path is made by means of commercial CAM systems by means of
certain alterations. The mechanism forms the area punching. The formability of the arrangement is furthermore examined resulting in the maximum forming angle. The test outcomes show that the new arrangement is operative for rapid sheet metal prototyping. Relating to the prevailing ISMF methods, it has a number of distinctive characteristics. Firstly its backing is provide by a mechanical idea, on its basis, the development of the portion along with the stress and strain of the portion can be forecasted as well. Secondly, alike to prevailing ISF approaches, the offered incremental punching technique is operative in production of free-form sheet metal portions. As it doesn’t require bottom support so it is comparatively simple. Moreover, it can deliver improved strength to the portion like the shot peening procedure. Thirdly, contrasting the robot-based ISMF, the setup is rigid, and therefore, is skilled of undertaking huge punching force. Also, the setup is simple to use as the control system is attuned with typical NC codes. Therefore it is supposed that the new setup will discover many applied usages in the imminent future.

Liu Wei and Zhang Hong-ying (2010) studied the basis of the deformation force equation along with constraints of parts of sheet metal being formed by incrementally with vibration, 08Al was presumed to be the sheet metal material, the magnitude of the deformation forces diverse with every parameter and transformation were considered distinctly via using MATLAB software. Outcomes display that the insignificant deformation force is acquired when vibrational frequency of 20 Hz, radius of forming tool 5 mm, amplitude of 0.2 mm and the descent of the forming tool on each lap was 0.2 mm. whereas the course of the deformation of sheet metal forming incrementally via vibration; the magnitude of deformation force amplified from 345.5 N to 369.1 N, the feed rate of the forming tools elevated from 1mm/s to 10mm/s, the development of the magnitude of deformation force is 6.4%, thus feed rate of the forming tools might be amplified appropriately on the condition that the surface quality and geometric accuracy of the portions wouldn't be missing, the machining efficiency can be enhanced, the energy consumption can be abridged.

Sena et al. (2010) studied current job apprehensions and is concentrated on an initial statistical revision of selected of the problems upraised in the statistical model of single point incremental forming processes (SPIF) using Finite Element Method.
For doing so, model of recognized SPIF point of reference is agreed, established on solid as well as solid-shell finite element constructions, accompanied by inherent combination arrangements. Assessments are prepared amongst different sorts of three-dimensional finite elements constructions in addition to investigating the impact of the quantity of through-thickness layers accepted. Additionally, solid-shell finite element constructions established on the superior implicit strain mode are also engaged into interpretation, permitting for prototypes by way of just one layer of finite elements however comprising a mutable amount of assimilation points alongside the thickness route. The attained consequences are related with experimental results. The finite element RESS delivers improved outcomes than solid elements of commercial software packages, and quite less computational fee.

Zhu et al. (2012) reported effect of pressing direction in incremental forming using 5 axis CNC machines through digital simulation method. Four kinds of finite element models were prepared and were simulated with the help of ANSYS/L-S DYNA software. By Comparing four finite element analysis model results, various observations are made. Thinning range of sheet thickness is declining when there is increase in pressing direction angle; similarly the equivalent strain of middle surface is also diminished gradually with the increase of pressing direction angle. Forming quality also studies in this paper using digital simulation method.

2.8 PARAMETRIC STUDY

Kim and Park (2002) studied the effect of process parameters such feed rate as tool size, friction between tool and sheet, tool type, and plane-anisotropy of a sheet on formability by experimentally and FEM analysis. The material used for this study was annealed aluminium 1050 sheet of thickness 0.3 mm. The formability of the material evaluated was by straight groove test. Formability was improved with the ball tool, little friction between tool and sheet interface and decreased feed rate. The 10 mm tool gives good formability and formability differs because of plane anisotropy.
Fratini et al. (2004) studied about material formability in incremental forming. Some relationship between the material formability and mechanical properties were reported. The test was conducted for the various materials like Copper, Brass and AA1050-O. The process parameters used was tool diameter 12mm, tool depth step 1 mm/loop and speed of the tool 600 rpm. The results shows that the material which has highest strain hardening coefficient and percentage elongation will gives the higher material formability in SPIF.

Ceretti et al. (2004) studied about the incremental forming by experimental and simulative method. The every tool components are designed by FEM simulations which have provided the value of the functional loads. The results of this study showed that the presences of die under the sheet guaranteed the parts with respect dimensional accuracy and geometrical tolerances. it can be applied to small batch production, rapid tooling (concrete die production) and flanging operations without die.

Strano (2005) reported effects of the some process parameters like vertical step down, wall angle, part curvature radius, tool radius and sheet thickness on formability of the negative dieless incremental forming process. A robotic cell was used for the carrying out the test on commercially pure aluminum sheets (AA 1050-O) of thickness 0.6 mm. the results shows that by increasing the vertical step down, the chance of having a good part decreases. By increasing the tool radius (for at least small vales of ‘r’) and sheet thickness, there is chance of producing sound part increases.

Cerro et al. (2006) analyzed the effect of process parameters in incremental sheet forming process by conducting experimental tests and finite element method modeling. The results shown that higher the overlapping results lower the strain produced in each stage. Hence, errors formed in each stage are lower. Forming process time also longer if better accuracy is required. The stages of overlapping increases then the forces required to form the part reduced. Forming the parts by many number of stages produced good results. To predict the number of stages process modeling could be a valuable tool. Another important aspect of formed
products is roughness. It was lower in the tool advancing direction when compared to perpendicular direction.

Ham and Jeswiet (2006) studied about the effect of parameters in single point incremental forming using AA 3003 alloy sheets. In this paper, two design of experiments with a six factor two level fractional factorial design were performed. First experiment gives the results as feed rate, spindle rotation speed, step size and forming angle affect the part. Faster spindle rotation improves the formability. The second experiment shows little effect of step size on maximum forming angle, whereas the material thickness, tool size and the interaction of material thickness and tool size have a significant effect on maximum forming angle.

Kim et al. (2007) reported about the incremental forming of magnesium alloy sheet and effect of process parameter like feeding depth per cycle, wall angle inclination and temperature on formability were also studied. For this study various shapes like pyramids and cones with various inclination angles were made in a new device which has halogen lamps moving with tool to produce local heat. Among the three parameter inclination wall angle found to be a most significant parameter deciding successful formation of parts. The authors suggested that incremental forming process is one of the good processes for the materials having poorer formability.

Duflou et al. (2007) studied the influence of four parameters like vertical step size, material thickness, wall angle and diameter of the tool on force measurements in incremental forming. The aluminium 3003 – O material of thicknesses 1.2 mm was used as the testing material. This study reveals that the tool diameter, vertical step size, wall angle or sheet thickness are increased, the forces also will increase accordingly. It was found that within the explored limits, vertical step size has the least significant impact on production time.

Hussain et al. (2007) studied the effect of curvature variation of the material on formability in incremental forming. This study reveals that the formability in terms of maximum wall angle is slight dependence on the radius of the curvature of the
parts formed. It was found that the formability increases with decreases in the radius of curvature (up to 500mm).

Hussain et al. (2008) did formability study of commercially pure titanium sheet. The process parameters like feed rate, vertical step down, friction between tool and the sheet metal and tool diameter were considered. The effect of these process parameters on formability was reported. The formability was evaluated in terms of maximum wall angle by varying wall angle test. Formability decreases with increase in pitch and tool diameter and feed rate reduction. Friction between tool and blank interface does not increase formability but it produces poorer surface finish.

Ambrogio et al. (2008) studied the role of the main process parameters on formability of Magnesium alloy AZ31 through a broad experimental campaign and a precise statistical analysis. The material used for the tests were AZ31–O sheets of thickness 1 mm and the target geometry was a truncated cone. Punch diameter, tool depth step and the sheet temperature of each three levels were used as main process parameters. The conclusions made based on this study were formability of the AZ31 enhanced at warm conditions and with smaller tool step depth. They concluded that the sheet temperature and tool depth step were more influenced parameter.

Durante et al. (2009) carried out a work to assess the influence of tool rotation, in terms of speed and direction. AA 7075-T0 sheets, a hemispherical headed tool and moved by a CNC machine, were used for this study. These investigations highlighted that reduced forming force peaks when the tool is set in rotation in both the direction. Roughness varies, but not significantly, depending on whether the tool is set in rotation or not, while speed and rotational direction of the influences this parameter.

Zhang et al. (2009) studied the effect of anisotropy of magnesium alloy AZ31 on single point incremental forming. The process parameters used in this study was tool material high speed steel, hemispherical end of 6mm diameter, feed rate in horizontal direction 1800mm/min, and vertical step down 0.2mm/revolution. The targeted shapes made for this study was circular, square, rotary cone. The results proved that the anisotropy of the sheet metal has significant effects on the formability.
and formed products surface quality and with increasing temperature the effect becomes weakened.

Hussain et al. (2010) studied the influence of new parameter like blank stiffness on formability in incremental forming. The findings of this study gives that if the backing plate hole increases then the equivalent blank stiffness of the material will increased and formability decreases with increase in equivalent blank stiffness.

Hamilton and Jeswiet (2010) reported that single point incremental forming can be done at high speeds and also it much more useful to manufacturers. Plan for forming at these levels were provided along with the effects on the external sheet surface, thickness distribution and grain size. A feasible model to predict the orange peel effect in SPIF was developed from measured roughness values and forming parameters.

Oleksik et al. (2010) studied experimentally about the SPIF on the surface quality of the medical implant used for the femoral condylar surface of the knee produced with titanium sheet. This paper discussed the roughness of the parts obtained in SPIF and the factors influencing. It was concluded that processed surface got worsened than initial stage of surface quality but still it is within acceptable limit when compared to conventional deep drawing process. It also reveals that quality of the product influenced by active surface of punch and friction condition between punch and sheet.

Eyckens et al. (2010) reported influences of friction in SPIF was experimentally examined by making cone shaped product in an aluminium alloy AA3103-O sheet into a large wall angle cone with and without imposed tool rotation. it was found that only one force component which is along the tool movement direction depends on the tool rotation, i.e. on the friction conditions. Finite element method was also reported to predict the forming forces and it was found that through thickness shear was affected by tool rotation.
Aerens et al. (2010) set the goal of this research as to institute real-world formularies permitting to forecast the forces happening throughout the single point incremental forming procedure. This research is grounded on a huge set of methodical experimentations on one hand and on the other outcomes of modeling of finite elements simulations. This led to investigative formulations permitting to calculate the three main constituents of the force for five designated materials in purpose of the working situations (step down, tool diameter, wall angle and sheet thickness) having a good accuracy. Furthermore, a universal prototype has been comprehended, permitting to calculate a near value for the force for any material, founded on information of the tensile strength of the materials only.

Ambrogio et al. (2011) Presented a study about the industrial suitability of incremental forming sheet forming process, because of slowness and limited accuracy spreading of this process is limited in industrial side. The authors investigated effect of high feed rates to reduce the process time and introduce a small strategy to improve the part accuracy. Aluminum alloy sheets of AA1050-O, AA6082-T6, and AA5754 were used. The parameters like the tool diameter, sheet thickness; wall inclination angle, the tool pitch, and feed rate were considered to find out the formability limit for each material in terms of maximum critical slope angle. High feed rate does not affect the formability and surface roughness of sheet metal. But at the same time it will lead to reduce process time. For the part accuracy, the wall inclination angle, the effect of the tool feed rate and its interaction with the sheet thickness are mostly concerned. Larger is the tool depth step resulting in a worse surface quality. The smaller is the tool punch, higher the geometrical precision.

Henrard et al. (2011) studied the accurateness of finite element simulations in forecasting the tool force developed during the single point incremental forming process. The experiments were conducted on the standard three axis milling machine and Kistler 9265B six-component force dynamometer was used to measure the tool forces. The aluminium material AA3003 – O of thickness 1.2 mm was used was a soft for this study. The targeted model of 20° and 60° cone was formed. The results showed that different stree and strain conditions for two different cones. Three factors show an influence on forming force prediction namely the type of finite element, the constitutive law and the identification procedure for the material.
parameters. For this higher wall angle cone it was clearly confirmed that a saturating hardening law such as Voce’s is important for precise force prediction for the aluminum alloy used.

2.9 STATISTICAL OPTIMIZATION FOR ISF

The influence of SPIF parameters using design of experiments (DOE) was first assessed by Ham and Jeswiet (2010). With modern technological advances, products and processes are becoming exceedingly complicated. DOE provides powerful and efficient methods for the simultaneous evaluation of two or more factors on their ability to affect the resultant average or variability of particular product or process characteristics (Montgomery, 2008). Taguchi method (TM) is a highly practical tool for process design, and it provides a simple, efficient, and systematic approach to optimize the experimental designs (Ross, 1995). However, researches show that the multi-response problem is still an issue with the TM. A series of theories and methods are available in seeking a combination of factors / levels to achieve the situation of optimal multi-response instead of using engineer’s judgment to make a decision in the TM. (Liao, 2006).

For the complex multi-variable optimization problems, the grey relational analysis (GRA) is used to evaluate the unknown relationship among the process parameters and the performances. Through the Taguchi method (TM) based GRA, optimization of the complicated multiple performance characteristics can be converted into a single grey relational grade (GRG). GRA was first proposed by Deng in 1989. But GRA uses the averages of normalized multi-objectives to calculate the GRG. So, the accuracy of the optimization can be improved by considering the weighting values in each response rather than the averages. Principal component analysis (PCA) is one of the efficient methods of evaluating the weighting values of the responses. Pearson (1901) proposed PCA which was successfully developed as a statistical tool by Hotelling (1933). This approach preserves as much original information as possible significantly simplifying a large number of correlated variables into fewer correlated and independent principle components. The design of experiment technique, i.e., TM based GRA coupled with PCA, has been used to accomplish the multi objectives (Lu et.al 2009 and Rajesh et.al 2013). This work
describes the experimental design, analysis method and subsequently the optimization of forming parameters based on GRA coupled with PCA.

2.10 CONCLUSION

From the literature survey and the conclusion of this chapter, it has been found that the following points are found to be the research gap.

- In terms of forming path and tool path strategy, geometry accuracy still needs to be improved.
- Although springback is one of the main obstacles of the process, it is almost neglected and hardly mentioned as a major subject.
- Further research is necessary to determine which mechanisms are of major relevance under particular process conditions.
- ISF and development of forming limit diagram have been done on only for the limited materials.
- Parameter Optimization also is very limited.
- Developments of mathematical model have been not at all attempted.
- The effect of n and r value of the sheet metal on IF formability is also very rarely found.
- Formability and its analysis for some of the aluminium alloys AA 1050, 1060, 2024, 3003, 3130, 5086, 6016, 6111 & 7075, and some of the other materials like AZ 31, C101, SS 304, pure titanium, Ti6Al4V, Brass H62-H28, Copper T2-H28, Steel DS, DDS and Steel 1050 have only been established. Since formability is independent and exclusive for a particular material quality, it has to be established for each material individually.

From the research gap, it is clear that formability and its analysis have not been established for all the aluminium alloy sheets. The aluminum alloys AA 5052, AA 6061 and AA 8011 are widely used in automotive, aerospace and structural applications. Therefore, these materials have been considered for this study. In this research, it is aimed at the multi objective optimization SPIF parameters for maximum formability and minimum surface roughness for the above sheet materials through which the optimum process parameters will be established and effect of each forming parameter on the responses will be thoroughly studied. It is aimed to analyze
the formability and surface roughness of above sheets. This work also aims at the construction of Forming Limit Diagram (FLD) for each of the sheet metal mentioned above when they are formed by SPIF. These analyses will be helpful for both the manufacturers and users of these sheet metals. In the next chapter, the materials, methods of forming, machine tool used, forming tool used, and procedure for each experiment/test carried out for this work and plan of experiments are explained.