CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

The study on the properties of materials especially of true stress and true strain relationship was carried out by a lot of researchers in way back 1900. These analyses are very much important in understanding the forming characteristics of a material during the sheet metal forming processes for a successful production of high quality components. Many researchers have focused their study on the metal flow during the sheet metal forming operations which is very difficult to predict due to complexity of the process. Without understanding these, the design of tools and selection of proper process parameters will be only a trial and error causing expensive tryout costs.

Also, the need for cost reduction and development of eco-friendly products necessitated the researchers to find an alternate material or innovative methods of manufacturing. A lot of research works are performed using finite element method (FEM) based simulation using software packages in the recent years. This is a very powerful tool used to analyse any complex forming operation without conducting the actual experiments but the validation of FEM is essential. Further, the study that is based on the metallurgical factors is also of equal importance for the researchers to understand better about the materials behaviour as well as the processes.

2.2 MATERIALS AND THEIR PROPERTIES

Many researchers have experimented with the high strength low formability materials like aluminium or magnesium alloys to evaluate their forming characteristics. These materials nowadays replace the steel in automobile and electronic industries due to their excellent properties like lightweight, high specific strength. Takuda et al (2002), Wang and Lee (2006), Van Den Boogaard and Huétink (2006), Gavas and Izciler (2007), Palumbo and Tricarico (2007) are some of those who used aluminium or aluminium alloys in their research work. Magnesium or magnesium alloys are used as investigating materials by Shoichiro Yoshihara et al (2003), Qun-Feng Chang et al (2007) (i & ii), Lee et al (2007) (i & ii), Ren et al (2009), Heung-Kyu Kim and Woo-Jin Kim (2010), Aimei Zhang et al (2011), to name a few.

Very few researchers used different materials in their investigations on sheet metal forming processes. Saran et al (1990) performed an analysis using different materials like deep drawing quality steel, high strength dual phase steel, brass, and aluminium-magnesium alloys. Moura et al (2004), Sheng et al (2004), Fan et al (2006), Vedat Savas and Omer Secgin (2007), Swadesh Kumar Singh et al (2010) (ii) used different carbon steel as a testing material. Dejmal et al (2002) used copper, Narayanasamy and Loganathan (2007) used zinc, Huang-Chi Tseng et al (2010) used aluminium /copper clad metals in their investigations.

In the past, very little efforts were made by the researchers to study the forming characteristics of stainless steel material. But in recent years, a few researchers concentrated on stainless sheet metal processing and to name those few are: Livitsanos and Thomson (1977), Saran et al (1990), Kazunari Shinagawa et al (1991), Chang and Chou (1995), Hadji and Badji (2002), Takuda et al (2003), Yongchao Xu et al (2004), Mahesh Kumar et al (2006), Narayanasamy and Loganathan (2007), Padmanabhan et al (2007), Håkan Hallberg et al (2007), Eren Billur et al (2009), Stachowicz et al (2010), Chinouilh et al of Arcelor Mittal Global R&D, Ramaekers et al (1994) , Erik Schedin of Avesta Polarit, R&D.

In forming operations, the mechanical properties of a material may determine the suitability for a particular application. Extensive studies on basic mechanical properties were carried out by numerous researchers in the past years. Pierre-Jean Cunat (2000), Claes Magnusson of Volvo cars body components and Roger Andersson of Swedish tool and die technology have discussed the properties of stainless steel with respect to the structural automotive applications. Stainless steel exhibits properties like large elongation percentage linked with the high strain rate sensitivity and high strength and due to these characteristics apart from their usual advantages makes it suitable in the field of crashworthy in passenger car structures.

The flow stress of a material is very important property for any forming operations. Exhaustive studies were carried out by many researchers to develop and modify the equation showing the functional relationship between the true stress and true strain. Ludwik first proposed the definition of true stress and developed an equation in 1909.Later modifications were done by Hollomon(1945), Voce (1948), Swift (1952), Ludwigson (1971), Hartley and Srinivasan (1983), and Baragar(1987). The strain rate, which is a rate at which the strain is applied, was another important factor influencing the flow stress. The strain rate sensitivity function is the one which relates the true stress with the strain rate. Some of the researchers who developed and modified the equation are: Kleemola and Ranta-Eskola (1979), Wagoner (1981), Hosford and Caddell (1983), Johnson and Cook (1983). The various formulae developed by the above mentioned researchers are shown in Appendix 1 (Ji Hyun Sung et al 2010).

Gordon Johnson and William Cook (1983) developed a constitutive model and data for 12 different materials subjected to large strains, high strain rates, and high temperatures. The data for material constants were obtained from torsion tests, static tensile tests, and Hopkinson bar tensile tests. The model and data were evaluated by comparing computational results with the data obtained from cylinder impact tests and found that they were in good agreement.

Ron Brucker (2001) discussed the properties of stainless steel sheet material with respect to the deep drawing operation. The selection of proper grade of stainless steel for deep drawing operation based on the hardness, grain size, directionality of properties and formability is explained for both 300 series and 400 series stainless steels. Also, he discussed the handling of stainless steel so as to avoid any possible contamination by the contact with the carbon steel materials to form the red rust. This fact is supported also by Peter Ulintz (2000) of Anchor manufacturing group, Inc.

Joshua Lightenfeld et al (2006) investigated the effect of strain rate on the evolution of mechanical properties and strain-induced martensite during room temperature deformation of two austenitic stainless steel, 304L, and 309 by conducting both continuous tests and interrupted tensile tests, and special attention was given to the increase in specimen temperature due to the deformational heating. The following conclusions were made from the experimental results: (i) both SS 309 and 304L, experience increasing yield strength as the strain rate is increased, (ii) the ultimate tensile strength (UTS) of 309 increases as the strain rate is increased, whereas, the UTS of 304L is the greatest at the lowest strain rate, and (iii) the uniform elongation (UEL) values of both steels follow a similar trend with high elongations at the lower strain rate.

The experimental forming limit curve (FLC) of 304L stainless steel has been determined by using the punch test together with an optical method, which allows to calculate the strain field under the punch by Rabih Makkouk et al (2006). The calculations are done by taking into account of the effects of the martensitic transformation by means of the constitutive model for TRIP steels. The numerical determination of the FLC is based on the localization approach and the elastic-plastic behavior of the material. The analysis is in agreement with the experimental observation of a very sudden occurrence of fracture without any indication of prior neck growth.

A constitutive model for diffusionless phase transition in elastoplastic materials undergoing large deformation was developed by Håkan Hallberg et al (2007). The proposed model provided a robust tool suitable for large scale simulations of phase transformations in austenitic stainless steel undergoing extensive deformations, like necking of a bar under tensile loading and also in deep drawing process.

Ravilson Antonio Chemin Filho et al (2010) studied the true strain profile as an alternative method to analyze the tool design influence on forming high stampability steels. The major true strain distribution profile was analyzed along the stamped mild steel sheet of 0.7 mm thickness using different punch geometries in order to identify the sheet deformation uniformity. Finite element analysis was also carried out using ANSYS/LS-Dyna software packages and compared with the experimental results. From the experimental and the numerical simulations, it was found that the maximum true strains occurred close to the die radius when using the cylindrical and shallow ellipse punches and close to the punch pole when using more pointed tools like deep and extra deep ellipse shaped punches.

A procedure for constructing an analytical solution for failure of strips under bending and tension was developed with the assumption of tension/bending damage coupling by Bai et al (2011). To check the analytical solution, carbon steel was taken as an example material. They tried to analyze the stretch-bending test from three aspects: (i) the global response of punch force versus punch displacement was obtained by full plastic bending hinge method, (ii) the local stretch-bending analysis gave the shift of neutral axis and magnitude of maximum equivalent logarithmic strain and (iii) the derivation of an analytical solution using the damage accumulation assumption of combined bending and tension.

2.3 CONVENTIONAL DEEP DRAWING AND ITS PROCESS PARAMETERS

The conventional deep drawing is a forming process that is carried out in room temperature. The performance of the operation under the influence of different process parameters has been investigated by numerous researchers. Fan et al (2006) studied the damage development and the formation of wrinkles under the influences of the blank holding force and coulomb friction. Experiments were conducted to form square shaped component of 1mm thickness from mild steel blank. It was concluded that the damage gets initiated at the location where large wrap deformation is produced by the punch corner and also near the edge of the blank where the wrinkling occurs. Both these damage zones propagate with an increase in magnitude as the punch stroke increases. Also, the degree of wrinkling weakens, when the blank holding force is increased and it was reported that all the wrinkles disappear when the blank holding force reaches 10kN.

Gavas and Izciler (2007) studied the effect of blank holder gap (BHG) on the forming quality of the product by performing drawing operation of square cups using 1mm thick aluminium sheets and also the occurrence of fracture. It was reported that the best forming quality was obtained when the blank holder gap ranged from 1.0 to 1.3 times the initial sheet thickness for the given tool geometry. When BHG is greater than 1.3 mm, the surface quality of the product deteriorated remarkably and the fracture occurred on the top corners for a BHG of 1.8 mm or more.

Vedat Savas and Omer Secgin (2007) investigated the effects of blank holder and die shapes on the forming characteristics of a low carbon steel material of 1mm thickness. The study was carried out on drawing of circular cups by providing an angle (α) to die and blank holder. The limiting draw ratio (LDR) of 2.175 from 1.75 for a particular value of α was achieved and for $\alpha_{min} = 2.5^{o}$, the blank holder force decreased from 10362 to 3002N for a constant LDR value.

Narayanasamy and Loganathan (2007) dealt with the deep drawing of pre-strained circular blanks into cylindrical cups when drawing through a conical die. Annealed pre-strained sheet blanks of zinc, SS301, SS304, SS316 having a thickness of 1.6mm were drawn under two different frictional conditions (smooth and rough surfaces of blanks). It was observed that the slope of the radial strain –circumferential strain curve changed suddenly when a wrinkle developed on the blank and this may be due to the increase in circumferential strain when the wrinkle was about to develop. Also, it was found that the behavior of both SS301 and SS304 were similar because of the reason that these materials responded to strain induced martensite phase change from austenite during plastic deformation.

Dejmal et al (2002) attempted to increase the limiting drawing ratio (LDR) by finding an optimal die curvature, which minimizes the drawing loads. Circular cups, made from aluminium and copper materials of 0.5, 0.8 and 1mm thickness, were drawn through the dies with different radii of curvature. The results showed that the thinning occurred near the bottom of the cup and thickening occurred at the rim of the flange. It was also observed that the optimal die curvature varies with the interfacial friction, material strain hardening exponent, limiting draw ratio, but not with respect to the blank thickness. It was found that the higher the friction, the larger is the die curvature needed to minimise the load.

Saran et al (1990) investigated the influences of the process parameters like strain hardening exponent (n), strength coefficient (K), coefficient of friction (μ) and plastic anisotropy value (R) on the press force. Experiments were conducted using different materials like deep drawing steel, high strength dual phase steel, brass with 0.7mm thick each, 0.95mm thick aluminium-magnesium alloy and austenitic stainless steel with 1mm thickness. It was observed that, for a given strain, the increase in n value, lowers the stress and consequently lowers the punch force. Also, increasing K by a factor of two increases the press force by the same factor whereas the R value has a small influence on the press force and a higher the μ value results in a higher punch force.

Ayari et al (2009) developed a parametric finite element analysis to predict accurately the final geometry of the sheet blank and the distribution of strains and stresses and also to control the various forming defects, such as thinning as well as parameters affecting strongly the final form of the sheet after forming process. The materials used for analysis are aluminium (0.81 mm thickness), mild steel (0.78 mm thickness) and hadfield steel (1.2 mm thickness) and simulation of deep drawing of square cups are carried out using ABAQUS/Explicit software package. Amplitude of the major error between the numerical and experimental values in strain variation profile was found to be 33% for mild steel.

In deep drawing process, which uses three-pieced tool, high contact pressure is induced in the blank area that is in single sided contact with the punch corner and in the flange area that is in double-sided contact with the holder and the die. If the plane stress condition is assumed in such area, the results obtained from analysis may be inaccurate and it is necessary to consider thickness stresses to improve the result's accuracy. So, a simplified scheme for considering the thickness stress of shell element induced by contact was presented by Cho et al (2002). Finite element analysis of cylindrical cup deep drawing was carried out using ABAQUS continuum element. It was shown that the proposed algorithm has almost the same accuracy as the static implicit finite element code, ABAQUS using continuum elements and almost the same efficiency as conventional dynamic explicit finite element method using shell elements.

Ramaekers et al (1994) tried to find the relationship between the limiting draw ratio and some process parameters like strain hardening exponent (n), anisotropy factor(R), and friction coefficient (μ). It was concluded that (i) R value has minor influence on the drawing force but major influence on critical force, (ii) pre-strain has no influence on drawing force whereas it has little influence on critical force, (iii) optimal die radius may be 4 to 6 times the initial blank thickness, (iv) as the product size increases, the influence of the flange friction increases and (v) LDR value increases as the value of friction coefficient decreases.

A simple analytical method for estimating the maximum drawing in the deep drawing of cylindrical cups with flat-nosed punch which could be used in practical press forming was developed by Korhonen (1982). In order to validate the analytical method, experiments were conducted using stainless steel, aluminium killed steel and brass and the results were compared. It was shown that at smaller punch profile to punch diameter ratios, the triaxiality of the stress state tend to decrease the maximum drawing force. Also, simple charts for determining the maximum drawing force as a function of anisotropy and tooling geometry were presented for the above materials.

Anupam Agrawal et al (2007) attempted to predict the minimum blank holding pressure required to avoid wrinkling in the flange region during axisymmetric deep drawing process. This approach relaxed the assumptions that the sheet thickness does not change during the deformation or the material is isotropic and non-hardening. A model based on energy equilibrium method was developed and predictions using this model were in good agreement with the experimental results.

The finite element method based simulations (FEM) on conventional deep drawing have been performed by a lot of researchers since 1969**.** Moura et al (2004) used simulation for failure analysis of a deep drawing die. The finite element analysis (FEA) utilizing DEFORM 7.0 software was used to evaluate the loads and strains in the component and in the dies. The validation of the simulation was performed by comparing with the experimental results.

Adaptive FEM simulation with PAM-STAMP 2000 was used to predict the variable blank holder force by Sheng et al (2004). This proposed simulation method can predict the optimum variable BHF profile for drawing conical cups and this profile can improve the formability of the component and uniformity of the wall thinning distribution.

Alexander Muthler et al (2006) presented a new approach for computing elastic spring back based on a strictly three dimensional, high order, solid, finite element formulation for curved, thin walled structures allowing for an anisotropic discretization using PAM-STAMP. It was shown that anisotropic three dimensional continuum elements led to an efficient discretization of thin walled structures.

Wang and Lee (2006) studied the effect of yield criteria on the prediction of forming limit curve (FLC) and simulation of the deep drawing process. Simulation was carried out with two yield criteria Hill 48 and Hill 90 with two types of materials mild steel and aluminium. For aluminium, the predicted results almost coincided with the experimental results whereas it was much underestimated for mild steel. The results with Hill 90 yield criterion were better than the one with Hill 48 to both mild steel and aluminium and however, Hill 48 and Hill 90 could be used for mild steel whereas Hill 90 was an advisable yield criterion for aluminium.

Taylan Altan et al (2006) attempted to develop a FEM based strategy for progressive die sequence in deep drawing of circular cups from 2.15 mm thick blank material. The analysis was carried out by a commercial implicit FEM code, DEFORM 2D and the results were compared with that obtained using past experience and trial-and-error approach. The major conclusions arrived were (i) integration of past experience and FEM can reduce the number of die tryouts and the associated cost and time (ii) FEM can allow further refinement and optimization of the die design so that the wall thickness tolerances can be improved.

A 3-D explicit finite element analysis was used by Wifi and Mosallam (2007), to investigate the influence of various blank holder force schemes on sheet metal formability limits. When a pulsating blank holder force was considered, the pulsating amplitude and frequency were the two main parameters which might affect the performance of forming. From the experiments, it was suggested that the frequency had no role in improving the severity of deformation under the given conditions, whereas, the amplitude played a decisive role.

Saanouni et al (2008) used an advanced numerical methodology to simulate virtually any sheet or bulk metal forming including various kinds of initial and induced anisotropies fully coupled to the isotropic ductile damage. Two 3D deep drawing simulations were carried out using ABAQUS software to test the ability of the proposed numerical methodology to predict the ductile damage.

The numerical simulation of an axisymmetric cylindrical cup deep drawing was carried out with finite element code ABAQUS/ Standard by Mahesh Kumar et al (2006). A range of blank holding force of 30-90 kN was used to investigate their effects on the deep drawing process. The simulation results had shown that, when the blank holding force was 30-80 kN, no necking was observed at the bottom corner of the cup and the cups were drawn fully whereas, when this force was increased to 90 kN, stresses were the maximum at the bottom corner of the cup indicating tearing of the cup.

Younis (2010) studied the effect of drawing ratio in deep drawing on the thickness distribution along the cup and also performed the finite element analysis using ANSYS 9 software package. From the experimental results, it was observed that there was no wrinkling and the difference between the maximum and minimum thickness was very small, so that, a fairly uniform distribution of thickness along the cup could be achieved. Also, the best results were found at the drawing ratio of 1.484, which gave minimum variation between the maximum and minimum thickness distribution (approximately 0.05) along the cup.

Stachowicz and Trzepieciński (2010) presented the experimental and numerical results of rectangular cup drawing of 1 mm thick extra drawing quality steel sheets. The aim of their experimental study was to analyze the material behavior under deformation. A 3D parametric finite element model was built using ABAQUS/Standard software package and the numerical simulation was carried out by taking friction and material anisotropy into consideration.

Mark Colgan and John Monaghan (2003) attempted to determine the most important factors influencing a drawing operation using the design of experiments and statistical analysis. It was found from the analysis that the die radius was the most significant parameter, followed by lubrication type, punch radius, lubrication position and punch velocity whereas BHF had little or no effect on the maximum punch force. Also, they performed finite element analysis (FEA) using the program Autoform to model the cup formation and compared with the experimental results. The FEA predicted punch force was generally 7% lower and the average value for thickness was 2% greater than the actual experimental values.

Similar attempt was made by Padmanabhan et al (2007) to study the significance of three important process parameters namely die radius, BHF, and friction coefficient on the deep drawing characteristics of a stainless steel axi-symmetric cup. FEM combined with Taguchi technique was employed to determine the influence of forming process parameters. The analysis of variance (ANOVA) was carried out to examine the influence of process parameters on the quality characteristics of the circular cup and their percentage contribution was calculated. Deep drawing simulations were carried out using the in-house finite element code DD3IMP (deep drawing 3D implicit code). From ANOVA, it was seen that the die radius (89.2%) had major influence on the deep drawing process, followed by friction coefficient (6.3%) and blank holder force (4.5%).

Assempour and Fathi (2003) presented a new methodology to evaluate forming severity, to estimate the punch load, and to predict the thickness variation in deep drawing process. The methodology was based on matrix method of slip line fields (SLF) and energy method and also an optimization technique of genetic algorithm was used for determination of the actual velocity field and ultimately gaining the thickness distribution all over the deep drawn part.

Mohammadi Majd et al (2011) employed back propagation artificial neural network (BPANN) to predict the limiting drawing ratio of the deep drawing process and to prepare a training set for BPANN, some finite element simulations were carried out. A four layer back propagation network was developed to best fit this non linear engineering problem and the error between the predicted and targeted value was little.

Singh et al (2011) investigated the roles of die radius, punch radius, friction coefficients, and drawing ratios for axi-symmetric cylindrical work pieces deep drawing by using evolutionary neural network, specifically, error back propagation in collaboration with genetic algorithm. Experiments were conducted on carbon steel st-14 with the initial uniform thickness of 1.0 mm. From the investigation, it was established that punch and die radii of 14 mm produced the best quality products. Also, it was noted that the error in the prediction by neural network depended on the density of the relative distribution of the training data.

An innovative study on effects of embossing and restoration process on the deep drawability of 1.0 mm thick aluminium alloy sheets was carried out by Namoco et al (2007). During deep drawing of thinner sheets, serious problems occur since the rigidity of the formed part decreases as the sheet thickness decreases and hence the formability of the sheet also decreases. To overcome these drawbacks, embossing and restoration processing of sheet metals are being investigated as strengthening methods. As the sheet is subjected to these processes, the rigidity and strength are increased due to the unevenness of the shape of the metal, which increases the section modulus and work hardening effect that is locally given to the sheet. From the experimental results it was shown that the maximum punch load with embossing and restoration was lower compared to that of plain sheet specimen due to the presence of small embossed portions in the flange area. Also, the punch load at fracture of specimen with restoration was higher than that of plain sheet and this was due to the strain hardening effect, which increased the resistance to the fracture. It was observed that the LDR value increased with the increase in embossing height and an increase of 20% in cup height was attained with the specimen subjected to embossing and restoration processes.

Research was carried out on the possibility of applying forming limit diagrams to the formability and fracture prediction of aluminium/copper(Al/Cu) clad metals with different thicknesses (A1050 -1.0, 1.5 and 2.0 mm/ C1100 – 1.0 mm) by Huang-Chi Tseng et al (2010). The specimens of Al/Cu clad metal sheets were obtained through a cold roll-bonding process. Then, mechanical properties of the clad metal sheets were measured by tensile tests and the punch stretching test was carried out to determine the forming limit data of the clad metal. Finally, the deep drawing tests of clad metal were done using a square punch. It was observed that the fracture occurred on the side wall of the part. When the blank holding force was increased, the metal flow of the clad metal sheet was constrained by larger frictional forces, with the result that the blocked metal flow caused the fracture at the top corner of the part.

Marumo et al (2007) studied the influence of sheet thickness on the blank holding force and the limiting drawing ratio by conducting experiments on metal foils of thickness varying from 0.01mm to 0.08mm. Decrease in the limiting drawing ratio and the easy occurrence of wrinkles on the deep drawn parts were the major problems encountered in the deep drawing of metal foils. The experimental results have shown that the blank holding force required for the elimination of wrinkling increased rapidly as the sheet thickness decreased and the limiting drawing ratio decreased as the sheet thickness decreased and it decreased rapidly below 0.04 mm thickness.

Yuung-Ming Huang and Shiao-Cheng Lu (2011) focused on the 0.8 mm thick stainless steel 304 elliptical drawing process to understand the forming limit of the material and a 3D Finite element model was established by considering the concept of deformation theory and updated lagrangian formulation. The results of experimental and numerical simulations have agreed on the following: (i) the punch load increases with the increase of punch stroke, and when it reaches the maximum, the blank continues to deform, but the load is gradually decreased until reaching the forming depth, (ii) the minimum thickness concentrates in contact regions of the workpiece and the long axis of the punch, and (iii) as the punch arc radius and the die arc radius increase, the limiting draw ratio is increased.

Claes Magnusson of Volvo cars body components and Roger Andersson of Swedish tool and die technology has described a study on high strength stainless steels and carbon steels at Volvo cars body components. The austenitic stainless steel and carbon steel undergo a microstructural transformation during plastic deformation. The traditional forming limit curves index the formability to low for these types of materials. Instead, a forming limit dome height diagram (FLDH) should be used to index the formability. The study showed that the crash impact absorbing capacities of high strength stainless steel was highest since the material had the highest yield stress of all the materials under their study. If stainless steel should be a material for weight savings, then it must take advantage of better formability to make thinner components with complex cross sectional area, with the same or improved stiffness and strength and this could be a possible way for stainless steel to become a new alternative for ultra high strength steels.

A study was carried out on the forming process, formability and the tribological properties of stainless steels by Erik Schedin of Avesta polarit, R&D. The techniques used for forming stainless steel sheet were basically the same as those used for forming carbon steel. Due to the lower normal anisotropy value (for austenitic stainless steel R value is approximately 1 where as for carbon steel R >2), it was not possible to draw workpieces so deeply by drawing material from the blank holder. So, certain modifications were required with regard to tool selection, tool material and lubricant in order to exploit the full potential of stainless steel forming properties. Austenitic stainless steel has inferior deep drawing properties compared to the carbon steels and this can be compensated for by the improved ability of austenitic stainless steel to resist thinning.

2.4 NON CONVENTIONAL DEEP DRAWING AND ITS PROCESS PARAMETERS

Requirements regarding the design of a part and the need for economic effectiveness lead to high demands of multifunctional parts with complex geometries. These demands regarding accuracy, sharp contoured component production and surface quality are very difficult to achieve by conventional forming process. In this context, serious problems are encountered while processing the high strength materials. So, the researchers are directing their efforts and energies to find an alternative or improved method of forming operations to achieve the above mentioned goals.

2.4.1 Electro Hydraulic and Hydro Mechanical Forming

Homberg et al (2010) investigated the forming of sharp edged contours by electro-hydraulic forming method. This forming method is a combination of quasi-static hydro forming and high speed forming methods. Different experimental set ups like (i) hydro forming (ii) high speed hydro forming (iii) electro hydraulic and (iv) pneumo mechanical were made and the results were compared. It was found that much smaller radius of 0.8mm could be achieved at discharge energy of less than 6 kJ in electro-hydraulic forming method when compared to the other methods.

Lang et al (2009) simulated warm hydro mechanical deep drawing of circular cups from aluminium alloy blank sheet of thickness 1.4mm up to the processing temperature of 300^{o}C using MSC.Marc. It was found from the simulations that, in the differential temperature forming process, the maximum drawing height increased as the temperature was increased and the critical fracture region moved from the punch corner to the die corner. Increase in punch speed decreased the drawing height and at 300^{o}C, the maximum drawing height decreased drastically.

Groche et al (2008) presented a technique that combines the hydro mechanical and warm deep drawing to reduce the drawing force and to increase the transmittable drawing force in the drawing of aluminium sheet by flange heating using laser radiation and also using a counter pressure. It was observed that the same limiting draw ratio as in deep drawing with a local heating was achievable in hydro mechanical deep drawing with thermal support at 200^{o}C instead of 250^{o}C. Also, a reduction of the drawing force of at least 20% at constant drawing ratio was recognized.

Aimei Zhang et al (2011) proposed a novel hydro mechanical deep drawing process for magnesium alloy sheets at gradient temperatures. It is the combination of hydraulic drawing and thermal drawing and the hydraulic can cool the sheet directly during drawing whereas the hydraulic pressure's inherent advantage for the deep drawing can further improve the quality of the drawing cup. The ideal temperature gradient can be obtained by controlling the condition of heating the flange and cooling the cup reasonably. A reasonable temperature gradient was obtained by controlling the fluid injection time during the deep drawing. It was concluded that the LDR value had improved due to the gradient temperature.

Yongchao Xu et al (2004) performed a warm hydro mechanical deep drawing of 0.8mm thick stainless steel 304 circular cups. The processing temperature was from 30^{o}C to 150^{O}C and in this range of temperatures, the deep drawing could be easily performed with respect to the fluid medium, seal, and hydraulic system. It was concluded that, at the temperature 90^{o}C, the formability of stainless steel was improved and property parameters like n-value and R-value was in favour of the process. It was also found that the limiting drawing ratio had increased to 3.3 greatly beyond the forming limit of 2.0 with the conventional deep drawing and the effective control of strain induced martensite, weakening of working hardness and strength of phase transformation were observed.

Swadesh Kumar Singh and Ravi Kumar (2005) applied artificial neural network (ANN) to predict the thickness along a cup wall of the components formed by hydro-mechanical deep drawing of low carbon extra deep drawing grade steel sheets of 0.96 mm thickness. Experiments were conducted and their results were used to train and test the ANN, which uses feed-forward back-propagation neural network, and a finite element simulation of the process was carried out using LS-Dyna 2D package. The experiments and simulations have shown that good quality products can be made by counter pressure deep drawing because of more uniform distribution of thickness strain as compared to conventional deep drawing.

Abdolhamid Gorji et al (2011) studied the forming pure copper and St14 conical-cylindrical cups in the hydrodynamic deep drawing process using experiment and finite element simulation. The effect of pressure path on the occurrence of defects, thickness distribution and drawing ratio of the sheet was investigated. It was concluded that, for the pressure paths with lower maximum pressures, the forming process were similar to the conventional deep drawing and because of high stresses applied on contact area of the sheet with the punch tip, local thinning or bursting occurred in this region. At higher maximum pressures, the part was formed, but the wall thickness distribution and the maximum thinning depended on the pressure path.

2.4.2 Warm Hydro Forming

Ho Choi et al (2007) developed an analytical model for warm hydro mechanical deep drawing to investigate the effects of process parameters. The analytical approach was applied to the deep drawing of aluminium and magnesium alloys of 1.05 or 1.2mm thickness up to the temperature of 260^{o}C. Finite element models were developed to validate the analytical model and the results were compared with the experimental results also. It was observed that under lower flange temperatures, higher hydraulic pressures were required and also the hydraulic pressure should be increased to ensure the floating conditions as well as radial drawing. The punch force decreased when the flange temperature is increased and depending on the floating conditions, it was decreased up to 4%.

Zhang et al (2007) investigated the warm hydro forming of rectangular shaped component of magnesium alloy of thickness 0.7mm up to the processing temperature of 200^{o}C. The influences of process parameters like forming temperature and pressure were studied to obtain the optimum value. It was observed from the experiments that the quality products were produced at the temperature 170^{o}C with the bulging pressure of 2MPa and the most suitable forming temperature range appeared to be 150- 200^{o}C.

Eren Billur et al (2009) performed the warm hydro forming using different grades of stainless steels of different thicknesses(AISI 201- 0.55mm thick, AISI 301- 0.76mm thick and AISI 304-1.0mm thick) up to the temperature of 200^{o}C.The deformation characteristics of three austenitic stainless steels were investigated using hydraulic bulge tests at cold and warm conditions. The flow curves were drawn for these materials and were used in FE simulation by MSC Marc. The conclusions that were arrived from the results were (i) Strain rate sensitivity of AISI 301 was significant even at room temperature whereas in AISI 304 it was not. (ii) AISI 201 grade had the highest formability, however, the strain rate sensitivity and stress level required was higher compared to other grades and (iii) the error percentage of the results got from FEA were 7.8% in height profile on the average and the maximum was 15.6% whereas in thickness prediction it was 7.5% and 16.4% respectively.

2.4.3 Electro Magnetic Forming

Warm electromagnetic forming (EMF) experiments were conducted up to the temperature of 250^{o}C by Ulacia et al (2010) using magnesium alloy sheet. In warm conditions, the yield strength as well as electrical conductivity of a material is decreased and increasing the forming temperature, for a given discharged energy, the height of the deformed part is decreased. So it was concluded that, in drawing operations, the influence of the electrical conductivity is more important than the decrease of flow strength, while in bending, the decrease in yield strength is more important.

Geier et al (2010) built a test bench for EMF of thin metal sheets for laboratorial experiments. Among the aspects considered for design, energy efficiency had been prioritized by the use of non conducting material to the dies. It was observed from their study that the main switch discharge was one of the most critical items of the system. Aluminium sheet plates of up to 3mm thick were successfully deformed by the proposed EMF machine.

Risch et al (2008) tried an innovative forming technique which was a combination of conventional deep drawing and in process electromagnetic forming. All the experiments were done with 1.2mm thick aluminium alloy and with the discharge energy of 2.6 kJ. The results showed that the geometry of the whole part could be achieved with good accuracy and without any significant deviation from the desired shape.

2.4.4 Superplastic Forming

Chandra and Kannan (1992)(i & ii) developed a model relating to the process parameters for the superplastic sheet metal forming of a generalized cup by considering (i) uniform thinning and (ii) non uniform thinning. These formulations are applicable to the forming of domes, right circular cylinders, deep slanted cups, and cones. The thickness profile and pressure-time profile were evaluated for a generalized cup based on the geometry of the forming profile in both cases. Pressure-time relationships were developed for maintaining superplastic conditions in the deformed materials, and the final thickness of the components for these shapes is determined.

Jung-Ho Chang (1996) developed a procedure for determining the parameters in a selected material model from a superplastic blow forming test. Analytical solutions were derived to correlate the true stresses and true strain rates from the experimental measurements of the inflation height of a hemispherical dome. Numerical solutions were also obtained using ABAQUS software and compared with the experimental results. The cost of the experimental devices of the present method was only one-tenth of that of the high precision tensile test equipment used conventionally for the same purpose.

Hwang et al (1997) proposed a mathematical model using the finite difference method and considering non-uniform thinning in the free bulged region to examine the plastic deformation behavior of the sheet during the blow forming in a circular closed die. It was concluded that (i) the forming pressure increased and the forming time decreased with increasing die entry radius, die diameter, whereas the pressure decreased and the time increased with increasing friction coefficient, height of the die and strain rate sensitivity (ii) the uniformity of the thickness distribution increases with increasing die entry radius, die diameter, and strain rate sensitivity, whereas it decreased with increasing height of the die and friction coefficient.

2.4.5 Warm Deep Drawing

Zeng and Mahdavian (1998) developed a theoretical model to predict the critical conditions of wrinkling and the number of wrinkles, both at room temperature and at elevated temperatures (100, 200 and 250^{o}C). The results of the theoretical solution were compared with the experimental results obtained by warm deep drawing of 1.0 mm thick aluminium. The blank, the die and the punch were heated in the furnace at a particular temperature prior to the test and then they were placed in the press. The results showed that the number of waves in case of free drawing was dependent only on the geometry of the drawing and was independent of material properties and even the elevated temperature of the blank.

Bolt et al (2001) carried out a study on the feasibility of using warm forming of box shaped and conical rectangular products with aluminium alloy of different thicknesses at 100^{o}C to 250^{o}C. The die and the blank holder were heated by means of electrical heating rods, which were located at the corners, whereas the punch was kept at room temperature by water cooling. It was found from the experiments that the maximum height of a box shaped product was increased by 25% when a die temperature was at 175^{o}C. Also, it was seen that within the range of the test temperature, warm forming did not have a strong effect on the hardness of the products and it offered the possibility of drawing complicated aluminium sheet products, which could not be made at room temperature without extra forming and/or joining operations.

Shyong Lee et al (2002) investigated the warm forming of extruded magnesium alloys of different thickness sheets (0.5, 1.3, 1.7 and 2.0 mm) at different temperatures up to 500^{o}C. There were two types of tooling employed, one with punch and the other punch less in which a pressurized gas was used to press the sheets into a die. At high temperature of 435^{o}C, all the specimens were formed successfully. At intermediate temperature, only one out of the five specimens was successfully formed and this indicated that other parameters such as lubrication, punch speed and clearance could exhibit an influence when the temperature factor was not dominating. The failures in this category occurred mostly at the corners where the punch exerted a concentrated pulling force to drag the sheet down, which is avoided in gas forming method. By gas forming, it was possible to deep draw 0.5 mm thick sheet successfully, which was considered to be an industrial challenge.

The study on the effects of warm deep drawing on the 1.0 mm thickness TRIP steel sheets and possible factors to improve the drawability was carried out by Dae Gyo Seo et al (2002) from room temperature to 250^{o}C. Finite element analsis also was performed using LS-Dyna code and results were compared with the experimental values. As a result of the study, the following conclusions were made: (i) the maximum drawing ratio and the maximum drawing depth increased slightly, from 2.2 to 2.3 and 28 mm to 30 mm respectively, and the maximum drawing force was decreased, (ii) the through-thickness strain was more uniform at elevated temperatures than at room temperature, and (iii) the formability of the TRIP steel sheet could be improved if the warm forming process were conducted within the range of 100-150°C.

Attempts were made to investigate the efficiency of sheet metal forming process at elevated temperatures by Emin Erdin et al (2005). The experiments were conducted using titanium copper alloy and low alloy steel blanks of 1mm thickness under the influence of temperature up to 850°C. Heating was done using electric current which passed through the die and/or the punch and sheet metal and localized heating was realized. Results gained from the researches are: (i) as the deformation temperature increases, the flow stress and maximum strength values decrease, maximum strain increases, hardening parameter (n) and strength factor (K) drop (ii) the deformed material's hardness increases when processed in room temperature, decreases when warm formed, and increases due to micro structural changes at hot forming (iii) the plastic anisotropy is a significant parameter for deep drawing since the plastic deformation properties of steel sheets are related with the rolling direction.

Palumbo and Tricarico (2007) performed a warm deep drawing process of circular 0.8mm thick specimens in aluminium alloy at the temperature range of 100-250°C. The blank holder was heated using electric heating rods and the punch was cooled by circulating the water at a different flow rates. Tests were performed to evaluate the effect of the most important process parameters affecting the WDD process: the strain rate and the temperature of the material in the critical regions like the centre of the blank and near the punch radius. It was noted that the high punch speed values led to early fracture of the blank and smaller cup height under the same maximum load required. Also, if the temperature was less than 110°C in the blank centre, the effect of material softening was predominant causing a load to decrease and when increasing the temperature in the centre to 125°C, the friction effect became dominant causing the friction tangential stress to increase.

Palumbo et al (2006) investigated the warm deep drawing of 0.6 mm thick magnesium alloy circular cups processed up to the temperature of 250°C. Three different heating strategies were employed: (i) heating the die and the blank holder using electric heating system up to the test temperatures while the punch and the blank were at room temperature (P); (ii) heating the die and the blank holder and cooling the punch by water circulation and it is kept far from the blank during heating phase (CP); (iii) cooled punch kept in contact with the blank during the whole heating phase (CPC). It was observed that the temperature at the blank centre was almost the same in both cases of CPC and CP while differences are limited to the blank holder region. Thus the corresponding higher punch load for the case CP could be justified with the lower temperature in the flange region of the blank.

Qun-Feng Chang et al (2007) (ii) experimented warm deep drawing of 0.8 mm magnesium alloys by variable blank holder force control. The die, sheet and the blank holder were heated by heating rods at the same time. In order to set the appropriate variable blank holder force profiles, the theoretical analysis was carried out on the basis of the principle of energy conservation. The experiments revealed that when the blank holder force (BHF) was too high (6KN), the holder restricted material flowing into the die cavity resulting in insufficient metal flow which caused tearing. However, when the BHF was too low (3KN), excessive material flow would cause wrinkles at the flange. It was revealed that the lowest wall thinning ratio decreased from 15.21% to 12.35%, if the variable BHF was adopted.

The main objective of the study carried out by Serhat Kaya et al (2008) was to determine the effects of various process parameters on warm deep drawing of round cups from aluminium and magnesium alloys of different thicknesses (1.2 and 1.3 mm) up to the temperature of 300°C. The die and the blank holder were heated with the cartridge heaters, while the punch was cooled approximately to the room temperature with water circulation. It was very clear that the higher temperature helped in reducing the thinning, due to the reduced bending stresses at the cup bottom corner which was the location of maximum thinning. Maximum thinning could take place at two locations in the cup, either at the cup bottom corner or in the cup wall just after the cup bottom corner. The results indicated that the location of maximum thinning depended on the initial size of the blank.

Analyses were performed by Ren et al (2008) to investigate the influences of deformation behavior of 0.7 mm thick magnesium alloy at warm working conditions. Heating rods were positioned inside the blank holder flange as a heating system and during the heating phase, the punch was far away from the heat source. The working range of temperature was from room temperature to the 300°C and the punch speed considered was 6, 15 and 60 mm/min. Three types of blank (i) right angled corner, (ii) round corner and (iii) chamfer corner were used. With the three types of blank shapes, the fractures all occurred in the cup wall along the diagonal of the drawn cup and in the vicinity of the punch corners during the experiments. It was observed that the elongation increased and the degree of work hardening decreased with the increase of temperature.

Hong Seok Kim et al (2008) developed an analytical model to investigate the effects of material, process, and geometric parameters in the warm forming of aluminium alloys under simple cylindrical deep drawing conditions. The initial blank thickness of 1.0 mm was used and the working range of temperature was from room temperature to 250°C. In isothermal condition, the critical failure location, where the limit strain developed, was the punch corner region. However, in non-isothermal condition, relatively uniform straining and thinning was observed at the same part depth. It was also shown that the increased temperature of the flange region delayed the onset of localized thinning and shifted the failure site to the die corner region due to the improved ductility of flange material and the increased flow stress of the punch corner region.

Warm deep drawing of magnesium alloy rectangular cups were made by Ren et al (2009) to evaluate the effect of the most important process parameters at a temperature from room to 250^{o}C. As a heating system, six 300W power heaters were positioned inside the equipment and during heating phase, the punch was kept far from the heaters and the blank was clamped between the blank holder and the die for a short time before drawing. It was highlighted from the experiments that the fracture occurred in the cup wall just above the punch radius since this region transmitted the largest deformation forces during the forming process. It was found that the sound cups were formed at 150^{o}C with the punch speed of 6 mm/min, when the temperature was increased up to 250^{o}C, defect free cups were formed with the highest punch speed of 120 mm/min.

Heung-Kyu Kim and Woo-Jin Kim (2010) attempted within the framework of continuum damage mechanics to propose a generalized version of the failure criteria based on Zener-Holloman parameter. To evaluate the predictability of the proposed fracture criteria, deep drawing of circular cups of 0.8mm thick magnesium alloy were conducted at different punch velocities and different temperatures (150 and 250^{o}C). The die and the blank holder were heated to the same temperature as the material and the punch were cooled by circulating water at 5^{o}C. It was found that the Zener- Hollowman parameter could be greatly affected by the microstructure parameter, such as grain size, as well as the size and volume fraction of the second phase.

Investigations on the influence of the temperature on the residual stresses and spring back effect were done by Grèze et al (2010) at elevated temperatures on aluminium alloy material. The deep drawing tests were performed in a heating furnace with a controlled temperature, in the range from 25 to 200^{o}C. It was observed that the increase in temperature tended to decrease slightly the thickness due to higher restraining forces compared to the yield stress. Warm forming condition reduced the maximum punch force needed for the forming of the cup which increased significantly the lifetime of the tools. The distribution of hoop stress in the cup wall was the main factor influencing the spring back in warm forming.

JaeHyung Cho et al (2010) studied the warm deep drawing of 0.6mm magnesium alloys prepared by twin roll strip rolling (TRC) and conventional ingot casting (IC) at various working temperatures ranging from 200 to 300^{o}C and punch speeds of 30, 40 and 50 mm/min. From the cup thickness measurements, it was seen that the curved region between the bottom and the cup walls showed the thinning effect and the flanges were thicker than any other region. At the temperature of 225^{o}C, deep drawing of the TRC samples was only successful at a speed rate of 30 mm/min whereas the IC samples succeeded in deep drawing at temperatures of 225-350^{o}C.

Pengcheng Wang et al (2011) investigated deep drawing of magnesium alloy of 3mm thickness at elevated temperatures. The cylindrical cups were produced and analyzed at different temperatures and under different forming speeds. The die and the blank holder were heated using heating rods which were inserted inside of it and the punch was kept at room temperature. Drawing performance of the cylindrical parts was gradually improved as the temperature was increased from room temperature to 325^{o}C and it decreased when the temperature exceeded 350^{o}C. Also, at 300^{o}C and punch velocity of 4mm/min, the wall thinned down at the punch corner or on the cup wall just nearby the punch corner and the maximum thinning observed was 30%.

Chang and Chou (1995) conducted deep drawing tests to examine 0.8 mm thick SS304 cylindrical cups produced at room temperature and 100^{o}C. Deep drawing was performed under a single temperature or two temperatures on both sides of the sheet. The two temperature processes meant that the warm working was done by heating the die and the punch was cooled, while the single temperature process indicated only heating or cold working. The results have shown that, at room temperature, a smaller range of drawing depth was associated with a much larger strain value. It was concluded that the rate of shear straining at the punch shoulder portion relative to the drawing depth was highest at room temperature. This could be reduced by increasing the processing temperature and the best results were obtained during two temperature deformation processes.

Stachowicz et al (2010) aimed at the improvement of plastic flow of the stainless steel material as well as to decrease the spring back effect of the formed component. Their investigation dealt with the effect of temperature in the range from room temperature to 700^{o}C on the basic material parameters. The following observations were made from the experiments: (i) both the yield stress and ultimate strength decreased with the increase of deforming temperatures,(ii) the ultimate elongation value increased with temperature, especially at highest temperatures, (iii) the uniform elongation achieved local maximum at the temperature of 500^{o}C, then decreased and again increased at the temperature of 700^{o}C, (iv) the value of strain hardening exponent decreased slowly with the temperature and more rapidly in the higher temperature range, and (v) the value of young’s modulus decreased with the increasing temperature.

2.5 METALLURGICAL ANALYSIS IN WARM DEEP DRAWING

The study on the metallurgical aspects like microstructure, grain size, micro hardness etc., are also have to be considered with equal importance like the process parameters, since the microstructure and the grain size greatly influence the mechanical properties of the material and also the drawing characteristics of the same.

Lee et al (2007) (i) investigated the microstructure evolution of magnesium alloys with normal rolling (NR) and different speeds rolling (DSR) during hot rolling. The methods of production of sheets affected the microstructure, texture and mechanical properties of magnesium alloy sheets. It was found that the boundaries of recrystallized grains with low density of dislocations were surrounded by some large crystallized grains. It was noted that the DSR samples were having good formability when compared to the NR samples. From the results, it was concluded that the DSR process had more influence on the improvement of grain refinement and press formability at the temperature around 500 K.

The deformed microstructure of the deep drawn components of magnesium alloy sheet at various forming temperatures was studied by Lee et al (2008). It was observed that the dynamic recrystallization started or proceeded slightly at forming temperature of 250^{o}C and 350^{o}C. On the other hand, the dynamically recrystallized microstructure progressed and necking began because of larger post uniform elongation.

JaeHyung Cho et al (2010) investigated the texture and microstructure evolutions during deep drawing of magnesium alloy sheet at various temperatures and deformation rates. From a viewpoint of microstructure and texture, fine grains and non basal texture were preferred for metal forming. During rolling of magnesium alloy sheet, strong basal textures usually develop and this result in poor workability and to alter the microstructure and the texture, twin roll casting (TRC) and ingot casting (IC) was used to prepare the magnesium alloy sheets. Microstructures taken from deep drawn cups using electron back scatter diffraction (EBSD) had showed that the IC samples had greater grains than TRC samples and the bottom region experienced little deformation during drawing and hence showed larger grains than the cup wall.

Investigations on warm deep drawing of metastable austenitic stainless steels by Livitsanos and Thomson (1977) suggested that increased drawing ratios may be achieved by allowing controlled transformation to martensite at a strain close to that at which instability of the austenite would otherwise occur. A maximum elongation temperature (M.E.T), the temperature at which the major principal strain is maximum, determined from tests in uniaxial tension, is usually quoted. The strain induced transformation of austenite to martensite, manifesting itself as an unusual work hardening which can provide an improved combination of strength and ductility, is of major importance in the mechanical working and therefore, significant in the warm formability of some austenitic steels. The results of their work have suggested that (i) the increase in tensile ductility with test speed of the specimens tested at $40^{o}C$ can be attributed to a decrease in the amount of martensite resulting from adiabatic heating during testing at higher speeds, (ii) the amount of martensite formed in tests at the lower temperatures is much greater than at the higher temperatures, and (iii) the amount of martensite formed at any given temperature approaches a constant value as test speed decreases.

Hadji and Badji (2002) studied the effect of austenite stability on the evolution of microstructure and mechanical properties of three austenitic stainless steels during cold rolling. The purpose of the study was to elucidate the effect of nickel content on the phase transformation of Cr-Ni austenitic stainless steel with respect to the formation of deformation induced martensite. In addition, the relationship between the change in microstructure and austenite stability with respect to strain induced martensite (SIM) formation (α′) was also investigated. Stress assisted martensite (SAM), with body-centered cubic (BCC) crystal structure, was formed during deformation. From the experimental data obtained, the following observations were made: (i) the volume fraction of SIM formed during deformation was grain size sensitive in 304 stainless steel and insensitive in 316 stainless steel and (ii) the strain hardening behavior indicated the contribution of both α′-martensite and grain size strengthening in case of both 304 stainless steels, while only the grain size contribution was found in 316 stainless steel.

The hot deformation behavior and the microstructural evolution of AISI 904Lsuper-austenitic stainless steel was investigated by means of hot compression tests by Bradaskja et al (2011). The measured mean grain size for the as-received material was 80 µm and after soaking at 1200^{o}C, before deformation, it was 140 µm. The austenite grains containing annealing twins are characteristic for the low stacking fault energy alloys. In the samples deformed with higher strain rates (1s^{-1} and 5s^{-1}) and below 950^{o}C, there were no recrystallized grains to be found in microstructure. However, the samples that were deformed either at temperatures above or below 950^{o}C with lower strain rates (below 0.1s^{-1}), recrystallized.

2.6 FORMABILITY IMPROVEMENT IN WARM DEEP DRAWING

Formability of a material is one of the important properties to be considered in deep drawing process since it is more useful in (i) designing of draw tools, (ii) deciding the number of tools required to form the desired component, (iii) understanding the ability of the material to attain the desired size and shape without any defects etc. Simple mechanical property measurements made from the tension tests are of limited value in sheet metal forming due to the complexity of the process. The formability is expressed in terms of limiting draw ratio (LDR), maximum drawn cup height etc. In the past few decades, the researchers were concentrating on the improvement of formability of low formable metals and alloys like aluminium and magnesium etc, as well as alloys like steel and stainless steel etc which have better formability than aluminium but difficult to process.

Jae Dong Lee et al (2001) studied some deep drawing characteristics at elevated temperatures for steel sheets by using chromium coated die. For this investigation, six different temperatures between room temperature to 250^{o}C, and six different drawing ratios ranging from 2.4 to 2.9 were considered. The conclusions made from the experimental results are as follows: (i) for the drawing ratio of 2.4, the maximum drawing depth (around 40 mm) is possible at all temperatures, (ii) for the drawing ratio of 2.6, the drawing depth is about 26 mm at room temperature and the maximum depth is achieved at the temperature of 100^{o}C or above, (iii) for DR of 2.8, the maximum depth is possible only at the temperature of 250^{o}C and this depth is 1.8 times that at room temperature, and (iv) for the DR of 2.9, the drawing is impossible up to the depth of 40 mm at any temperature and at 250^{o}C, the depth formed is 1.6 times larger than the value measured at room temperature.

Takuda et al (2002) investigated the effect of the die profile radius on the forming limit of aluminium alloy sheet in the deep drawing tests at room temperature and at 250^{o}C. Circular cups were made using the dies with different profile radius of 3, 5, 7.5 and 10mm. In deep drawing at room temperature, the forming limit depends on the fracture around the punch corner, and the limiting draw ratio was only about 2.1, almost independent of the die profile radius. In the warm deep drawing, the forming limit depends on the fracture around the die corner and the limiting draw ratio increased with the die profile radius and amounted to 2.8 for the radius of 10 mm. Also, the limiting draw ratio increased with the increasing processing temperatures.

Shoichiro Yoshihara et al (2003) made a study which aimed to clarify how much the formability of the magnesium alloy sheet could be enhanced by warm deep drawing technique with variable blank holder pressure (BHP) control. A magnesium alloy sheet of 0.5 mm thickness was deep drawn by heating at the flange and cooling at the die throat and punch parts. In the constant temperature study, the LDR was limited to 2.14, where as the LDR values of 3.6 and 4.0 were obtained by local heating and constant quantity of direct cooling water injection with constant BHP. LDR value of 5.0 was attained by injecting the cooling water with variable BHP control adjustment. The fracture was avoided by improving the strength of the material at the punch shoulder part by injecting cooling water directly into the drawn cup.

Comparison of formability was made by Zhang et al (2005) on the fine grained magnesium alloy sheets which were produced by extrusion and various rolling process. Warm deep drawing operations at the temperature range of room temperature to 400^{o}C were carried out to investigate the effect of different variables on the formability. It was seen that the extruded magnesium alloy sheets exhibit the best deep drawability when working in the temperature range of 250-350^{o}C. Extruded and rolled sheets of 0.8 mm thick were also deep drawn in the lower temperature range of 105-170^{o}C, showing good formability and reaching a LDR up to 2.6 at 170^{o}C for rolled sheets. The reason for these results is that the cross rolled magnesium alloy sheets have more uniform equal axis microstructure and low anisotropy resulting in improved formability and good deep drawability at low temperatures.

Investigation was done on the formability of magnesium alloy sheet which was produced by the multi pass friction stir process (FSP) by Sato et al (2005). The formability was evaluated using a FLD and this diagram shows the critical combination of ε_{major} and ε_{minor} in the sheet surface at the onset of necking. The higher the ε_{major} in FLD, the higher the formability the material has. The tests results revealed that the sheet/ plate containing this FSP microstructure exhibited fracture limit major strains six times larger than the die cast sheet in the FLD.

An experimental study was carried out on the formability of non isothermal deep drawing at elevated temperatures of magnesium alloy of 0.5 and 0.58 mm thickness sheets by Tyng-Bin Huang et al (2006). The forming temperature, lubricant and sheet thickness were considered to be the main factors influencing the formability of the material. The results had shown that the peak punch force with molybdenum disulfide was lower due to lower coefficient of friction value, whereas the oil no.5 had higher peak punch force, which was more than the limit strength, and hence the blank fractured. The highest LDR obtained at 260^{o}C for 0.58 mm thickness sheet was 2.63 for molybdenum disulfide and 2.37 for oil no.5 whereas at 200^{o}C for 0.5 mm thick sheet, it was 2.5.

Hong Seok Kim et al (2006) (ii) performed an experimental study to determine the failure criteria in warm forming of aluminium alloy sheets. Three different criteria (maximum load, minimum thickness and thickness ratio) were studied to evaluate their applicability and accuracy in predicting the failure during forming operation. It was noticed that when the die temperature levels were 200, 250 and 300^{o}C, part depth decreased with increasing punch temperature whereas when the die temperature was 350^{o}C, the variation of the part depth was not dependent on the punch temperature. Less than 10% increase of part depth values was observed as the punch temperature changed from 200 to 350^{o}C. The FLDs obtained from the experiments at the temperatures of 250, 300 and 350^{o}C had shown that the forming limit strain increased with increasing temperatures, especially, it was notable between 250 and 300^{o}C. In general, the larger temperature differences between the die and punch and lower BHP resulted in the improvement of formability.

Palumbo et al (2007) focused their work on the warm deep drawing by superimposing a thermal gradient between the blank centre in contact with the punch and the blank flange which was going to be drawn in order to improve the limiting draw ratio. As a final result of the investigations, it may be stated that the amplitude of the temperature gradient is the key for enlarging the drawability of the magnesium alloys. By decreasing the punch speed from 30 to 6 mm/min, the LDR value is increased from 2.2 to 3.25 at blank holder temperature of 180^{o}C and from 2.8 to 3.375 at blank holder temperature of 230^{o}C. By means of decreasing the DR or increasing the blank holder temperature, the maximum punch speed is able to avoid ruptures in cup could be remarkably raised.

A systematic study was carried out by Qun-Feng Chang et al (2007) (i) on the formability of magnesium alloy sheet, including the studies on magnesium sheet rolling, the uniaxial tensile tests and the LDR experiments in the range of temperatures of 150-300^{o}C. The raw material was the extruded plate with a thickness of 1.2 mm and this extruded plate is very poor in formability due to its coarseness and non uniform grains. A multipass cross rolling was performed to refine the grains and the final thickness was reduced to 0.6 mm and then, annealing was done to make the alloying ingredient more homogeneous. Experiments have shown that the LDR value obtained at the temperature from 150 to 200^{o}C was 2.5 and at temperature from 200 to 300^{o}C, it reached to 3.0 due to the good formability of the material.

Lee et al (2007) (ii) investigated on the formability of magnesium alloy by warm deep drawing square cups at temperatures up to 400^{o}C. Poor formability characteristics of magnesium alloy sheet causes difficulties in designing the die for complex shaped parts and hence the data for forming limit of the material is necessary to prevent the defects and get the dimensionally accurate components. But the data establishment of the forming limit is not easy because of many stress situations and further, the forming limit prediction is still more complicated due to the temperature effect. It was observed that the defect free square cups were formed at 250^{o}C whereas fractures were generated at each corner at room temperature due to localized necking and at 400^{o}C due to diffuse necking.

Serhat Kaya et al (2008) performed warm deep drawing process using aluminium and magnesium alloy sheets to determine the effects of initial blank temperature and constant/variable punch velocity on the attainable LDR and the formed cup quality. Also, several lubricants for elevated temperature forming were evaluated using the deep draw tests. The experimental results of deep drawing of aluminium alloys have shown that the LDR value of 2.1 was achieved at room temperature with the punch velocity of 50 mm/sec whereas it was 2.9 at 300^{o}C when the punch velocity is 2.5 mm/sec. In case of deep drawing of magnesium alloy, the forming of components was not successful at room temperature and at 300^{o}C, the LDR obtained was 3.2 for the punch velocity of 2.5 mm/sec.

The relationship between the strain rate and the formability was studied by Lee et al (2008) to predict the occurrence of failure in square cup deep of drawing of magnesium alloy sheet processed under the temperature up to 400^{o}C. The failure occurrences according to the strain rate at 250^{o}C forming temperature were predicted by the measured FLD curve. It was concluded from the experiments that (i) the UEL was decreased by increasing the temperature and increased by the increasing strain rate. On the other hand, the post- UEL increased with higher temperature and lower strain rate and (ii) forming limit by FLD test was worse on higher strain rate. Also, the failures occurred frequently at high forming speed on square cup deep drawing.

The influence of deformation conditions on the formability of magnesium alloy was systematically investigated using the warm working experimental method by Ren et al (2008). From a large number of tests, it was noted that the highest drawn depth was always obtained with the lowest punch speed of 6 mm/min, while at high speed of 60 mm/min, the fracture occurred in the formed parts at the temperature of 250^{o}C. This is because the ductility of magnesium alloy decreases significantly with the increasing strain rates, making the drawing-in of the flange rather difficult and thus lowering the deep drawability. The optimum process parameters, including forming temperature of 250^{o}C and the punch speed of 6 mm/min, were proposed for warm deep drawing of rectangular cups with 0.7 mm magnesium alloy.

Zhang Tingfang and Xie Shikun (2010) attempted to study the constitutive relationship of ME20M magnesium alloy sheet at different temperatures (up to 250^{o}C) and different strain rates, including the softening factor also. Magnesium alloy has shown flow softening behaviour during deformation at high temperatures, which increases the difficulty to describe the flow stress behaviour at high temperatures. Flow softening may be caused by the deformation heat and microstructural instabilities inside the deforming material, such as texture formation, dynamic precipitation and dissolution. The experiments have revealed that the maximum deep drawing height obtained at room temperature was 5.33 mm and this draw height increased with the temperatures and the maximum height achieved at 300^{o}C was 15.98 mm.

Swadesh Kumar Singh et al (2010) (i) investigated the warm deep drawing process to find the formability and the friction coefficient of extra deep drawing steels (EDD steels). The initial blank thickness used was 1.0 mm and the working temperature range was from ambient temperature to 200^{o}C. The investigations have revealed that the LDR value obtained was 2.43 at 200^{o}C against the LDR of 2.23 at room temperature. Also it was noticed that the extent of thinning was more at room temperature and thickness was more uniform in the formed cups at 200^{o}C.

Pengchang Wang et al (2011) performed the warm deep drawing at different temperatures and at different drawing speeds on 3mm thick magnesium alloy sheets to understand the formability of the material. The unidirectional hot tensile tests showed that the hot deformation of magnesium alloy was the dynamic balance of competing both the work hardening and dynamic recrystallization process of softening. It was observed that the deep drawing performance gradually improved as the temperature was increased from room temperature to 300^{o}C. In between 300-325^{o}C, the height of the parts was between 22.64 to 23.4 and the LDR was 2.0 to 2.02, but, as the temperature was increased further, the drawing performance decreased and when the temperature exceeded 350^{o}C, crack occurs.

Chinouilh et al of Arcelor Mittal global R&D/ Arcelor Mittal stainless Europe studied the behavior of stainless steel and predicted the forming limit diagram for the same by both experimental and analytical methods. Strain rate and consequently temperature gradient might have a significant influence on the hardening of unstable stainless steels and consequently on their forming and crash behavior. The final model took into account of four parameters: (i) the hardening coefficient (n), (ii) the rate sensitivity coefficient (m), (iii) the Lankford parameter (R) and (iv) the thickness. This model provided a good prediction of the FLD level and obtained 85% in austenitic grades and 80% in ferritic grades, of the results with an error lower than 0.03 for major strain and 92.5% in austenitic grades and 100% in ferritic grades, of results with an error lower than 0.05.

Takuda et al (2003) examined experimentally the forming limit of stainless steel 304 of 1 mm thickness in warm deep drawing that was carried out at the room temperature to 150^{o}C. For the warm deep drawing tests, the die and the blank holder were heated by the built-in heaters in the tools, while the punch was cooled by the circulation of water under 10^{o}C. In comparison with the mild steel sheet, the dependence of the tensile properties of the type 304 stainless steel upon temperature was notably high and only the normal anisotropy parameter, R, was almost constant at 1.0, independent of temperature. The experiments have revealed that the fracture occurs around the punch corner and that the LDR is lower than 2.2 at room temperature and the LDR increases with the temperature and amounts to 2.7 at 120^{o}C.

Ajay Yadav et al (2006) conducted an experimental study on the formability of stainless steel at elevated temperatures. Material used in the experiment was stainless steel 304 of 0.87 mm thickness at the working temperature range of room temperature to 150^{o}C and the teflon resin was selected as a lubricant. The results have shown that the LDR increased with increasing die temperature and at 150^{o}C die temperature, a cup with a 2.5 draw ratio was successfully drawn. At the same time, at a die temperature of 150^{o}C, the LDR dropped from 2.5 (for forming velocity of 2.5 mm/sec) to 2.3 (for forming velocity of 50 mm/sec). This drop in LDR can be attributed to the reduced contact time between the cooled punch and the warm sheet at higher forming velocities. Also, it was found that the greatest thinning always occurred at the punch corner location, and this thinning increased with increasing LDR.

2.7 FINITE ELEMENT ANALYSIS IN WARM DEEP DRAWING

Hariharasudhan Palaniswamy et al (2004) conducted a non-isothermal finite element simulation for forming round cups and rectangular pans from magnesium alloy sheet at elevated temperatures of upto 300^{o}C. DEFORM 2D and 3D, coupled thermo-elastic-visco-plastic commercial finite element method codes were used to analyse warm forming. From the results of simulation, the following conclusions were made: (i) the forming load predicted by simulation overestimated the experimental results, (ii) the maximum thinning and tearing was observed at the cup wall in both simulation and experiment,(iii) LDR predicted by simulations for round cup for different forming temperatures was lower compared to the experimental values.

Finite element analysis using MSC Superform were carried out on non-isothermal (up to 300^{o}C) deep drawing of magnesium alloy sheets by Tyng-Bin Huang et al (2006). The forming temperature, lubricant and sheet thickness were considered as important factors to study the formability of the material. According to the simulation results, the temperature of the blank near the punch corner was lowered because of the contact with the water cooled punch, and its strength was increased and the temperature drop observed in experiment was slower than that of the simulation.

Abdel-Wahab El-Morsy and Ken-Ichi Manabe (2006) presented the investigation on finite element analysis of warm deep drawing of magnesium alloy simulated up to the temperature of 300^{o}C with two primary objectives. First, to have first-hand knowledge of warm deep drawing process considering heat transfer effect between blank and die components, second to investigate the improvement of drawability and the temperature distribution of the alloy sheet. The results of the simulations revealed the following: (i) heat transfer has strong effect on the final deformation profile of deep drawing process, (ii) the improvement in the drawability is achieved in case where the cup wall is cooled by the punch, whereas it is not under the uniform temperature condition and (iii) with increasing the punch speed, the effect of heat transfer and the cup height are decreased.

Palumbo et al (2006) aimed to study the warm deep drawing process of magnesium alloy using ABAQUS/Standard finite element simulation software up to the temperature of 250^{o}C. In addition a thermo-mechanical finite element model was used for investigating the more efficient positioning of the electric heaters and the prediction of critical conditions occurrence was based on the quantitative comparison with the forming limit diagram. The three heating techniques were used in the simulations and the results revealed that no variation in the microstructure occurred in the specimen if the temperature was kept lower during all the process.

Qun-Feng Chang et al (2007) (ii) performed the numerical simulation of warm deep drawing of magnesium alloy sheet between 150^{o}C to 300^{o}C temperatures to study the formability of the material under the influence of temperatures and variable blank holder forces using LS-Dyna. From the simulation results, it was found that the limiting draw ratio could be improved from 3.0 to 3.5, and the wall thinning ratio could be decreased from 15.21% to 12.35% by adopting the variable blank holding force technology. It was also found that the part thinning reduced not only at the round corner of the punch, but also at the other locations throughout the cylinder wall.

Lee et al (2007) (ii) investigated the formability of magnesium alloy under warm deep drawing of square cups at temperatures ranging from room temperature to 400^{o}C using LS-Dyna. Finite element analyses were also performed to reconfirm the confidence for forming limit diagram using the typically designed model. The forming limit curve was calculated based on the measured tensile properties and it could predict well the fracture of formed part by finite element method analysis.

The non-isothermal drawing process of magnesium alloy sheet, during which the temperature of the die, the blank holder and the blank were kept at 200°C while the punch was kept at room temperature, was simulated by thermo-mechanical coupled finite element method by Dayong Li et al (2007). The deformation behavior and the temperature change in the drawing process were investigated using LS-Dyna. The simulation results showed that the non-isothermal drawing could further improve the warm formability of magnesium alloy sheet through non-uniform distribution of temperature in different material areas and also the simulation provided a good guide to develop non-isothermal drawing techniques.

Finite element simulations were run in order to investigate the stress and the strain distribution in the material determined by the temperature gradient (up to 400°C) on warm deep drawing of magnesium alloy sheet using ABAQUS/Standard software by Palumbo et al (2007). The numerical simulation results confirmed that the temperature gradient between the blank bottom and the blank flange area determined an inverse yielding gradient, fundamental for the safety of the cup; in fact, it caused (i) lower drawing force and (ii) higher material strength in the cup. It may also be stated that the amplitude of the temperature gradient is the key for enlarging the formability of the material.

Yang (2008) simulated the elliptical cup deep drawing of magnesium alloy sheet at elevated temperature up to 300°C using a finite element software DEFORM-3D. It was also used to investigate the effective stress and forming loads under various process parameters. The simulation results have shown that the maximum forming load and the maximum effective stress decreased when the temperature or the die profile radius is increased, whereas, it is increased as the blank holder force is increased.

Finite element analyses were performed to investigate the effects of process parameters on the drawability of rectangular cups of magnesium alloy sheet at the temperature range of room temperature to 250^{o}C and to predict the formation of process defects by Ren et al (2009) using MSC.Marc software package. It was confirmed from the simulation results that the most important factor affecting the deep drawability of the magnesium alloy sheet was temperature and, at higher temperature, the effect of forming speed was much significant.

Heung-Kyu Kim and Woo-Jin Kim (2010) predicted the maximum drawing depths in circular cup deep drawing of magnesium alloy sheet up to the temperature of 250^{o}C using MSC.Marc finite element software coupled with the newly developed fracture criteria. The finite slement simulation showed good predictability of the dependence of drawing depth in a wide range of punch velocity at 523 K and the predictability was also good at 423 K but only at the very low speeds. It was also concluded that the proposed fracture criteria were quite useful for predicting the fracture behavior during non-isothermal warm forming.

Simulation experiments had been done to measure friction coefficients online at punch and die rounded corners under different process parameters during warm deep forming of magnesium alloy sheet (up to 250^{o}C) by Zhang Tingfang et al (2010). Coulomb friction model and dynamically changed friction coefficients models were added into the ABAQUS/Explicit by user subroutine VFRIC to build the real friction condition. From the results of simulation, it was found that the temperature showed the greatest effect on friction coefficients, the effect of blank holder force secondly, and no significant effect of lubricant on the friction coefficients.

Takuda et al (2002) simulated the deformation behavior and the temperature change in cylindrical deep drawing of an aluminium alloy sheet of 1.0 mm thickness at elevated temperatures (maximum of 250^{o}C) by the combination of the rigid-plastic and the heat conduction finite element methods. In the simulation, the fracture was predicted to occur around the punch corner at all temperatures and the limiting draw ratio decreased with increase in the temperature in case of the uniform temperature condition. It was also shown that the appropriate difference in the flow stress, due to temperature difference, must exist between the blank part around the punch corner and the part between the die and the blank holder to achieve higher drawability.

Van Den Boogaard and Huétink (2006) derived the finite element equations using coupled thermo-mechanical conservation laws to simulate cylindrical cup deep drawing of 1.2 mm aluminium alloy sheet up to the temperature of 200^{o}C. The simulations were performed with the in-house code DIEKA and only the deformable blank was modeled with finite elements. It was concluded from the results of simulations that the yield locus had an important effect on the calculated punch force-displacement curve and most notably on the predicted thickness distribution.

Hong Seok Kim et al (2006)(i) studied a two- phase procedure for efficient and accurate determination of proper temperature condition for warm forming of aluminium sheet metal blanks using a hybrid 3D isothermal/non-isothermal by ABAQUS/Explicit package and design of experiments (DOE) approach. The determined proper temperature distribution for the rectangular cup part model by simulation (up to 350^{o}C) enabled to achieve much increased formability when compared to the room temperature forming by introducing a large temperature gradient between the punch corner and the flange region of the blank. At room temperature, punch speed showed negligible influence on formability, while its effect greatly increased when the tooling temperatures were locally controlled and also lower blank holder force was preferred for the increased formability.

Combined isothermal/ non-isothermal finite element analysis with design of experiments tools using ABAQUS/Standard was used to predict appropriate warm forming temperature conditions for deep drawing by Chen Peng et al (2006). The results of simulation showed that the combination of hot blank holder and cold punch corner gave higher deep drawability of the material. It was also stated that the isothermal finite element analysis had some limitations because the blank temperature was mainly determined by the tooling temperature, but in reality, it was not a controllable factor.

Grèze et al (2010) investigated the spring back in an aluminium alloy of 1.0 mm thickness at different temperatures up to 200^{o}C from room temperature using ABAQUS. Numerical simulations of the split- ring test were performed to predict material deformation during forming and the simulated cup was partitioned into three parts to allow ring cutting and the spring back was calculated by letting the split part to relax. From the simulation results, it was found that the distribution of the hoop stress in the cup wall was the main factor influencing spring back in warm forming condition.

3D thermo-mechanically coupled finite element deep drawing of aluminium alloy sheet simulation model up to 250^{o}C using LS-Dyna and its validation was presented by Johannes Winklhofer (2010). Based on the validated simulation model, the process was optimized regarding formability and cycle time and the optimization focused on the temperature distribution of the tooling and the blank, the punch velocity and the blank holder force. The simulation results showed that increasing the tool velocity in warm forming of aluminium sheet metal was practical for industrial application, but had a negative influence on formability and optimised process strategies and advanced tailor made tooling technology could improve warm forming properties of the material.

Swadesh Kumar Singh et al (2010) (i) simulated the deep drawing of different diameter circular blanks of 1.0 mm thick extra deep drawing quality steel to investigate the limiting drawing ratio and the coefficient of friction at room temperature and at 200°C. The finite element analysis was done using a Dynaform version 5.6.1 with LS-Dyna with coupled thermal analysis. In the simulations, formability limit diagrams were used to identify the deformation step at which the deformation in the sheet reached a stage where the strains at some locations exceeded the maximum safe strains. From simulation results, it was seen that there was a uniform distribution of thickness throughout the cup wall when drawing at elevated temperatures.

Kazunari Shinagawa et al (1991) performed simulation on deep drawing of 1.2 mm thick stainless steel up to the temperature of 200°C. Simulations were carried out using rigid- plastic finite element method combined with heat conduction to study the plastic deformation and temperature distribution. The formulated method made it possible to deal with the flow stress expressed by a complicated function of strain-rate and the simulation results have revealed that the limiting draw ratio (LDR) was influenced by the punch speed and the temperature of the tools. It was found that the LDR had a peak around 200°C and the localized necking occurred in the vicinity of the die corner above 200°C. The LDR at 100°C for type 304 was larger than that for type 316, because of the strength around the punch corner was increased by the formation of martensite.

Similar attempt was made by Takuda et al (2003) on 1.0 mm thick stainless steel sheet up to the temperature of 150°C to investigate the formability of the material by taking the deformation induced martensitic transformation into consideration. The simulations have revealed that the calculated transition of the blank profile with increase in the punch stroke showed the appearance of the localized necking around the punch corner and predicts the fracture initiation there. The LDR value obtained in the experiment was 2.7 where as it was 2.8, in the simulation.

2.8 SUMMARY

From the literature survey, the following observations are made regarding the deep drawing process with respect to the past and the ongoing research works:

(i) Need for new or improved manufacturing process to produce high quality and cost-effective products to sustain in the stiff global competition.

(ii) Numerous researchers put their efforts to study the deep drawing or warm deep drawing of high strength, low formability materials like Al and Mg alloys, since these materials are competitive alternative to low carbon steel sheets nowadays in automobile industries due to the light weight in nature, which reduces the fuel consumption and hazardous emissions in the transportation vehicles.

(iii) Very little amount of research work has been carried out in deep drawing or warm deep drawing of materials like stainless steel, copper, high strength low alloy steels etc, even though these materials are very extensively used in many industries like automobile, aeronautics, electronics industries and so on.

(iv) The information regarding the metallurgical aspects of warm deep drawing is very much limited, even though it is as important as the mechanical properties of the materials especially in sheet metal forming processes.

(v) Few of the conclusions arrived by the researchers in the past regarding the warm deep drawing of stainless steel are:

a) The LDR value attains a peak value at around 200^{o}C and LDR decreases as the punch speed increases. The flow stress of SS 304 is affected by the deformation induced martensite (Kazunari Shinagawa et al 1991).

b) At 100^{o}C of the single temperature process, SS 304 had poor drawbility where as in two temperature process, it had better drawability (Chang and Chou 1995).

c) The blank is drawn successfully without any fracture initiation in warm deep drawing at 120^{o}C even for a high DR of 2.7. By warm forming, the concentration of the deformation induced martensite at the rim of the drawn cup is avoided (Takuda et al 2003).