WARM DEEP DRAWING PROCESS of ALUMINIUM ALLOYS AND STRENGTHENING MECHANISMS

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1. Introduction

The formability of any sheet material depends on the material properties, process parameters, and strain bounding criteria. Evaluating the formability of aluminum alloys is crucial for industries like aerospace and automotive due to their significant advantages over other materials. Among all, 2xxx, 5xxx, 6xxx, and 7xxx are having majority of applications in any industry. Specifically, the warm deep drawing process, incremental forming process, tube hydroforming process, and stretching process are discussed on different aluminum alloys.

2. Key Factors Influencing Formability

2.1 Material Properties

Ductility - Aluminum alloys typically exhibit moderate ductility. Alloying elements (e.g., Cu, Mg, Zn) and heat treatments can significantly affect ductility and strain-hardening behavior.

Work Hardening (n-value) - A higher strain-hardening coefficient improves formability by allowing greater redistribution of strain in the material during forming.

Anisotropy (r-value) - Anisotropy affects the material's resistance to thinning. High planar anisotropy can lead to earing defects, while low values are preferred for deep drawing.

Springback - Aluminum has a tendency to spring back after being deformed, which can complicate the process of achieving precise geometries. This issue can be mitigated by using a hydraulic press with precise force control or by designing the die to compensate for springback.

2.2 Process Conditions

Lubrication - Proper lubrication reduces friction between the die and the workpiece, minimizing surface defects and improving formability.

Blank Holder Force - Excessive blank holder force can lead to tearing, while insufficient force causes wrinkling.

Tool Design - Die geometry, punch profile, and clearance are critical for avoiding defects like tearing and wrinkling.

Temperature - Elevated temperature enhances ductility and reduces flow stress, improving formability (e.g., warm or hot deep drawing processes).

3. Defects in Deep Drawing:

Tearing - Occurs when tensile stress exceeds the material's tensile strength.

Wrinkling - Results from compressive stresses causing instability in unsupported areas.

Earing - Caused by anisotropic properties of the sheet, leading to uneven flange heights.

4. Strengthening Mechanisms in Aluminum Alloys

The mechanical properties of aluminum alloys are enhanced through various strengthening mechanisms. These mechanisms play a crucial role in balancing strength and formability for deep drawing applications.

4.1 Solid Solution Strengthening - Alloying elements like Mg, Cu, Si, and Zn dissolve into the aluminum matrix and distort the lattice structure, impeding dislocation motion and increasing strength.

4.2 Precipitation Hardening (Age Hardening)

In precipitation-hardenable alloys (e.g., 2xxx, 6xxx, 7xxx series), fine precipitates (e.g., Mg2Si, Al2Cu) form during aging treatments. These precipitates act as barriers to dislocation motion, significantly improving strength. The trade-off between strength and ductility must be managed carefully for forming applications.

4.3 Work Hardening (Strain Hardening)

Cold working introduces dislocations into the aluminum lattice. These dislocations interact and impede further motion, increasing strength but reducing ductility. Overworked material may exhibit reduced formability.

4.4 Grain Refinement

A fine-grained microstructure enhances strength through the Hall-Petch relationship, where grain boundaries act as barriers to dislocation motion.

Fine grains also improve ductility, enhancing formability.

4.5 Dispersion Strengthening

Non-soluble particles (e.g., Al2O3, SiC) are added to the aluminum matrix. These particles obstruct dislocation motion, enhancing strength.

4.6 Texture Control

Control of crystallographic texture through rolling, annealing, and recrystallization affects anisotropy, ductility, and earing tendency in deep drawing processes.

5. Aluminum alloy behavior during deep drawing process

Instead of tool temperatures, forming temperature curves (FTCs) were characterized from AA5754-O as a workpiece temperature at the warm deep drawing (WDD) process. The distinctive behavior of these curves was examined under non-isothermal WDD of AA 5754-O. The process parameters were considered such as FTC, blank holder force, and punch velocity to assure deep drawability. Optimum conditions were investigated by evaluating the cup volume and springback parameters. In the findings, 330°C in the flange-die radius region and 100°C in the cup wall-punch bottom region were the ideal optimum temperatures for the warm deep drawing process. The stress-strain response of AA2014, AA5052, and AA6082 aluminum alloys at four temperatures: 303, 423, 523 and 623 K, and three strain rates: 0.0022, 0.022, and 0.22 s^{-1} was evaluated through uniaxial tensile tests. It was found that the Cowper-Symonds model was not a robust constitutive model, and failed to predict the flow behavior. A comparative study was followed for modeling of three aluminum alloys under the mentioned strain rates and temperatures. For comparison, the capability of Johnson-Cook model, modified models of Zerilli-Armstrong and Arrhenius and artificial neural network were considered for constitutive behavior. Better formability of the materials was observed at an elevated temperature of 623 K in terms of cup height and maximum safe strains by conducting cylindrical cup deep drawing experiments under two different punch speeds of 4 and 400 mm/min. Tensile tests of AA5754-H22 aluminum alloy were carried out at five different temperatures and three different strain rates to investigate the deformation behavior correlating with the Cowper-Symonds constitutive equation.

When punch and die were heated to 200°C, the forming limit strain and dome height were improved. Significant enhancement was noted when the die and punch temperatures were maintained at 200 and 30°C, respectively, in deep drawn cup depth. Using a thermo-mechanical FE model, the forming behavior at different isothermal and non-isothermal conditions was predicted. In the FE model, temperature-dependent properties in Barlat-89 yield criterion and coupled with Cowper-Symonds hardening model were used. The validation had taken place using thinning/failure location in deformed cups by implementing the experimental limiting strains as damage model.

Deep drawing of aluminum alloy AA6111 at elevated temperatures was analyzed with the effect of friction coefficient through experiments and finite element method. Results indicated that the friction coefficient and lubrication position influence the minimum thickness, the thickness deviation, and the failure mode of the formed parts. During the hot forming process, the failure modes were draw mode, stretch mode, and equi-biaxial stretch mode. Fracture occurred at the center of cup bottom or near the cup corner in a ductile mode or ductile brittle mixed mode. Simulations of deep drawing tests at elevated temperatures were carried out with experimental validation on aluminum alloy 7075. For stamping operations, some of the important parameters such as blank holder force, stamping speed, blank temperature, and friction coefficient were considered. During the experimentation, stamping tests were performed at temperature between 350 and 500°C, 0 and 10 kN blank holding force, 50 and 150 mm/s stamping speed, and 0.1 and 0.3 frictional coefficient. At lower values of temperature, blank holder force and friction coefficient improvement were seen in thickness homogeneity whereas formability was improved with the well lubricated blank at about 400°C temperature and stamping speed 50 mm s^{-1}. Tailor friction stir welded blanks (TFSWBs) of AA5754-H22 and AA5052-H32 sheet metals were fabricated using a tool with optimized design along with optimized process parameters. For optimization to design the friction stir welding experiments, Taguchi L9 orthogonal array was used. For the multi-objective optimization to maximize the weld strength and total elongation reducing the surface roughness and energy consumption, the gray relational analysis was applied. The formability was evaluated and compared with TFSWBs and parent materials using LDR tests. The analysis had proved that TFSWBs were comparable with parent materials more specifically without any failure in the weld zone area. For improvement in the LRD, a modified conical tractrix die was proposed and 27% improvement was observed.

Simulations of cylindrical cup drawing were carried out with experimental validation on AA6111 aluminum alloy at elevated temperatures. The influence of four important process parameters, namely, punch velocity, blank holder force (BHF), friction coefficient, and initial forming temperature of blank on drawing characteristics was investigated using design of experiments (DOE), analysis of variance (ANOVA), and analysis of mean (ANOM). Based on the results of ANOVA, the BHF had the greatest influence on minimum thickness. The significance of punch velocity for thickness deviation, BHF, friction coefficient, and initial forming temperature of blank was 44.35, 24.88, 15.77, and 14.995% respectively. Further, the effect of each factor on forming characteristics was analyzed by ANOM.

A design optimization problem was constructed to identify the formability window, in which the punch stroke was maximized subject to wrinkling and tearing. For this, the formability window of a difficult-to-draw material AA 5402 was explained with the pulsating blank holder force (PBHF) and the variable blank holder force (VBHF). Some parameters in the VBHF and PBHF were included and taken as the design variables. A sequential approximate optimization (SAO) using a radial basis function (RBF) network was used to determine the optimal parameter of PBHF and VBHF. From numerical simulation coupled with the SAO using the RBF network using the PBHF and VBHF, formability window was observed. It was identified that the proposed approach was highly useful for clarifying the formability window of a difficult-to-draw material. The tailored heat treated blank (THTB) technique was demonstrated to create a material property gradient through a suitable artificial aging treatment carried out prior to the forming process on the effectiveness of combining the hydromechanical deep-drawing process. This method was coupled with a simple finite element model and a multi-objective optimization platform. For determining the effect of the aging treatment on the mechanical and deformative behavior of the AC170PX aluminum alloy, a preliminary experimental campaign was carried out. The adoption of aged blanks in the hydromechanical deep drawing allows to increase the limit drawing ratio and to simplify the process proved from the optimization results.

For increasing the drawability of AA1200 aluminum alloy cylindrical cups, one technique was developed. For optimal process design, effects of die and punch along with fillet radius of die and punch on LDR, drawing load with respect to punch stroke and strain of the cup wall was investigated numerically. To determine the optimum LDR form numerical analysis, a commercial finite element simulation package, ANSYS 14.0, was used. The effects of the original blank on the various LDR and punch load were numerically investigated. This process successfully produced cylindrical cups with considerable drawing ratio. The effect of pulsating blank-holder system was investigated on improving the formability of aluminum 1050 alloy. Using ABAQUS6.7 software, the deep drawing process was simulated for cylindrical cup of AA 1050. Later on, experimental and numerical analyses were compared for depth of cup, tearing, and thickness distribution. The results indicated that with proper frequency and gap, the cup depth and thickness distribution can be improved by using the pulsating blank-holder system. Further, good agreement was observed between simulation and experimental results. An analytical model was proposed for the non-uniform fluid pressure distribution in the cavity and for the hydrodynamic flow of the fluid film between the blank and die for AA5086 aluminum alloy. From Reynolds equation solution, the hydrodynamic flow was calculated and model was implemented in ABAQUS/Explicit, finite element software. The approach was validated and investigated for the influences of the blank holder force and the fluid pressure on the formability of the blank metal. The results exhibited that the choice of an appropriate blank holder force reduced the strain in the blank and prevented the risk of fracture. A study was made on deep drawing of SiCp/2024Al composite sheets by considering the effect of pulse current on heating performance and thermal. The high-intensity pulse current flows through the sheet and generates the tremendous Joule heat. The specimen temperature was kept around 673 K at a rate of 13.5 K/s under the current density of 21.7 A/mm^2. The temperature difference was reduced by 73.3% by inserting the stainless-steel inserts. Besides, the SiCp/2024Al composite was successfully deep drawn with good surface quality. Deep drawing process characteristics of AA 6xxx alloy sheet were discussed under different process parameters such as punch force, lubrication, fillet radius, punch speed etc., and the formability was evaluated.

5. Optimization of Aluminum Alloys for Deep Drawing

Alloy Selection - Alloys like AA5xxx (Al-Mg) and AA3xxx (Al-Mn) series are commonly used for their good formability and moderate strength.

Heat Treatment - Proper annealing softens the material and reduces residual stresses, improving formability.

Process Modifications - Warm forming processes enhance ductility by taking advantage of the temperature-dependent behavior of aluminum alloys.

Advanced Coatings - Surface coatings or lubricants can further minimize friction and enhance surface quality during forming.

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