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Deep Drawing of Sandwich Plate with Aluminum Foam Core

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Abstract **-** In this paper, the ability of deep drawing of a composite sheet consisting of aluminum foam as a core and metal sheets of aluminum, copper and brass as a shell to produce a cylindrical cup was studied. The main objective of the paper is to take advantage of the properties of different materials in one part at the same time (low density, high strength and corrosion resistance). Specimens of aluminum foam were manufactured using powder metallurgy technique with different weight percentages of sodium chloride salt (10%, 20%, 30%, 40%) NaCl. After that, three types of sandwiches were made by placing a thin layer of 0.2 mm thickness for each type of aluminum, copper and brass on top and bottom of the aluminum foam by pasting it with an adhesive substance. After completing the samples, a deep drawing die was manufactured to carry out deep drawing operations to obtain a cylindrical cup under different drawing speeds with different holding forces with different lubrication conditions (wax and die oil). The thickness of the sandwich specimen was (1.3 and 1.6) mm and the diameter was 110 mm. The cups were formed with failure to draw a full cup for the aluminum sandwich and a full cup for the copper and brass sandwich with the presence of minor wrinkles in the edge of the cup, which were avoided by changing the holding force.

Index Terms **-** Deep drawing process, Aluminum foam, sintering dissolution process, NaCl space holder, Adhesive, Sandwich plate.

1. INTRODUCTION

In the recent years, deep-drawing of laminated materials consisting of metal, composite and metal-composite laminates have been widely investigated in various studies. A laminated sheet comprises of at least two metals with different material arrangements and various thicknesses Generally, layered sheets can be made by many processes, such as cold and hot roll bonding, adhesive bonding or explosive bonding. The use of sandwich panels made from metal sheet shells and polymer cores has increased in aerospace, automobile and construction industries due to the advantages of these sheets compared to single-layer metal sheets[1] .The deep drawing operations of composite sheet metal can be utilized in producing of components with different internal and external conditions like resistance of corrosion and wear, electrical and thermal conductivities. With this regard, such products are progressively utilized in numerous fields like the vessels, aerospace, automotive , medical instruments, and electrical industries[2]. Recently, many research efforts have been focused on composite sheets due to the extensive variety of uses. Gresham et al. [3] studied on drawing behavior of metal composite sandwich structures. They observed that blank holder force has a significant effect on the failure mode of the metal–composite system with lower forces resulting in wrinkling as the dominate mode and higher forces resulting in splitting and fracture. Padmanabhan et al. [4]] focused on the effects of process parameters on the deep effect on the drawing. They showed that radius was found to be the most important, followed by the blank holder deep drawing of stainless steel blank sheet force, and friction application and coefficient. Further, it is shown that a blank holder force quality of the formed part. local lubrication scheme improved the quality of the formed part. Huang-Chi Tseng et al.[5] studied the formability of Aluminum/ copper (Al/Cu) clad metals through Punch stretching test and square deep drawing. O.A.Sokolovan et al. [6] studied the formability of(stainless steel polypropylene-polyethylene polymers PP–PE/ stainless steel) sandwich composites. Deep drawing process carried out by using two punches square and circular. The result shown that the geometry of punch and the core thickness have a high effect on the forming behaviour of the three-layered sandwiches. Amir Atrian and Faramarz Fereshteh Saniee [7] studied the effects of some parameters on the deep drawing process of steel / brass laminated sheets, experimentally and with finite element analysis. Morovati et al.[8] studied the wrinkling of two-layer (aluminum-stainless steel) sheets in the deep drawing process through an analytical method, numerical simulation and experimental tests. Jalali Aghchai et al.[9] studied formability of two-layer (Al1100–St12) sheet. They applied M-K model to the two-layer sheet and obtained the forming limit diagram theoretically. Hussein et al.[10] studied the drawability of two-layer (steel-brass) sheets to produce square cup. They concluded the greatest thinning appear in the corner of the cup near the punch radius due to extreme stretching take place in this area, also show that the lubricant results cause a reduction in the maximum drawing force, and the usage of lubricants produce a good surface finish. In the present work, the deep drawing process of sandwich sheet with Aluminum foam core to produce cylindrical cups is investigated. The effects of some process parameters, such as blank holder force, drawing speed and lubrication conditions (wax and die oil) on the forming product, thickness distribution and required drawing force.

2. Experimental studies

2.1 Aluminum foam Manufacturing

The raw materials used in this study were aluminum powder with particle size of ~2.09µm and sodium chloride (NaCl) with particle size of 75-300µm. The particle morphology of NaCl is shown in Figure(1a). NaCl particles have semi-equiaxed shape and the morphology of aluminum powder is given in figure (1b).

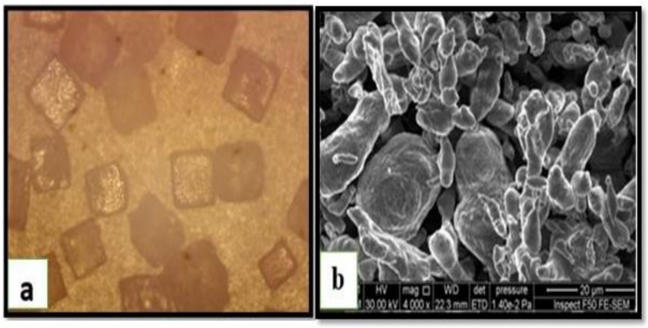

Figure1 :(1a) Morphology of NaCl particles by optical microscope. (1b) Aluminum powder particles by SEM

The Aluminum powder was mixed with different ratios of NaCl powder (10, 20, 30, 40) wt.% as a space holder to create porosity, the mixture was weighted using a 4-digit digital balance and then is mixed for 2 hrs. using an electrical parallel mixer with 70 rpm. The powder mixture is compacted into mold with a cylindrical shape (110mm dia. × 0.7- 1mm height), under a compaction stress (206MPa) using a hydraulic press The press model (ENERPAC) , made in USA and it is capacity (200) tons. Figure 2a ,2b and 2c shown the pressed aluminum samples with different pressure.

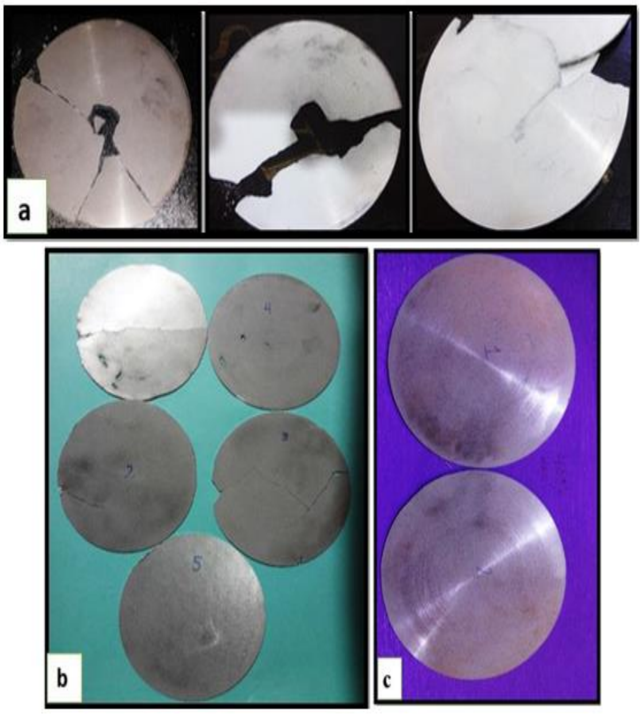

Figure 2 :(a) Failure samples due to low applied load,(b) Failure samples due to high applied load and (c) Successful at compaction pressure 206 MPa

Figure (3) shows the pressed aluminum samples were sintered into a direct furnace under argon (Ar) atmosphere at 650°C for 2 hours and then allowed to cool to the room temperature.

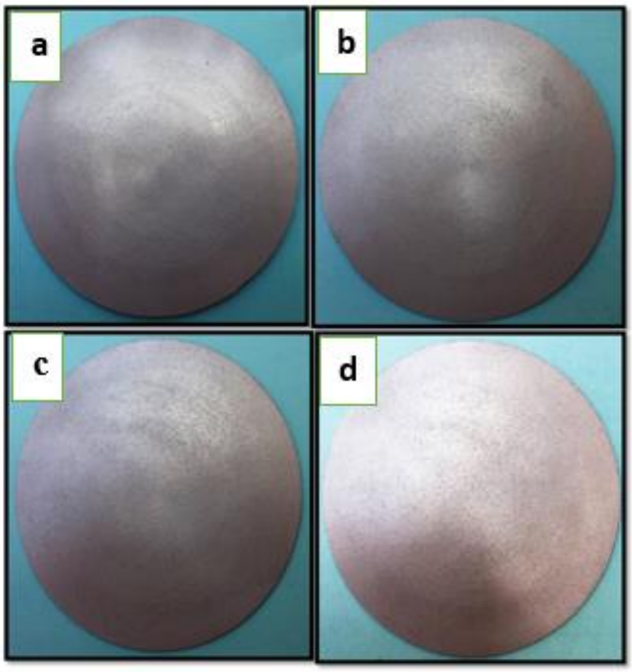

Figure 3: Aluminum specimens after sintering (a)10%NaCl , (b)20%NaCl, (c)30%NaCl, (d)40%NaCl

Figure (4) The last step was the dissolution process, which consists of placed the samples in hot water with temperature of 95° for dissolution time (12 hrs) to remove NaCl particles and create aluminum foam.

Figure 4: Aluminum specimens after dissolution process (a)10%NaCl,(b)20%NaCl, (c)30%NaCl,(d)40%NaCl

2.2 Fabrication of sandwich sheets

To fabricate the three-layered blanks, it is necessary at first to remove the oxide on the surface of sheets. Then**,** the surface is washed using acetone to remove any remaining oils or metal powders and produce a clear surface. The stacked layers are aluminum foam core with thickness of (0.7,1) mm, two metals sheets(aluminum or copper or brass) with thickness of 0.2 mm. , uniform layer of epoxy adhesive on each surface of the core is applied, then face sheet is placed on the core and a uniform weight is placed over the sandwich and is allowed to cure for 24 hours and last the weight is removed and the same procedure is followed to bond second face sheet to the core as shown in Figure 5 shows a sample of the fabricated sandwich sheets.

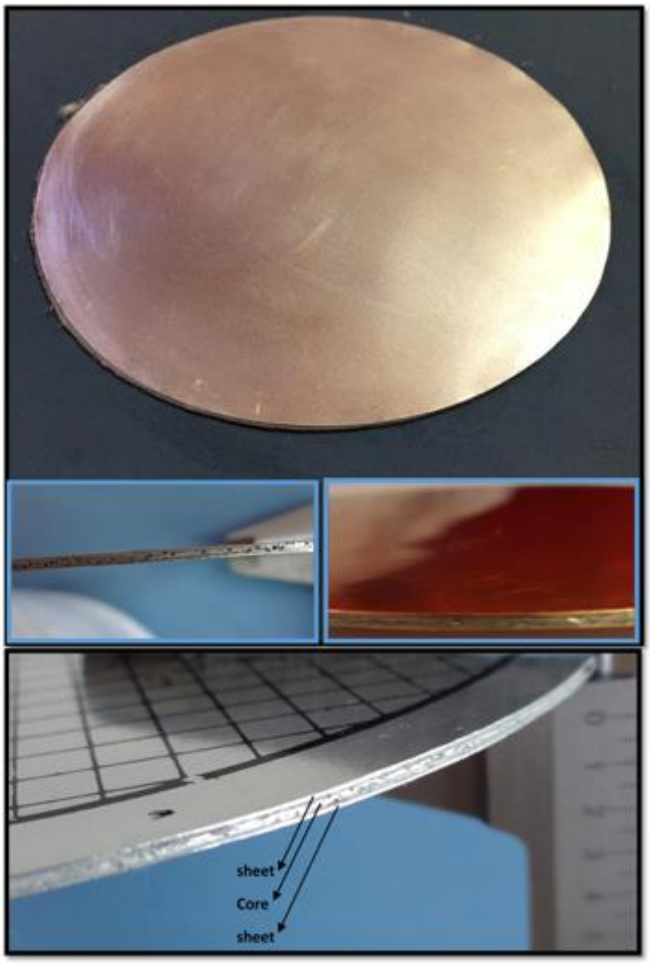

Figure 5: Sample of sandwich plate and its cross section.

2.3 Deep Drawing process

After fabrication the sandwich sheets, deep drawing process was carried out to study formability by deep drawing of sandwich plate with Aluminum Foam Core. The experimental works included material properties, deep drawing die design and manufacturing, forming process, and measurements of the drawn part. The characteristics of the material to be drawn have a significant influence on the success of a drawing operation. Three different raw materials were selected as the skin layers, Aluminium Al1100, Copper Cu and Brass CuZn30 with thickness of (t_o= 0.2 mm) are utilized in this study to produce various Sandwich blanks for Cylindrical deep drawing experiments.

The chemical compositions were determined using spectro max X instrument, results of which are, as shown in Table 2,3 and 4

Table (1): Chemical composition of Aluminium (Al 1100)

Elements / Material	Si%	Fe%	Cu%	Mn%	Mg%	Cr%	Ni%	Zn%	Ti%	Sn%	Pb%	Al%
Plate Al 1100	0.0403	0.367	0.0011	0.0104	0.0007	<0.0005	0.0020	0.0020	0.0192	<0.0010	<0.0010	Bal

Table (2): Chemical composition of copper (Cu)

Element / Material	Zn%	Pb%	Sn%	**P %**	**Fe%**	Ni%	As%	Sb%	Cr%	Mn%	S%	Cu%
Plate Copper	<0.0677	0.0010	0.0007	<0.0010	0.0082	<0.0005	0.0014	<0.0035	0.005	<0.0005	0.0027	99.9

Table (3): Chemical composition of brass (CuZn30).

Element	Zn%	Pb%	Sn%	P %	Fe%	Ni%	As%	Sb%	Ag%	Al%	S%	Cu%
Plate Brass	33.33	0.0036	0.0044	0.0067	0.0254	0.0064	0.0089	0.0173	0.0110	0.0054	0.0103	66.5

Tensile tests were conducted to find out the mechanical properties of the three metals. The test is carried out using computerized testing machine type Tinius Olsen made in USA. specimens were cutted and tested according to ASTM (American society for testing and materials) standard E8M specification[11] .The important properties are listed in table 5.

Table (4): Material properties of Al 1100,Cu and CuZn30

Property / Material	Ultimate stress (Re) N/mm^2	Yield strength (Re) N/mm^2	Elongation (%)
Aluminum 1100	140.4	36.19	8.85
Copper Cu	223.3	32.5	46.37
Brass CuZn30	217	142	31.57

2.4 Experimental Tooling

A deep drawing die was designed and built to produce cylindrical cups as shown in Figure (6), The basic die parts (punch, blank holder ,die, base plate, and changeable punch centering ring) which were machined to their final dimensions by ordinary machining operations such as (turning, milling and grinding). Punch with profile radius (r_p = 6mm) and its diameter of (d_p =62mm), the inner diameter of die (D_d =65.45 mm) and its profile radius of (r_p =6mm). The tool is arranged with fixed die and moveable punch. Die-punch clearance was chosen to be 1.73 mm. to ensure that there is no any misalignment, the die is designed to have edge for positioning itself into the blank holder, which it's consisted of blank holder, changeable centering ring. The blank holder is designed to be slide fit with punch via centering ring and have groove to locate the blank and position the die. The outer diameter of blank holder were 165 mm and it's inner diameter supplied with punch centering ring In order to appropriate with the punch required for the work.

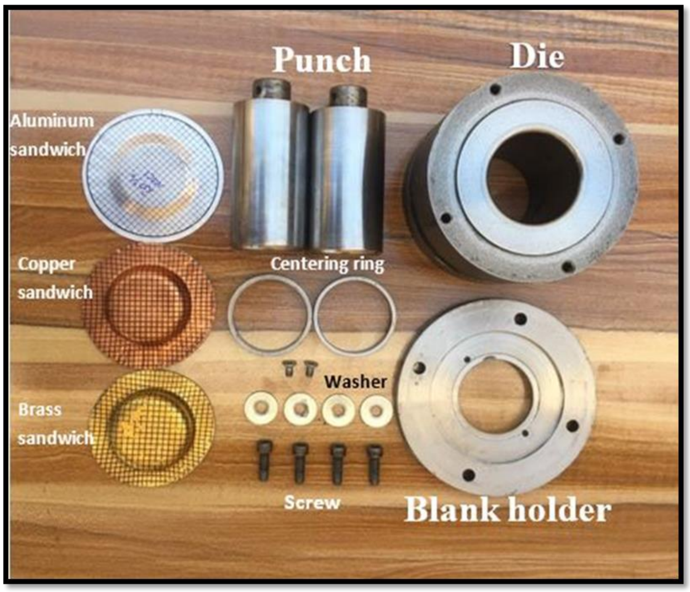

Figure (6): The equipment's of Deep drawing process

2.5 Lubricants

Lubricants are used to reduce friction between the working material and the tools, which also aids in removing the part from the punch. Lubricant films on both sides of the work piece help in getting a fine surface. The lubricant used was Die oil and wax. The wax is employed in this work very effectively for aluminum blank. Die oil was very effectively for copper and brass.

2.6 Deep Drawing Test

The deep drawing experiments were carried out to obtain cylindrical cup by using Electonic Universal Testing Machines (UTM) of 300 kN capacity with required tooling was used for deep drawing process. The tooling for deep drawing was mounted on Universal Testing Machine (UTM) as shown in Figure (7). The purpose of the experimental investigation is to study the effect of drawing force, thickness strains, radial strains and circumferential strains. Experiments are carried out by deep drawing of the sandwich plate blanks into cylinderical cups. The sandwich blanks was made from aluminum,copper and brass sheets with aluminum foam core .The blank is placed over the surface of the die edge and held it in a position by the groove in the blank holder. The die has been held stationary, while the punch has been moved by the ram of UTM. The blank holding force was determined experimentally. The punch speed of the testing machine was kept constant at (0.1,0.5,1) mm/min To avoid the effect of speed. Before starting to work on the blank of the sandwich, experiments were carried out on the aluminum sheets to ensure that the tools worked correctly. All the problems that occurred during the process of deep drawing were obtained and benefited from, to avoid those problems when working on the sandwich blanks. The tests were performed with die oil lubricant and wax. . Figure (8) shows the drawn cups with flange and completely of different metals sandwich.

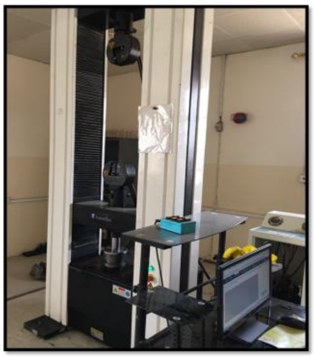

Figure 7: Universal testing machine with drawing equipment.

Figure 8: The drawn cups of different Sandwich plates

2.7 Strain measurement

In order to study the strain distribution of the produced cup during deep drawing operation. The square grid is printed with dimensions of (4×4) mm as shown in Figure (9) by using screen printing. The grid pattern is printed directly onto the sandwich plate using a suitable ink which is acceptable for the forming process.

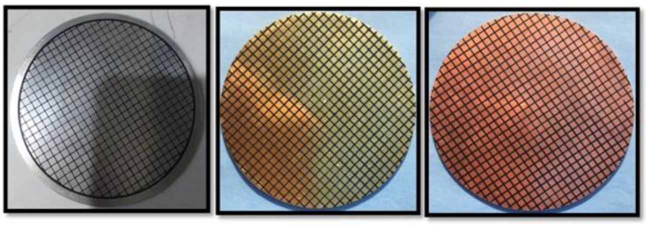

Figure 9 Grid pattern before deformation.

3. Results and discussion

3.1 Porosity and density

Figure10 illustrates the effect of NaCl content on porosity and foam density of Al foam The porosity increases when the NaCl content increased in the Al/NaCl sample and the foam density decrease with increasing NaCl content. During the dissolution process when the NaCl is removed the solid Al turned into a foam. NaCl particle dissolves in a hot water, and the space that created after dissolving process become pores, and that make the sample become lighter .With a higher NaCl content in the sample which is 40 wt. %, some of NaCl particles are in touch with each other and make a continuous three- dimensional network. All the particles in the mesh (network) shape dissolve in the hot water, which results high porosity and low foam density. However, there is a small amount of residual NaCl in the final sample[12].

In contrast, with a smaller NaCl content which is 10 wt. %, some of the NaCl particles are restricted by the Al matrix and that cause the particles unable to dissolve in the hot water, and thus, remain in the foam sample and cause high density and low porosity[12]. Figure10. shows the porosity increases from (27% to 50%), and the foam density decreases from (1.98 to 1.34g/cm^3), when the NaCl content increases from(10 wt. % to 40wt.%).

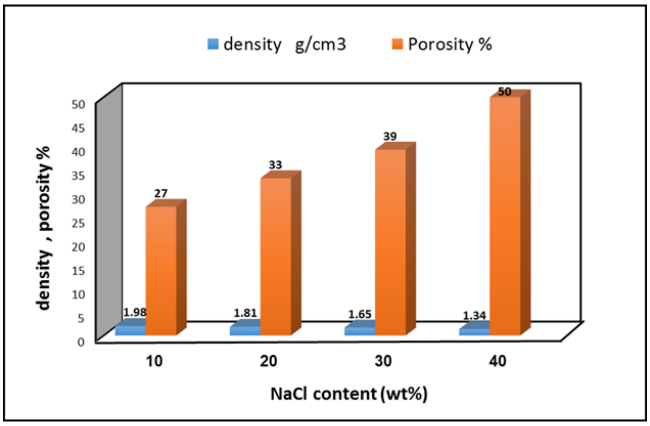

Figure 10: The effect of NaCl content on porosity and density

3.2 Microstructural analysis - Optical Microscope

Figure (11) shows the morphology of foam (pore size and cell walls), It has been shown that when the NaCl content increased larger pore size and higher quantities of pores were achieved. The isolated pores with thick cell wall observed at 10wt.% NaCl content , and the interconnected pores with thinner cell wall at 40wt.% NaCl content. Table (5) illustrates the average pore size of Al foam with different NaCl content, because of a high NaCl contents leads to the generation of interconnected pores increased because of the formation of numerous channels between cells.

Table (5): shows the pore size of aluminum foams with different NaCl content

Foam samples	NaCl content			
	Al-10NaCl	Al-20NaCl	Al-30NaCl	Al-40NaCl
pore size(μm)	208.60	233.32	306.80	385.20

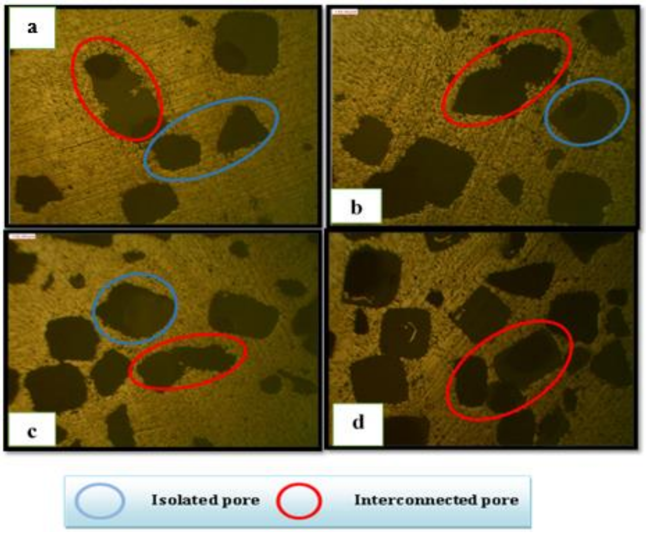

Figure (11): Shows optical micrograph of samples with different NaCl content; a) Al-10NaCl, b) Al-20NaCl, c) Al-30NaCl, d) Al-40NaCl with magnification 5X.

3.3 FESEM Result

The examination was used to identify the maximum and minimum pore size of Aluminum foam NaCl 40%, cell walls and the displacement between the pores. Figure (12a,b,c) illustrated the SEM images of the pores of the aluminum foam with (3mm,and100, 400μm) magnification. The image (a) shows the size and shape of the aluminum foam formed after the dissolution process. It is observed that the shape and size of the pores are irregular, image (b) show the formed pores interfering with each other and this indicates that the sodium chloride molecules were connected with each other and gave this overlapping shape of the pores and the cell wall in this case is thinner when There will be pores connected to each other. while the image (c) The pore shape also represent the particle characteristics of the original NaCl powder.

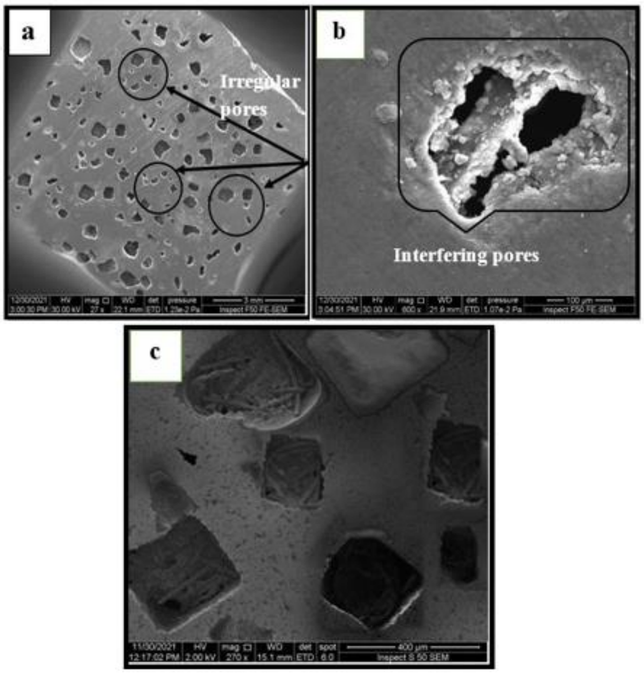

Figure (12):a,b,c SEM images of aluminum foam pores after dissolution process at 3mm, 100, 400µm magnification.

Figure (13): shows the maximum and the minimum size of the pores after dissolution process.

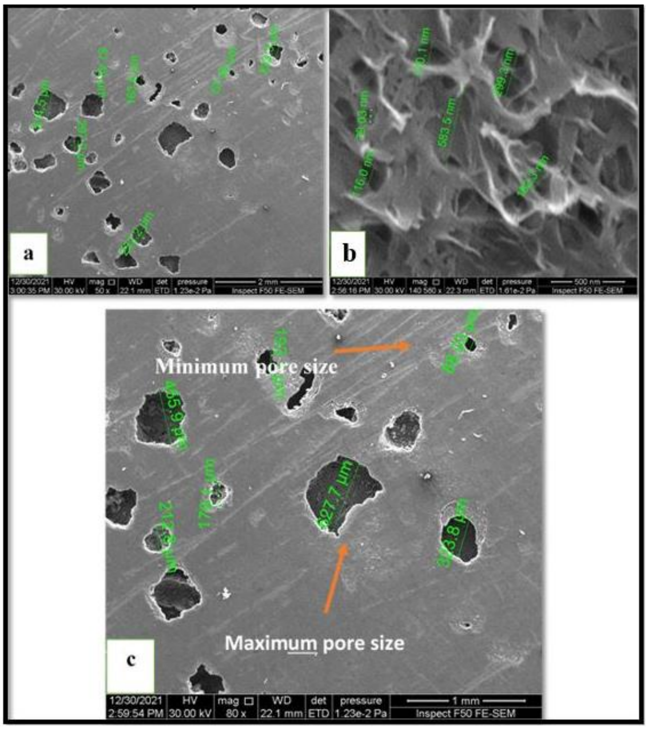

Figure (13):a,b,c, The SEM images of aluminum foam pore size after dissolution process.

Figure (14) shows the distance between the pores after dissolution process. Through the dimensions between the gap, we notice that the average dimension varies between (400-450µm), and this gives the impression that the general distribution is regular according to the mixing ratio of the sample.

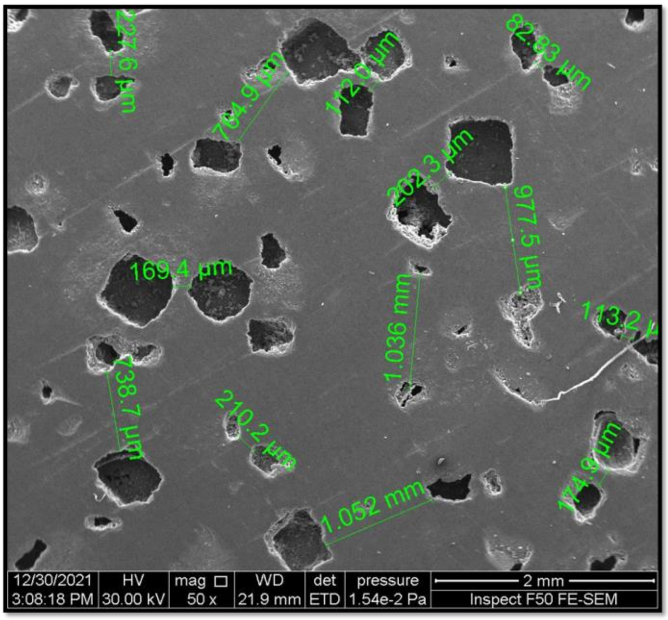

Figure (14): SEM images displacement between the pores of aluminum foam after dissolution process.

3.4 Effect of blank-holder force in deep drawing process:

The blank holder force is one of the most important parameters which affects the drawability of the sheet metal. The selection of suitable blank holder force is critical. When it is insufficient, the wrinkling can take place. On other hand, fracture or tearing can occur when the blank holder load is too high. For sandwich plate with thickness of 1.3 and 1.6mm ,aluminum sheets(AS) as skin and aluminum foam(AF) with ratio(10%,20%,30% and 40% NaCl) as core, the wrinkling was occurred when BHF of 1kN was used in experimental. By increasing BHF to the value of 3 kN in experimental test. It is seen that the tearing occurs at the edge part due to the high BHF. A desirable part without wrinkling and fracture was produced when BHF of 2.5kN as shown in figure (15).

Figure (15): Final blank shapes with different BHFs for (Al1100 sheets-Al foam core).

For sandwich plate with thickness of 1.6mm,copper sheets(COS) as skin and aluminum foam with ratio (10%,20%,30% and 40% NaCl) as core, the wrinkling was occurred when BHF of 1.5kN was used in experimental and product completely cup ,where the force was gradually increased until the wrinkles were removed at BHF of 2.8kN as shown in figure (16).

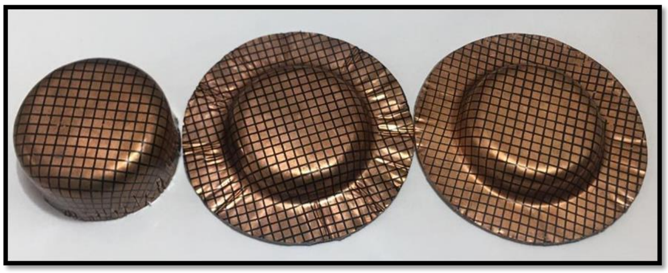

Figure (16): Final blank shapes with different BHFs for (Cu sheets-Al foam core).

The wrinkling was happened when the BHF of 2 kN was used in experimental test for sandwich plate brass sheets(BS) as skin and aluminum foam with ratio (10%,20%,30% and 40% NaCl) as core while the proper part was produced when using BHF of 2.6 kN in experimental test as shown in figure (16).

Figure (17): Final blank shapes with different BHFs for (CuZn30 sheets-Al foam core).

Based on the experimental and theoretical calculations (obtained from empirical equations) that have been presented in Table (6),(7) and (8) the minimum BHF for sandwich plate Aluminium sheet as skin is lower than the value required for sandwich plate Copper and Brass sheets as skin .Then, it can be concluded that the sheet with higher strength requires more BHF rather than the sheet with lower strength. Also, less BHF can be used for a sheet with higher ductility to control its wrinkling. The wrinkles are formed due to the insufficient blank holder force and the rupture has appeared at the punch radius area due to excessive stresses.

Table 6: Experimental and Theoretical results of BHF for Wrinkling mode studied cases

Wrinkling mode			
component	**BHF(KN) Experimental**	**BHF(KN) Theoretical**	**Deviation (%)** $\frac{(Exp-Theo)}{(EXP)}$ **X100**
Al 1100-Al foam	1	1.38	38
Cu-Al foam	1.5	2.2	46
CuZn30-Al foam	2	2.1	5

Table 7: Experimental and Theoretical results of BHF for Safe mode studied cases

Safe mode			
component	**BHF(KN) Experimental**	**BHF(KN) Theoretical**	**Deviation (%)** $\frac{(Exp-Theo)}{(EXP)}$ **X100**
Al 1100-Al foam	2.5	1.38	44.8
Cu-Al foam	2.8	2.2	21.4
CuZn30-Al foam	2.6	2.1	19.2

Table 8: Experimental and Theoretical results of BHF for Fracture mode studied cases

Fracture mode			
component	**BHF(KN) Experimental**	**BHF(KN) Theoretical**	**Deviation (%)** $\frac{(Exp-Theo)}{(EXP)}$ **X100**
Al 1100-Al foam	3	1.38	54
Cu-Al foam	-----	-----	-----
CuZn30-Al foam	-----	-----	-----

3.5 Effect of Punch Speed

An experimental method, digital image processing was used to study the effect of drawing speed on cup wall thickness and strain distribution, three speeds are used (v = 0.1, 0.5, 1 mm/min). Four percentage ratio of aluminum foam (10%, 20%, 30% and 40% NaCl) as core, with aluminum,copper and brass sheets as skin, blank diameter (110 mm), blank holder force (BHF=2.5,2.8 and 2.6 KN) respectively.

Figure (18) and (19) represents the effect of drawing speed on the cup wall thickness using sandwich sheet from aluminum, copper and brass material, the thickness remains constant of cup which made from sandwich aluminum material because the drawing is simple in sandwich sheet aluminum cup due to low elongation which is (8.58 %) compared with copper and brass which are (46.73%) and (31.57 %) respectively . while sandwich sheet from copper with thickness (1.6mm) and brass with thickness (1.3mm) material. It is evident that; the thickness remains constant under the punch face (cup bottom) for all the speeds, where no deformation occurs in this area due to friction which prevents any deformation of the metal under the punch. At the next zone (punch corner), the variation in thickness is not big with increasing in drawing speed from (0.1to 0.5 mm/min), but when drawing at speed of (1 mm/min), it is noticed that the maximum thinning will occur due to an increase in stretching exerted by the high tensile stress in this area. Afterward the cup wall thickness will increase because of the applied compressive stress in this region which has approximately the same thickness at all speeds.

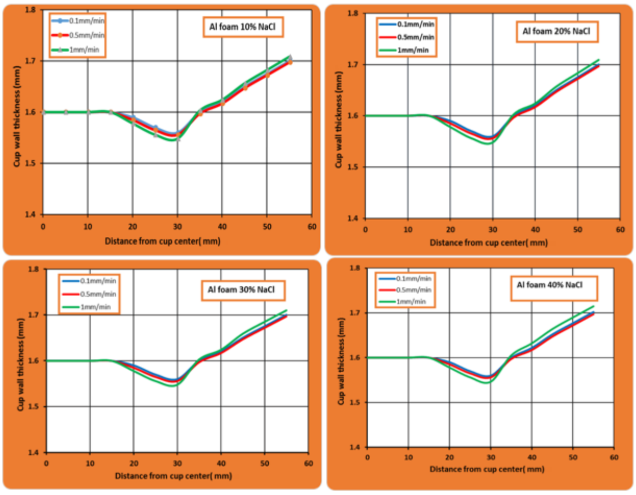

Figure (18): Effect of drawing speed on cup wall thickness of sandwich sheet from copper with Al foam 10% ,20% ,30%, 40% NaCl

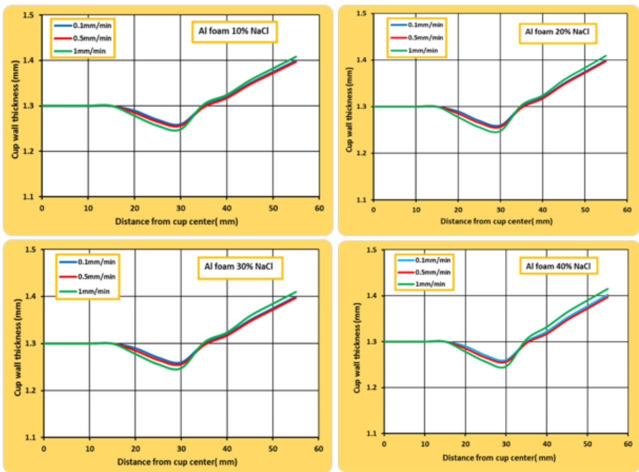

Figure (19): Effect of drawing speed on cup wall thickness of sandwich sheet from brass with Al foam 10% ,20% ,30%, 40% NaCl

Figure (20) and (21) shows the effect of drawing speed on the radial strain distribution at four-percentage ratio of aluminum foam (10%, 20%, 30% and 40% NaCl) as core, with aluminum, copper and brass sheets as skin. In any case, of forming, there are three zones of forming. The first zone starts from center of blank to 30 mm forward the edge, which found below punch. it is observed that the value of radial strain at the bottom of cup is approach to zero, where very small deformation occurs in this areas. The second zone is the radius of the punch corner which the strains are suddenly increase compared to first zone. The strain in this region is take place due to the friction between the blank and surface of die and this region consider zone of stresses concentration. In the last region, continue strains in increasing until reaches the maximum value at the cup edge, due to tension in this direction.

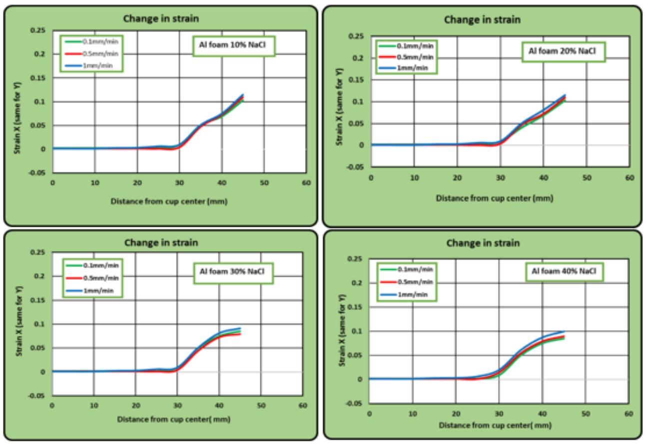

Figure (20): Effect of drawing speed on the radial strain distribution of sandwich sheet from copper with Al foam 10%, 20% ,30%, 40% NaCl

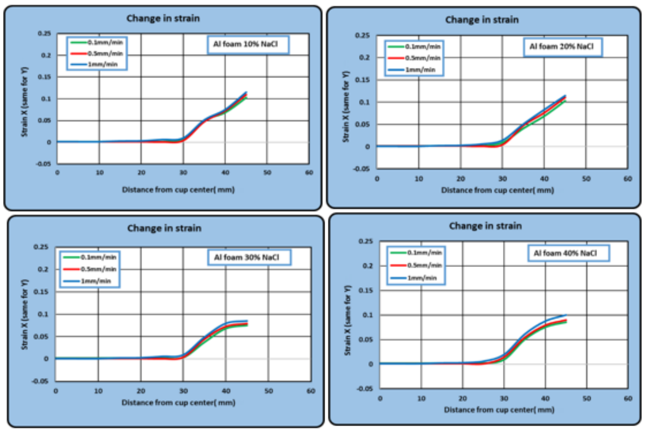

Figure (21): Effect of drawing speed on the radial strain distribution of sandwich sheet from brass with Al foam 10%, 20% ,30%, 40% NaCl

3.6 Effect of lubrication on drawing force

Deep drawing test was performed with lubricant in order to investigate the effect of lubricants on the deep drawing load of the drawn cup. In this work, two types of lubricant (die oil and wax) were used. Thus, lubricant with high slip properties must be applied to the die surface and blank surface face under the blank holder. Load displacement curves under lubricant conditions for various cases are given in Figure (22) and (23). It can be observed from these graphs that for cases where the wax lubricant is used, it leads to a decrease in the maximum force of sandwich sheet aluminum as skin rather than as a die oil lubricant. The effect of die oil lubricant on sandwich sheet copper and brass as skin is to increase the surface smoothness of the die when compared with wax lubricant, which consequently leads to a decreased maximum drawing force for them. This indicates that an increase in friction between the blank and the tool leads to an increase in the punch force.

In experimental results for aluminum sheet case, the wax lubricant was reduced the maximum required drawing force about 2.5%, compared with die oil lubricant, while for copper sheet case the lubricant was reduced the force about 6.6%. Also for brass sheet, the force is reduced about 5.7%.

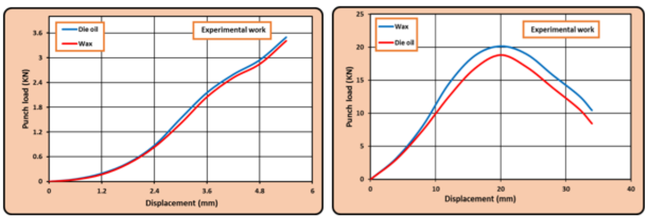

Figure (22): Effect of lubrication conditions on the Forming load(left) aluminum and (right) copper sheet cases

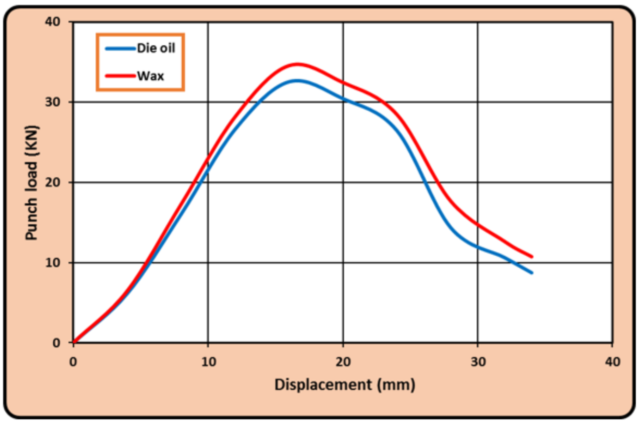

Figure (23): Effect of lubrication conditions on the Forming load brass sheet case

4. Conclusion

Based on the deep drawing tests of composite blanks carried out in the present research work and the results obtained, the conclusions can be summarized as follow:

1. By controlling the amount of sodium chloride particles, the porosity value can be controlled.

2. The dissolution time when increased leads to a slight increase in the porosity compared with the increasing in the NaCl content.

3. Optical microscope photos demonstrate that pore size increased as NaCl content and dissolving time increased, resulting in increased porosity on a light weight foam.

4. Failed to pull a full cup from the aluminum sandwich, where the maximum pull was with deep 5.5 mm. While the copper and brass sandwich was successful deep drawn Cu/AF/Cu and ZnCu30/AF/Cu sandwich composite cup

5. For sandwich made from aluminum, increasing the BHF from 1KN to 2.5 KN, wrinkling decrease, and sandwich made from copper , with the BHF 1.5KN appeared wrinkling when the cup was completely and its disappear as the BHF 2.8KN .while wrinkling disappear from the cup when the BHF was 2.6KN for sandwich made from brass.

6. The lubricant results cause a reduction in the maximum drawing force (about 2.5%, 6.6%, and 5.7% for Al/AF/Al, Cu/AF/Cu and ZnCu30/AF/Cu), also, the usage of lubricants eliminates scratches of the drawn cups and reduces the tool wear at long-term.

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