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FORMABILITY IN HOLE EXPANSION OF 2-PLY (BRASS/ALUMINUM) SHEET USING A BALL-SHAPED PUNCH

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ABSTRACT

Hole expansion process (HE) of metallic sheets is used to the manufacture of many products like parts for the household appliances, automotive, medical and electrical industries. Due to the importance of brass and aluminum in the sheet metal industry, the present work presents an experimental investigation of the formability in the HE process of 2-ply sheet (brass supported by an aluminum sheet) using a ball-shaped punch. The main objective of is to investigate the effects of the pre-hole diameter, type of support on the forming loads, occurrence of maximum load, limiting expansion ratio (LER), and fracture modes. 1 mm thick brass and 3 mm thick w Aluminum were used. Holes were drilled in the specimen center on an upright drill. Hole diameters were 3, 6, 8, 10, 12 and 14 mm respectively. Uniaxial tension, cupping tests and HE experiments were performed for brass supported either by blind or holed Aluminum sheet. Results showed that the force required to expand the hole, the position at which the maximum force was reached, fracture mode and forming limits were dependent on the pre-hole diameter and type and condition of support. It was concluded that in HE of brass specimens supported by (either a blind or holed) Aluminum sheet, the force required to expand the hole and the position at which the maximum force was reached decreased as the pre-hole diameter of the brass specimen increased. Fracture mode proved to depend on the type of support (blind or holed) and the hole diameter in both brass sheet and supporting Aluminum sheet. Forming limit curve (FLC's) could be constructed for the range of hole diameters in both brass and Aluminum sheets showing safe and unsafe regions in the HE process assuming two criteria: occurrence of failures in the brass sheet and occurrence of failures in the supporting Aluminum sheet. Such curves are of distinguished industrial importance in determining the success or failure in the HE process.

Keywords: Formability, hole expansion (HE), 2-ply (brass/Aluminum) sheet, hole expansion loads, limiting Expansion Ratios (LER's), Forming Limit curves (FLC's), Fracture modes.

1. Introduction

Nowadays, enhanced industry requires an increasing demand on precision products for single and multiple assembly parts. Products produced by the hole expansion (HE) have an increasing use mainly in automotive industry, as they allow getting lighter and more

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resistant vehicle structures, meeting demands for increased safety and less fuel consumption. Such products have wide difficulties with regard to formability. Examples include multi-layer collars and sheet-to-tube joints. In HE, a hole in the sheet is forced to expand by pushing an over-sized punch into the die, see Fig. 1. For a punch diameter (d) and pre hole diameter (d_o), an initial sheet thickness of to, coordinates of the points (A) and (B) on the surface of the original sheet change after deformation, while these of point (C) remain unchanged. The lip at the lowest point of the formed hole suffers some thinning.an. At hole edge, material points undergo uniaxial tensile stress [1].

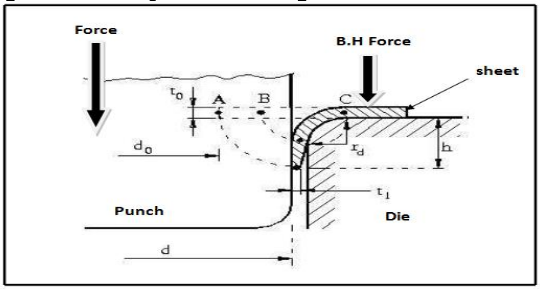


Fig. 1. A schematic of the hole expansion (HE) process (HE [1].

The maximum possible hole expansion ratio (HER), often known as Expansion Limit [1], is defined as follows:

$$\mathbf{HER_{max} = HEL = [\,(D_{max} - D_{initial\ hole}) / D_{initial\ hole}\,]} \qquad \mathbf{(1)}$$

HER depends mainly on hole diameter, material mechanical properties, r and hole surface quality, punch geometry and friction and lubrication conditions. The deformation pattern in the HE process is simulative to these in the beginnings of both edge bending and deep drawing processes. Circumferential stresses may cause fractures by necking and tearing in the edges of expanded holes. **Thesing et al [2]** investigated the factors which affect the HE capacity of a martensitic steel sheet using 2punch geometries. Elleptical punch proved the give higher HER, which proved to decrease as hole diameter increased, see **Figs. 2.** Samples of cracks obtained in martensitic AHSS steel specimens are shown in **Fig, 3**. As a validation criterion for determining the HE limit, it was considered that failure occurs through the entire thickness of the plate.

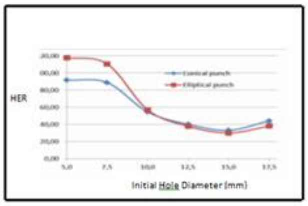


Fig. 2. HE ratio as a function of hole diameter for 2 punch geometries(from **[2]**

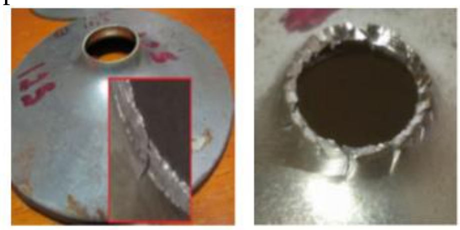


Fig.3. samples of cracks obtained in martensitic AHSS steel rupture through the thickness (left) and cracks on the external surface, consequence of bending around the punch

Dunckelmeyer et al [3] designed a special forming tool to conduct the HE test on standard testing machine. The work had the advantage of putting the HE test in an optimized and unifying test method in the industrial scale. **Huang and Singh [4]** pointed out the importance of the HE test as a most–commonly used test to evaluate the edge cracking resistance, bend ability and stretch flange ability. They found that the HER of water-jet cut and EDM and reamed holes were higher than these for punched holes.

Surface friction and large contact areas have led to stucked samples (to the punch) especially for high HER's. Instead of cracking, edges appeared to fail by splitting or necking and holes deviated from circularity. **Stachowicz et al [1]** made use of the fracture tension test and the ductile fracture criteria to forecast the fracture occurrence in the HE process. In **Naryanasamy et al [5]** study of HE in automobile steels, fracture were noticed likely to occur for specimens having pierced holes. Many authors studied the simple tension test and the cupping test to investigate the material formability. **Reddy et al** [6] studied the basic forming characteristics of sheet metals from tensile tests. High strain hardening exponents proved to undergo large uniform strains during biaxial stretching operations. Lower yield strength gave lower spring back and facilitates shape attainment in lightly formed parts. A high valve of the strain rate sensitivity index improved stretch ability by delaying the concept of localized necking. It is, therefore, essential to have tests that simulate the processing conditions and deformation modes existing during the practical industrial forming of sheet metal components.

Goutam et al [7] used the Erichsion cupping test to investigate the formability of AA6061 sheets. Blind specimens and circular and hemispherical punches were utilized. The most important factors which influence on formability were yield point, elongation, anisotropy, grain size, residual stresses, spring back, wrinkling, friction and lubrication at various. **Paul et al [8]** work focused on characterizing and predicting the HE ratio of steel sheets from uniaxial tensile properties. A fracture-based failure criterion was employed to predict the HER, considering that the test stop criteria of the HE process is the formation of through thickness cracks. Due to the importance of dual sheet components in various applications, the main objective of the present work is to study the HE in a pre-holed brass sheet specimens supported by a ductile material (aluminum sheet) using both blind and holed specimens. Effects of pre-hole diameter in both brass and Al sheets, type of support (blind or holed sheet) on the forming loads, fracture mode and forming limits are also presented.

2. Experimental work

2.1. Materials and specimen preparation

Specimens of 70/30 brass and commercial purity aluminum (99.5% al) were prepared from 1 m width and 2 m long sheets supplied from the Egyptian Copper factories Co, Alexandria, EGYPT. Thickness of the brass sheet was 1 mm while for aluminum was 3 mm. Specimens were cut to the required dimensions shown in **Fig. 4**and curved from the 4 corners to facilitate adjustment into the die cavity. Holes were drilled in the specimen center on an upright drill. Hole diameters were 3, 6, 8, 10, 12 and 14 mm respectively. Burr was removed from holes and an emery paper (grade 400) was used to finish the holes Standard tension test specimens were prepared from brass and Al.

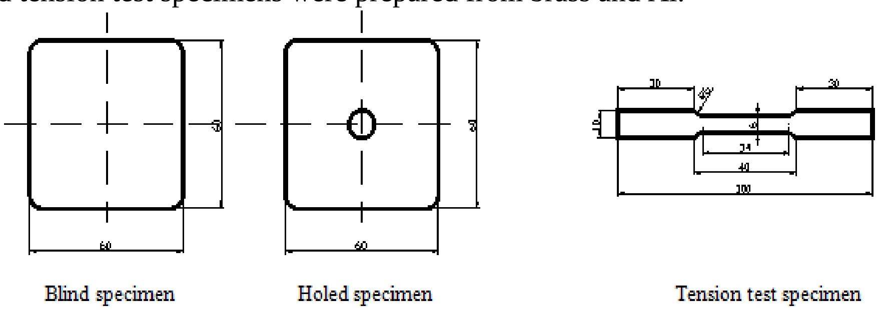
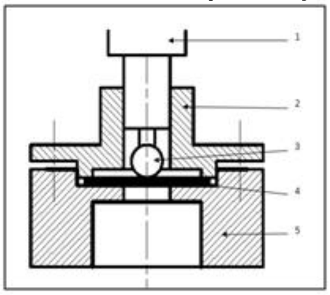


Fig. 4. Specimen geometry (dimensions in mm). Thickness of brass and Aluminum are 1 and 3 mm respectively.

2.2. Tension machine

A 30 ton capacity (300 kN), model UNITED hydraulic MTS was used for the tension. Load/displacement curves and data files could be obtained directly from the machine. Cross head speed was kept at 10 mm/min for all experiments. All tests were done at room temperature. A setup was designed and manufactured to carry out the hole expansion tests. A drawing of the set up used for HE process is presented in **Fig. 5.** Specimens were positioned in the middle and die cavity and adjusted with help of the round corners of the specimens.



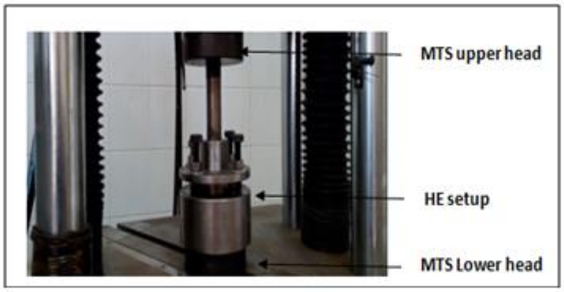


Fig. 5. The designed setup (left) and a photo of the MTS machine
1-Upper Platen of testing machine, 2- Cover,3- Spherical punch, 4- Work sheet, 5-die block,

2.3. Experimental plan

Experimental plan curried was as follows:

1-Uniaxial tension test for both brass and aluminum sheet specimens,
2-Cupping (penetration) tests for both materials using a bell shaped indenter (blind and holed),
3-Hole expansion tests of holed brass specimens supported with blind aluminum and,
4-Hole expansion (HE) of pre-holed 1 mm Thick Brass Specimen supported with 3 mm Thick Holed aluminum. Six groups of HE experiments were performed:

G1: 3 mm pre-holed brass specimens supported with holed aluminum specimens having different hole diameters,

G2: 6 mm pre-holed brass specimens supported with holed aluminum specimens having different hole diameters,

G3: 8 mm pre-holed brass specimens supported with holed aluminum specimens having different hole diameters,

G4: 10 mm pre-holed brass specimens supported with holed aluminum specimen having different hole diameters,

G5 12 mm pre-holed brass specimens supported with holed aluminum specimens having different hole diameters and

G6: 14 mm pre-holed brass specimens supported with holed aluminum specimens having different hole diameters.

A sketch of the experimental program is shown **in Fig. 6.** After experiments were carried out, specimens were photographed. For 2-ply specimens, the 2 specimens (Brass and Aluminum) were separated and every layer was photographed.

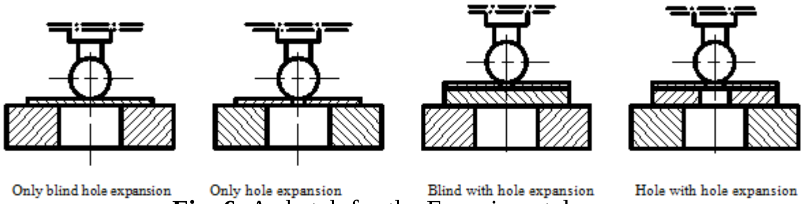


Fig. 6. A sketch for the Experimental program

3. Results and discussions

3.1. Uniaxial tension tests and penetration tests of blind specimens with a 19 mm dia. ball-shaped tool

Figs. 7(a and b) show the load/displacement diagrams for the brass and aluminum specimens in simple tension tests and in blind specimen penetration tests for both materials.

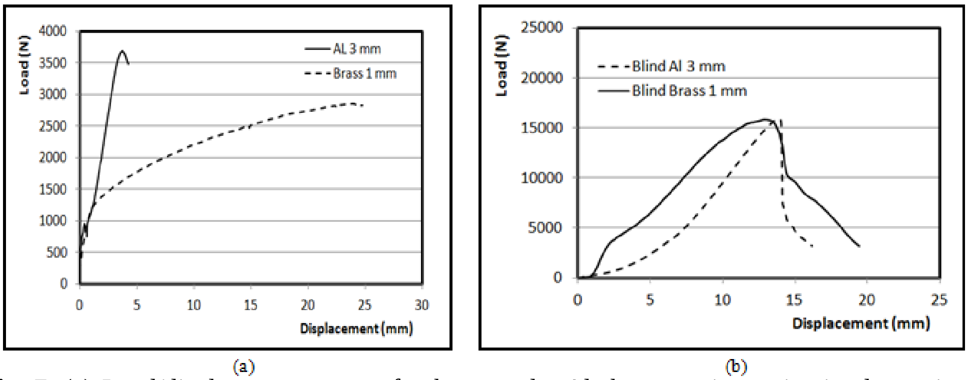
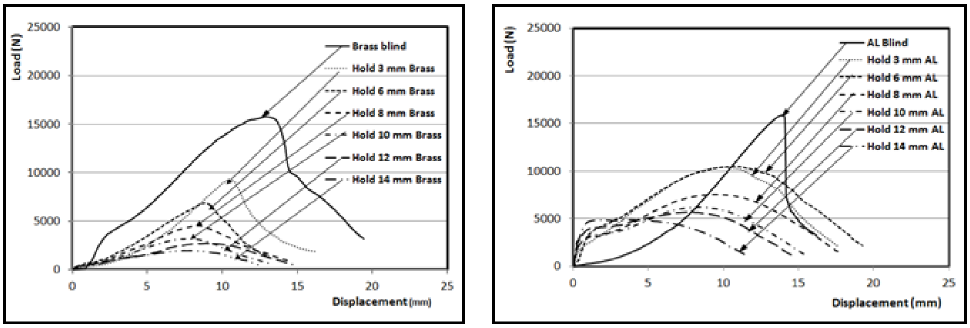


Fig. 7. (a) Load/displacement curves foe brass and Al sheet specimens in simple tension and (b): Load/displacement

Curves in Penetrates of Blind brass and Aluminum specimens With a 19 mm Dia. Ball-Shaped Tool

3.2. HE tests with a 19 mm dia. ball-shaped tool of brass and al specimens

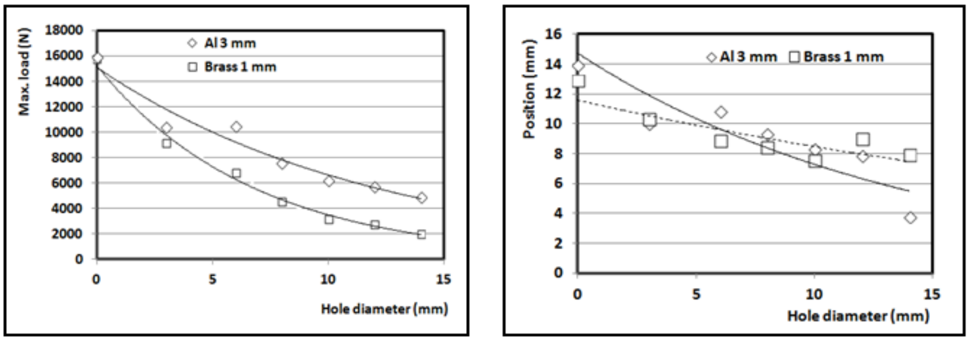
Fig. 8a shows load/displacement diagrams in HE of pre-holed brass specimens, 1 mm thick (compared with penetration of blind brass specimen) using a 19 mm diameter steel ball. For the blind specimen curve, the load increases as the ball-shaped punch contacts the specimen surface and penetrates till reaching a maximum value then decreases as a sign of beginning of fracture. This is due to the increase in contact area as penetration proceeds. This curve is typical for brittle material behavior, one stage till fracture begins. For holed specimens, the curves have a similar behavior but with less load values. Load values are less for larger hole diameters because the volume needed to be displaced in this case decreases. **Fig. 8b**shows load/displacement diagrams in HE of pre-holed aluminum specimens, 3 mm thick (compared with penetration of blind brass specimen) using a 19 mm diameter steel ball. For the blind specimen curve, the load increases as the steel ball contacts the specimen surface and penetrates till reaching the maximum value then decreases as a sign of beginning of fracture. This is due to the increase in contact area as penetration proceeds. This curve is typical for ductile material behavior, two stages till. For holed specimens, the curves have a similar behavior but with less load values. As for brass, the loads are less for larger hole diameters.



(a) (b)

Fig. 8. Load/displacement curves in HE using a 19 mm diameter ball-shaped punch of (a) pre-holed brass specimens, 1 mm thick and (b) pre-holed, 3 mm thick aluminum specimens. Both cases were compared to penetration test curves.

Fig. 9a shows the effect of pre-hole diameter on the maximum load reached in the HE process for both brass and Aluminum. It is clear that the maximum load value decreases as the hole diameter is increased. **Fig. 9b** shows the effect of pre-hole diameter on the displacement (position) at which maximum load is reached for both brass and Aluminum. As the pre-hole diameter increases, the position at which maximum load was reached is less.



(a) (b)

Fig. 9. Effect of pre-hole diameter on
a) maximum load and b) the position at which maximum load is reached for both brass and Aluminum HE tests. The hole diameter zero refers to blind specimens

3.3. HE of pre-holed brass supported with a blind aluminum

Fig. 10 presents load/displacement curves in HE of pre-holed 1 mm thick brass supported with a 3 mm thick blind aluminum. Two stage curves are apparent, presenting the effect of presence of a ductile supporting material. Load values were higher than the HE of case of brass only. Maximum loads were less as the pre-hole diameter increases due to less volume of material to be displaced in this case. **Fig. 11a** shows the effect of brass pre-hole diameter on the maximum load in HE of pre-holed brass. Maximum load values decreases as the hole diameter is increased. **Fig.11b** shows the effect of brass pre-hole diameter on the displacement (position) at which maximum load is reached. As brass pre-hole diameter is increased, the position at which maximum load is reached is less.

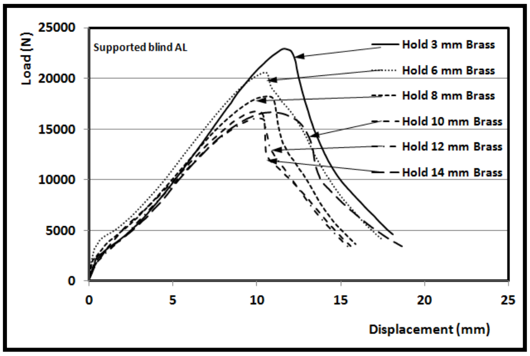
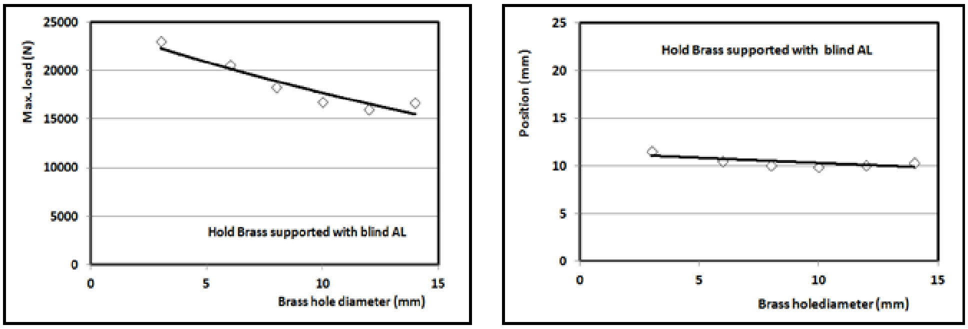


Fig. 10. Load/displacement curves in HE using a 19 mm diameter ball of pre-holed 1 mm thick brass supported with a 3 mm thick blind aluminum.



(a) (b)

Fig. 11. Effect of brass pre-hole diameter on

a) maximum load and b) position at which maximum load is reached

in HE of pre-holed, 1 mm thick brass supported with a 3 mm thick blind aluminum using a 19 mm diameter ball

3.4. HE of pre-holed brass supported with 3 mm thick holed aluminum

Figs. 12, 13 and 14 show the load/displacement diagrams in HE of 3,6, 8, 10 ,12 and 14 mm pre-holed, 1 mm thick brass supported with holed aluminum**.** For all the six groups, loads decreased as the pre-hole diameter in the brass increases due to the decrease in volume to be displaced in this case. Also, as the pre-hole diameter in the supporting Aluminum increases, the load decreased for the same reason.

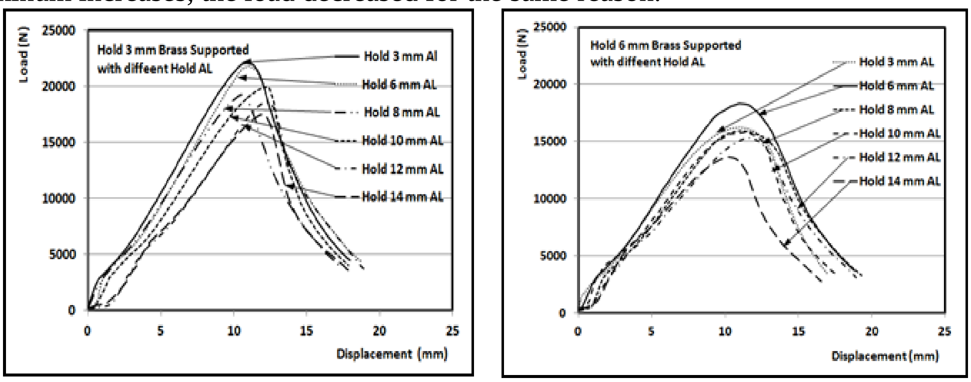
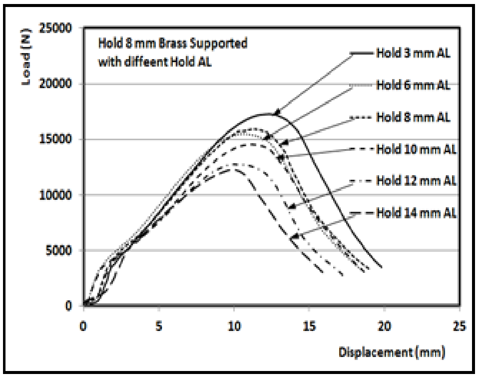


Fig. 12. Load/displacement diagrams in HE of 3 mm (left) and 6 mm (right) pre-holed, 1 mm thick brass specimens supported with holed Aluminum.



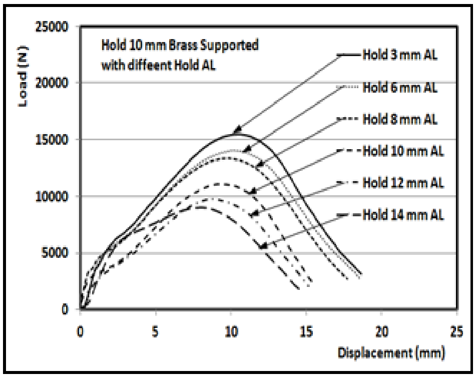
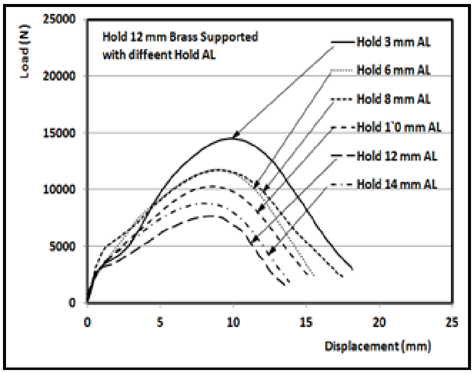


Fig. 13. Load/displacement diagrams in HE of 8 mm (left) and 10 mm (right) pre-holed, 1 mm thick brass specimens supported with holed Aluminum



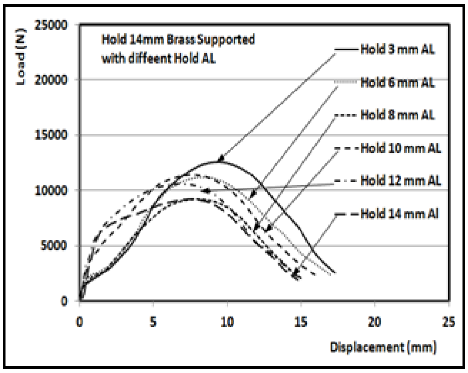
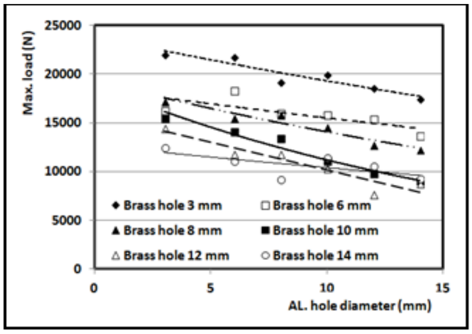
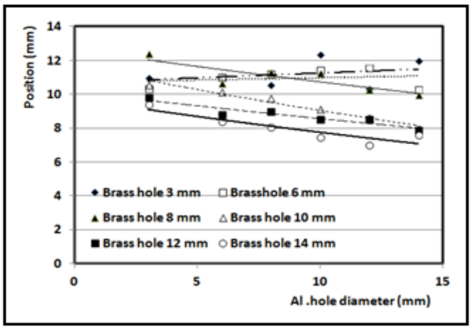


Fig. 14. Load/displacement diagrams in HE of 12 mm (left) and 14 mm (right) pre-holed, 1 mm thick brass specimens supported with holed Aluminum.

Figs. 15 a and b show the effects of Aluminum pre-hole diameter on the maximum load and position at which maximum load is reached in HE of brass specimens supported with holed aluminum specimens. As hole diameter increases, the maximum load decreases and the position at which maximum load is reached is also decreased.





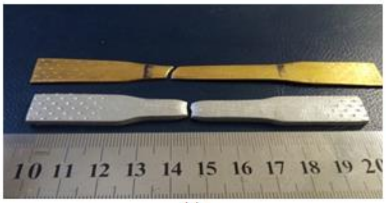
(a) **(b)**

Fig. 15. Effects of Aluminum pre-hole diameter on
a) maximum load and b) position at which maximum load is reached in HE of pre-holed, 1 mm thick brass supported with holed aluminum using a 19 mm diameter ball

4. Fractography

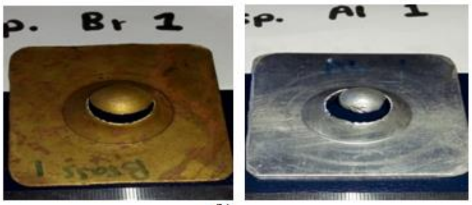
4.1. Fractures in simple tension test and in cupping (penetration) of blind brass and aluminum

Fig. 16.a shows the fractures in both brass and Al sheet in the uniaxial tension test. The necking in both materials is clear while fracture proceeds after different displacements. **Fig. 16 b** shows the fractures in both brass and Aluminum specimens in cupping (penetration) with a 19 mm dia. Steel ball. The cracks are typical for this type of tests.



(a)

Fig.16a. Fractures in both brass and Al sheet specimens in simple tension test

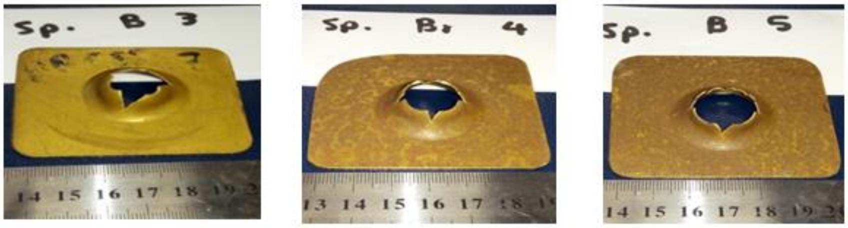


(b)

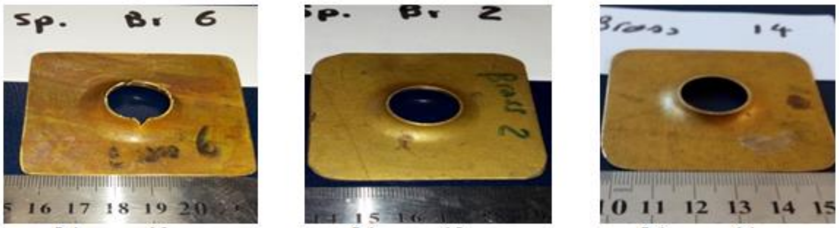
Fig. 6b. Fracture in penetration of (left) brass, 1 mm thick and (right) Aluminum, 3 mm thick blind specimens using a 19 mm diameter ball-shaped punch

4.2. Fractures in HE of holed brass and aluminum having different hole diameters

Fig.17 shows the fractures in HE of holed 1 mm thick brass specimens with a 19 mm dia. Steel ball. As it is clear, cracks appeared only at hole diameters 3, 6 , 8 and 10 mm. For large hole diameters, 12 and 14, no cracks were detected.



Φ brass = 3 mm　　Φ brass = 6 mm　　Φ brass = 8 mm

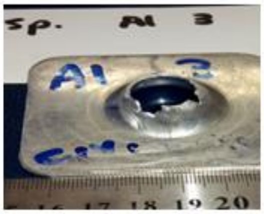
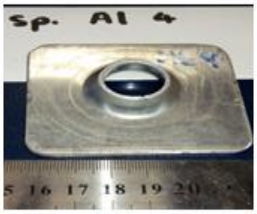
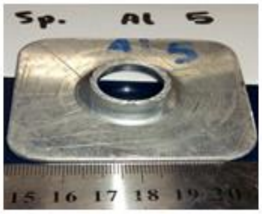


Φ brass = 10 mm　　Φ brass = 12 mm　　Φ brass = 14mm

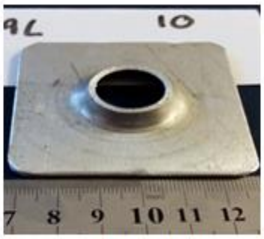
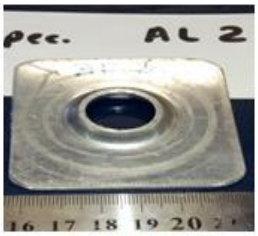
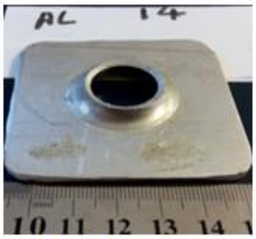
Fig. 17. Fractures in HE of holed 1 mm thick brass with a 19 mm dia. Steel ball

4.3. Fractures in HE of holed3 mm thick AL specimens with a 19 mm dia. Steel ball

FIg. 18 shows the fractures in HE of holed 3 mm thick Al specimens with a 19 mm dia. ball. As it is clear, cracks appeared only at hole diameters 3, 6 , and 8 mm. For large hole diameters, 10 to 14, no cracks were detected.

Φ Al = 3 mm Φ Al = 6 mm Φ Al = 8 mm

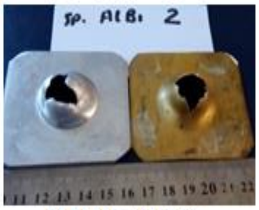




Φ Al = 10mm Φ Al = 12 mm Φ Al = 14 mm

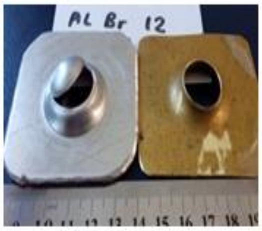
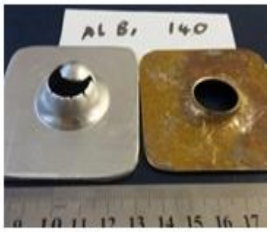
Fig.18. fractures in HE of holed Al with a 19 mm dia. Steel ball.

4.4. Fractures in HE of holed brass specimens supported with blind aluminum with a 19 mm dia. Steel ball

Fig. 19 shows the fractures in penetration of holed brass specimens supported with blind aluminum with a 19 mm dia. Steel ball. The presence of the supporting blind Al specimens affected the fracture mode in both brass and Al. For the brass specimens, cracks were present till hole diameter of 10 mm. On the other hand, all Al specimens fractured. For small hole diameters in brass, 3mm, wall cracks appeared in aluminum, disappeared as the brass hole diameter increased.


Φ brass = 3 mm Φ brass = 6 mm Φ brass = 8 mm

Φ brass = 10 mm Φ brass = 12 mm Φ brass = 14 mm

Fig. 19. Fractures in HE of holed brass specimens supported with blind aluminum with a 19 mm dia. Steel ball

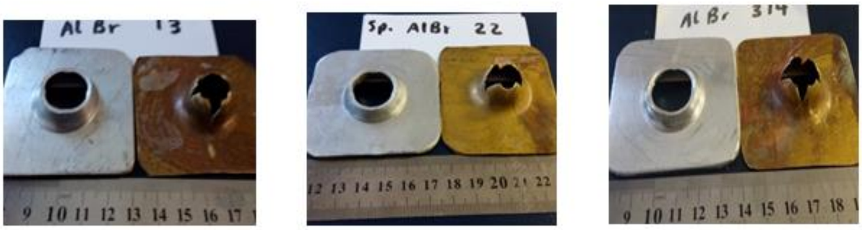
4.5. Fractures in HE of 1 mm thick holed brass supported with 3 mm thick holed aluminum

<u>G1: 3 mm Holed Brass specimens supported with Different Holed Aluminum</u>

a) Criterion: Occurrence of cracking in brass specimens: All specimens fractured, most of these are 4/90^{o}, cracks became smaller as aluminum specimen hole diameter increased.

b) Criterion : Occurrence of cracking in Aluminum specimens: The Al specimens with small hole diameters (3 and 6 mm) cracked in the form of $4/90^{o}$, becoming smaller for the hole dia. 6 mm compared to 3mm. For the hole 8 mm, no cracks were detected. For holes 10, 12 and 14 mm, no fractures were detected, see **Fig. 20**

Φ Al = 3 mm   Φ Al = 6 mm   Φ Al = 8 mm



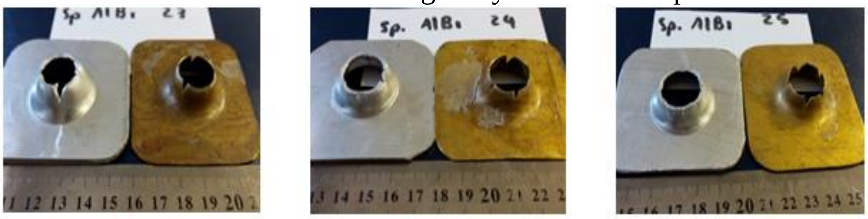
Φ Al = 10mm   Φ Al = 12 mm   Φ Al = 14 mm

Fig. 20. Fractures in HE of a 3 mm Holed Brass specimens supported with Different diameter Holed Al

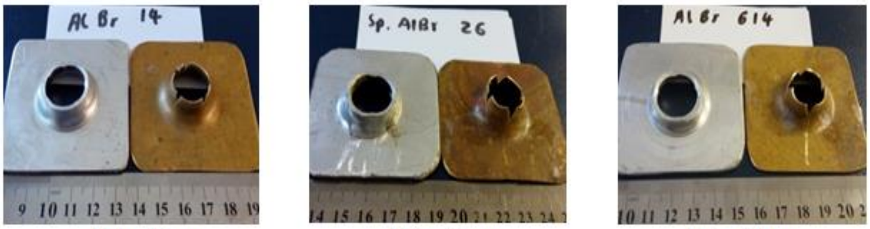
G2: 6 mm Holed Brass specimens supported with Different Holed AL

a) Criterion: Occurrence of cracking in brass specimens: All brass specimens cracked and cracks became smaller as aluminum specimen hole diameter increased.

b) Criterion: Occurrence of cracking in Aluminum specimens: For hole diameters 3, 6 and 8 mm in Aluminum specimens, cracks were present and became smaller as the hole diameter was increased. For hole diameters 10, 12 and 14 mm in Aluminum specimens, no fractures were noticed but some irregularity in section was present shown in **Fig. 21.**



Φ Al = 3 mm   Φ Al = 6 mm   Φ Al = 8 mm

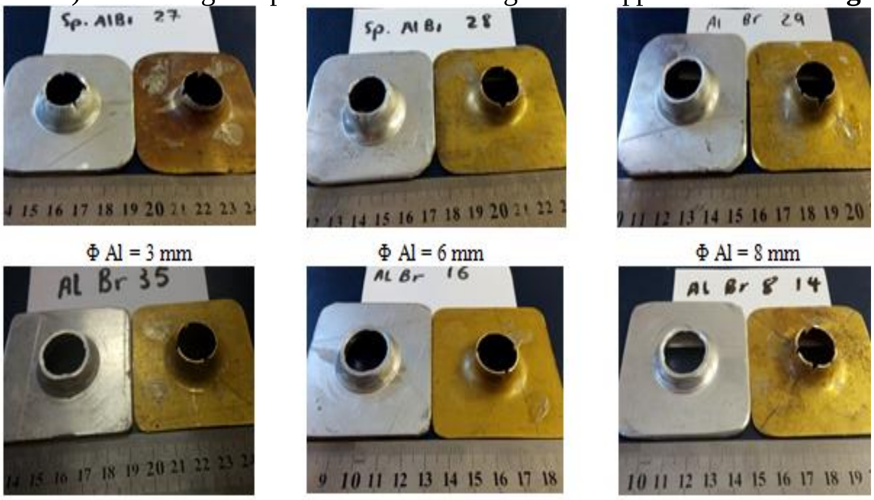


Φ Al = 10 mm   Φ Al = 12 mm   Φ Al = 14 mm

Fig. 21. Fractures appearing in HE of a 6 mm Holed Brass specimens supported with Different diameter Holed AL

G3: 8 mm Holed Brass specimens supported with Different Holed AL

a) Criterion: Occurrence of cracking in brass specimens: All specimens fractured, most of these are 4/90^o, cracks became smaller as aluminum specimen holed diameter increased like in G1 and G2.
b) Criterion :Occurrence of cracking in Aluminum specimens: Smaller 4/90^o cracks appeared on Al specimens for holed diameters 3 and 6 mm, however for larger holes (8.10, 12 and 14 mm) no cracking was present and some irregularities appeared shown in **Fig. 22**



Φ Al = 3 mm　Φ Al = 6 mm　Φ Al = 8 mm

Φ Al = 10 mm　Φ Al = 12 mm　Φ Al = 14 mm

Fig. 22. Fractures appearing in HE of a 8 mm Holed Brass specimens supported with Different diameter Holed AL

G4: 10 mm Holed Brass specimens supported with Different Holed AL

a) Criterion: Occurrence of cracking in brass specimens: Using Al holed diameters of 3 and 6 mm as a support resulted in presence of very small cracks in brass. When the Al holed diameter was increased to 8 and 10 mm, almost no cracks were present. This is due to sufficient supported Al under brass at small deviation between hole of Al and brass. Fracture was delayed at brass pre-hole diameter of 10 mm when supported by 8 and 10 mm holed Aluminum. Such delay is due to the small deviation between the two pre-hole diameters. As deviation increased, like in pre-hole of Al was 12 and 14 mm, the supported area is less leading to stronger possibility of crack initiation first in brass.
b) Criterion: Occurrence of cracking in Aluminum specimens: For the smallest Al holed diameter only (3 mm), cracks were present. For other diameters, no cracks were detected shown in **Fig. 23**

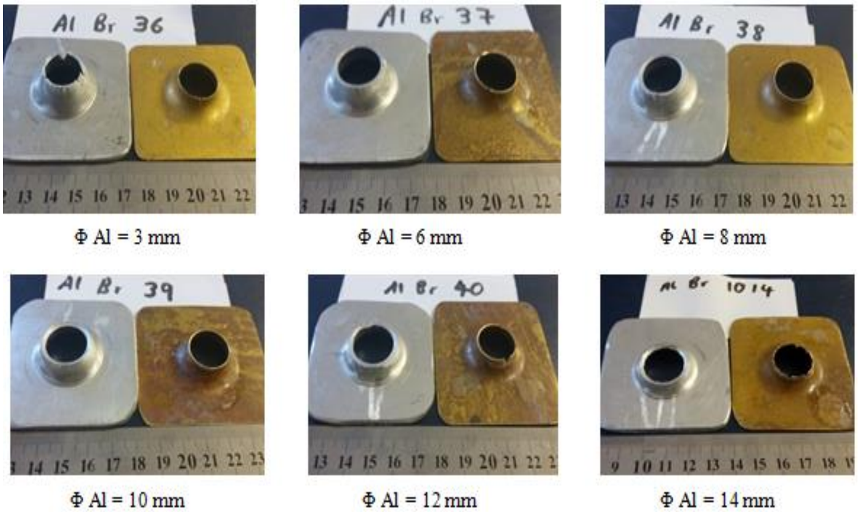


Fig. 23. Fractures appearing in HE of a 10 mm Holed Brass specimens supported with Different diameter Holed AL

G5: 12 mm Holed Brass specimens supported with Different Holed AL

a) Criterion: Occurrence of cracking in brass specimens: All specimens were successful for all values of Al specimen hole diameter values.
b) Criterion: Occurrence of cracking in Aluminum specimens: For Al hole diameters of 3 and 6 mm, cracks and some peeling were present. For larger values of Al hole diameter (8, 10, 12 and 14 mm), no fractures were observed shown in **Fig.24**.

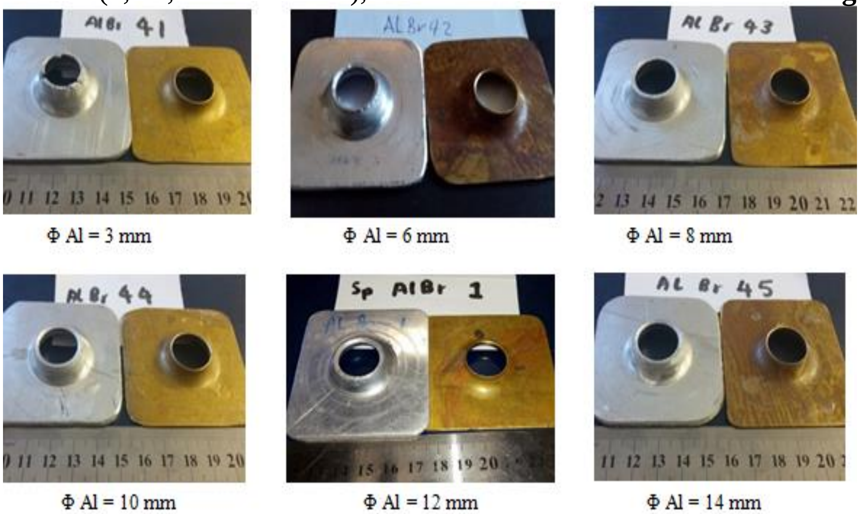


Fig. 24. Fractures appearing in HE of a 12 mm Holed Brass specimens supported with Different diameter Holed AL

G6: 14 mm Holed Brass specimens supported with Different Holed AL

a) Criterion: Occurrence of cracking in brass specimens: All specimens were successful for all values of Al specimen hole diameter values.
b) Criterion: Occurrence of cracking in Aluminum specimens: For Al hole diameters of 3 mm, cracks and some peeling were present. For larger values of Al hole diameter (6, 8, 10, 12 and 14 mm), no fractures were observed shown in **Fig.25**.

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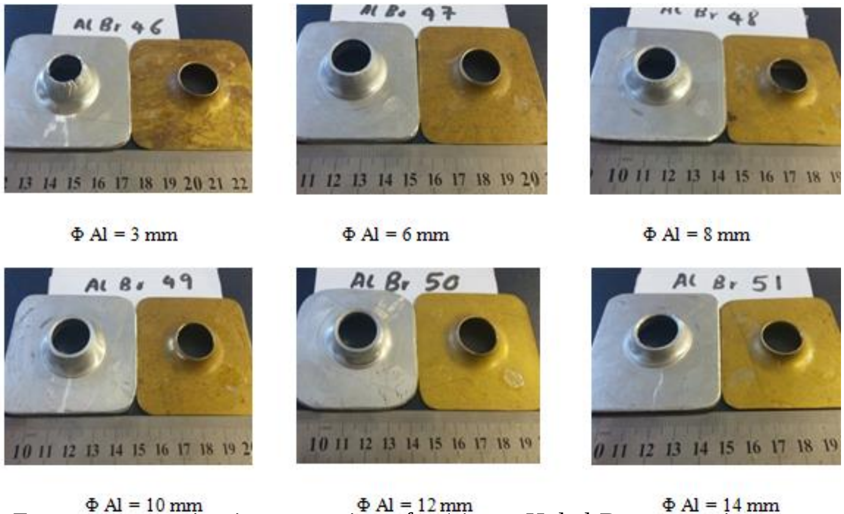

Fig. 25. Fractures appearing in penetration of a 14 mm Holed Brass specimens supported with Different diameter Holed AL

5. Forming limit curves (FLC's)

5.1. FLC'S relative to the criterion of occurrence of cracking in brass sheet

Fig. 26 shows the Forming Limit curves (FLC's) relative to the criterion of occurrence of cracking in brass sheet. Fracture occurred at all holed brass specimens having hole diameters of 3, 6 and 8 mm supported by blind and holed Aluminum sheets. The corresponding expansion ratios for such holes diameters are 0.843, 0.684 and 0.578 respectively, which are relatively high enough to produce safe brass sheet specimen. For brass specimens having hole diameter of 10 mm, fractures were observed when supported with blind Aluminum (hole diameter is zero) and also for aluminum hole diameter of 3 and 6 mm. When Aluminum hole diameter was increased to 8 and 10 mm, no fractures appeared in brass specimens. However, when the holed diameter was increased to 12 and 14 mm, fractures were present in the brass sheets. This can be explained by the following: When brass hole diameter is equal to (10 mm) or larger than the Aluminum hole diameter (3 and 6 mm) , the expansion ratio for Aluminum sheet here is relatively high (0.843, 0.684 respectively) which leads to fracture in the supporting material first followed by a failure in the brass specimen.

When the Aluminum holed diameter is increased to 8 or 10 mm, the aluminum sheet expansion ratio is decreased to 0.578 and 0.4736 respectively, which leads to a successful brass specimen. Added to this, the support is 80% and 100% at the beginning of loading which helps in producing safe product. When the Aluminum holed diameter is increased further to 12 and 14 mm, the contact area become less at the beginning of the expansion, plus the fact that the expansion ratio becomes higher. This means weaker support of the brass specimen and hence helps to initiate cracks in brass. Meanwhile, the Aluminum does not suffer any cracking because of the low expansion ratio in this case. For the holed brass specimens having high values of diameters (12 and 14 mm), no fractures were observed in brass sheet in case of supporting them with Aluminum sheet either blind or holed with different hole diameters (from 3 to 14 mm). Success of such specimens may be referred to the decrease of expansion ratios in these two cases corresponding to 0.3684 and 0.2631 respectively which are low enough to process the operation successfully.

5.2. FLC'S relative to the criterion of occurrence of cracking in an aluminum sheet

Fig. 27 shows the Forming Limit Diagram (FLD) relative to the criterion of occurrence of cracking in aluminum sheet. The **blind** AL specimens fractured upon cupping of duplex sheets (brass/Al) for all values of brass hole diameters. When the hole diameter for the brass specimen was 3 mm, the cracks took the shape of 3/120^o. For other values of brass hole diameter (6, 8, 10, 12 and 14), the cracks were typical like those obtained in free cupping of a single aluminum sheet. Occurrence of fracture in blind specimens can be explained as follows: when the brass hole diameter was small (3 and 6mm), the ratio required to expand the brass hole is high ((0842 and 0.684 respectively) and hence cracking began in the brass sheet, transferring to the Al sheet due to the increased contact area as expansion proceeds. This may explain the similarity of cracking mode of the two materials in this case.

When the brass hole diameter Increased (8,10,12 and 14 mm) the contact area between the ball and the Al sheet became always larger, leading to simulate the cupping of a pure Al specimen, resulting in a typical failure like in single specimen. All 3-mm hole diameter Aluminum specimen fractured when supporting holed brass specimens (all hole diameters) in cupping. This is due to the high expansion ratio required to safely complete the process. In this case (0.842) even if there were successful brass specimens having hole diameters of 12 and 14 mm due to low ER in these case (ER here is 0.368 and 0.263 respectively)For 6- mm hole diameter Aluminum specimens supporting brass, specimen fractured for the brass hole diameter of 3 and 6mm only. However, for larger brass hole diameters, the Aluminum specimens were successful. The presence of two different hole diameters in the two contacting sheets, load distribution may differ due to the fractures resulting in the brass specimens. Similar fractures may generate on the Al surface. When Aluminum hole diameter was increased, 8,10, 12 and 14 mm, no fractures were noticed for all brass specimen hole diameters due to the small ER values in this case, expansions proceeds successfully in the Al specimen.

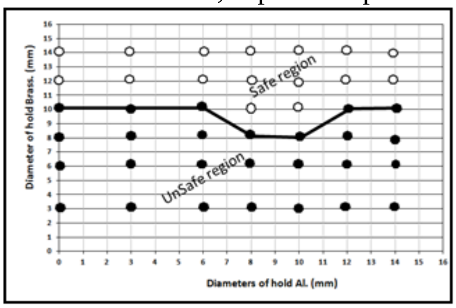

Fig. 26. FLC in the HE process related to the occurrence of cracking in brass sheet

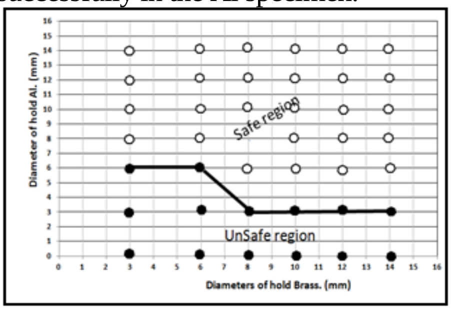

Fig. 27. FLC in the HE process related to the occurrence of cracking in Aluminum sheet

Forming limit curves (FLC's) can be of industrial importance since such curves can determine the success or failure if the HE process plus the safe and unsafe region limits in this commonly-used process. Design modifications, including change of both process and product parameters can be altered to widen the range of safe region limits for more process and material utilization which leads to improve the manufacturing process technical and economic efficiency.

6. Conclusions

The experimental results obtained from the hole expansion tests of hole of 2-layer (brass/Aluminum) sheet using a ball-shaped punch had led to the following conclusions:

1- When holed brass specimens were supported by blind Al sheets, the maximum force reached decreased and the position at which the maximum force was reached decreased as the hole diameter in brass specimens increased.
2- When supporting with holed Al sheets, in general the forces required decreased as the hole diameter in the brass specimens increased. For the above case, however, when fixing the brass hole diameter, the force required decreased as the hole diameter in the Al specimen increased.
3- Fracture showed different shapes depending on the type of support (blind or holed) and the pre-hole diameter in both the brass and supporting Aluminum sheet. The role of the deviation between pre-hole diameters is evident. Fracture is delayed for small deviation. As that deviation increased, the supported area is less leading to stronger possibility of crack initiation first in brass.
4- Forming limit curves (FLC's) could be constructed for the case of HE of 2-ply (brass/Aluminum) sheet using a ball-shaped Punch. Two criteria were assumed: occurrence of fractures in the brass sheet and occurrence of fractures in the supporting Al sheet. Safe and unsafe regions were determined. Such curves are of importance in determining the success or failure if the HE process.

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قابلية التشكيل فى عملية توسيع الثقوب فى لوح مكون من طبقتين (نحاس اصفر/الومنيوم) بأستخدام دافع ذو نهاية كروية

الملخص باللغة العربية

تستخدم عمليات توسيع الثقوب فى الالواح المعدنية لتصنيع العديد من اجزاء المنتجات مثل الاجهزة المنزلية , صناعة السيارات , الاجهزة الطبية والاجهزة الالكترونية ونظراَ لأهميه للاجزاء التى يمكن تصنيعها من النحاس الاصفر فى صناعة تتشكيل الألواح فان البحث الحالى يقوم بتحديد قابلية التشكيل للوح مكون من طبقتين (نحاس اصفر مسنودا (مدعوماَ) بلوح من الالومنيوم) وذلك بأستخدام دافع ذى نهاية كروية . ويركز الهدف الرئيسى لهذا البحث على دراسة تأثير قطر الثقب المسبق , نوع وطريقة سند اللوح الأصلى (النحاس الاصفر) من قبل اللوح الساند (الألومنيوم) سواء كان مثقوباَ او مصمتاَ على احمال التشكيل وعلى المسافة التى يحدث عندها اقصى حمل فى الحالات المختلفة. وقد تم تجهيزالثقوب فى مركز العينات بأقطار 3, 6, 8, 10, 12, 14 مم على الترتيب. وتم اجراء اختبارات شد محورية واختبار اختراق بدافع ذى نهاية كروية. وقد تم عمل اختبارات توسيع الثقوب للحالات المختلفة. وقد اظهرت النتائج ان الاحمال المطلوبة لتوسيع الثقوب و المسافات (الاوضاع) التى يحدث عندها الحمل الاقصى وانماط الانهيار(الكسر) وكذا نسب التوسيع تعتمد على قطر الثقب المسبق وايضا على طريقة سند لوح النحاس الاصفر من قبل لوح الالومنيوم. وقد خلص البحث الى أن الاحمال المطلوبة للتوسيع واوضاع حدوث الحمل الاقصى تقل كلما زاد قطر الثقب المسبق . كما اظهر البحث ان نوع الكسر يختلف بأختلاف نوع الدعم من قبل لوح الالومنيوم . و أمكن انشاء خرائط حدود التشكيل للمدى المستعمل من اقطار التقوب فى كل من النحاس الاصفر والالوميوم وهذه الخرائط تحدد المناطق الآمنة والغير آمنة للتشكيل فى عمليات توسيع الثقوب. وقد أستخدمت نظريتان فى هذا الصدد : حدوث الانهيار فى لوح النحاس , وحدوث الانهيار فى لوح الالومنيوم. وهذه الخرائط ذات أهمية صناعيه فى تحديد نجاح او فشل عملية التوسيع للثقوب.