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A. VINO[1*], K. KALAICHELVAN[1], S. SAJITH[2], G. KUMARESAN[3]

STUDIES ON FLEXURAL PROPERTIES AND CONSTRUCTION OF FAILURE MODE MAP FOR COPPER SANDWICH PANELS

This paper is focused on investigating the mechanisms associated with different failure modes of copper (C101) sandwich panels with honeycomb cores of different heights subjected to flexural loading. Honeycomb core is made up of copper strips which were formed to required shapes using Dies fabricated by Electric Discharge Wire cut machining technique. All the joints in the sandwich panel were established through Brazing technique. Three-point bending test was conducted as per ASTM standard C-393. It was observed that increase in height of the core resulted in panels with higher strength to weight ratio. It also exhibited higher stiffness to weight ratio and very high strain energy absorption ability. An increase in flexural strength was reported with a maximum of 43% improvement for 10.9 mm core compared to 6.9 mm core. Further, 81.75% increase in absorbed strain energy was reported for 10.9 mm thick panel compared to 6.9 mm. The Optical and scanning electron microscope (SEM) analysis confirmed the establishment of good bonding between the filler and the substrate. Energy-dispersive Spectroscopic (EDS) analysis revealed the presence of Cu, Al, Zn, SiO_2 and $CaCO_3$ in the substrate. Further it also revealed the presence of Cu, $CaCO_3$ and GaP in the filler material. The failure mode map was constructed which can be used for predicting different types of failures more likely to occur for specific parameters of copper sandwich panel. The dominant failures occurred during testing was in good agreement with the prediction done through failure mode map. The appreciable results in the proposed research may be supportive in construction of cooling system. The structure development and process control are convenient in mass production in automobile industries.

Keywords: Brazing; Forming; Honeycomb; Strain energy; Flexural stiffness; ED Wire cutting; Dies; EDS

1. Introduction

The sandwich composites are widely used in aircrafts, high-speed automobiles, building construction, wind energy systems and ships because of its good stiffness to weight ratio, strength and energy absorption abilities [1,2,12]. Normally, the sandwich core has poor stiffness and low density but when the core is joined to the face sheet, it provides dramatic improvement in the stiffness with only a slight increase in the density [3]. The face sheet tolerates axial tensile and compressive stresses whereas the core material tolerates shear and compressive stresses and the core-to-facing bond joins the face sheets and core materials and makes them to act as a single entity with a high torsional and flexural rigidity [4,5]. Energy absorption properties are enhanced by both honeycomb core and face sheet materials. The energy dissipated by the core was significantly high [6]. Long wan et al. [7] presented that the Fluxless soldering process had better metallic bonding between face sheets and foam core because of good wetting characteristics. Guo-yin ZU et al. [8] joined the aluminum foam with steel face sheet using polyamide-epoxy resin and observed that the delamination occurred on the adhesive interface. Cost effective truss and textile core offered higher specific strength compared to the honeycomb core [9]. In fusion welding, huge amount of filler material is required to weld cellular structure. Moreover, fusion welding process leads to many defects such as crack, gas pores and other defects because of the mismatch in Thermal properties of the core and face sheets [10]. The demand for light weight and high stiffness materials are increasing day by day and different types of sandwich panels are also developed to cater the need.

Yi-Ming Jen et al. [11] presented the two-stage cumulative bending fatigue loading of adhesively bonded aluminum honeycomb sandwich panels and reported better resistance to stiffness degradation under cyclic loading. A failure mode map was

1 ANNA UNIVERSITY, DEPARTMENT OF CERAMICS, AC TECHCAMPUS, CHENNAI, INDIA
2 ANNA UNIVERSITY, DEPARTMENT OF AEROSPACE ENGINEERING, MIT CAMPUS, CHENNAI, INDIA
3 BANNARI AMMAN INSTITUTE OF TECHNOLOGY, DEPARTMENT OF MECHANICAL ENGINEERING, SATHYAMANGALAM, ERODE – 638 401, INDIA

* Corresponding author: vinomechsss@gmail.com

constructed using the ratio of skin thickness to the span length and relative density of honeycomb sandwich panels which are very useful for the design of sandwich panels [12]. The energy dissipated during the failure was influenced by the material. Othman et al. [13] found through the impact tests that the large portion of the kinetic energy was dissipated during deformation of core followed by the top skin failure. Yuping Sun et al. [14] studied the web-core laser-welded sandwich plate under three point bending test and the result showed that an elastic phase was created at the weld junction between the web and the face sheet [14]. In this paper, it was found that energy absorption capability and failures mode are mainly influenced by the size of the honeycomb cells under bending load [15,16]. The energy dissipation capacity is mainly affected by parameters like face to core bonding and cell size of the foam under bend loading [16]. Jeom Kee Paik et al. [17] discovered that in aluminum honeycomb-cored sandwich panel, increase in core thickness resulted in delayed plastic deformation. Belouettar et al. [18] inferred that the maximum shear stress occurs at the middle of the specimen. Mujika[19] found that the high core height provide high stiffness but might be subjected to greater shear stresses. Out-of-plane strength mainly depends on the height of the honeycomb core [20]. In the past decade the structural design of copper base honey comb structures are used / proposed for investigation as they are good for thermal cooling systems and getting recommended for automobile industries [27-29].

Thus, a number of techniques were followed to enhance various mechanical properties of the sandwich composite structures. So, it is very important to adopt better fabrication techniques for the preparation of honeycomb sandwich composite structures. This paper experimentally investigates the flexural properties of sandwich panels (Cu -honeycomb core and Cu face sheets) prepared by joining through brazing technique and the associated failure mechanisms were characterize. Based on the literature survey the thickness (6.9 mm, 8.9 mm and 10.9 mm) of the panel is decided and experiments are proposed.

2. Material fabrication and test procedures

2.1. Material fabrication

Sandwich composite panels were prepared using copper C101 material for core as well as face sheets. TABLE 1 shows the specification of sandwich panels. The honeycomb core was formed out of copper (C101) sheets of thickness 0.5 mm using die forming technique with desired heights. The H11 & H13 die materials were used to fabricate the dies and the required profile was cut out using wire cut EDM. The sheets were formed with the help of 35T mechanical linkage press and were joined together to produce a full hexagon shaped honeycomb core as shown in Fig. 1. The joining process was accomplished using heat flux brazing technique. Fig. 1 shows the procedure involved in the preparation of honeycomb core. Sheets of three different heights 4 mm, 6 mm and 8 mm were used for the preparation of honeycomb.

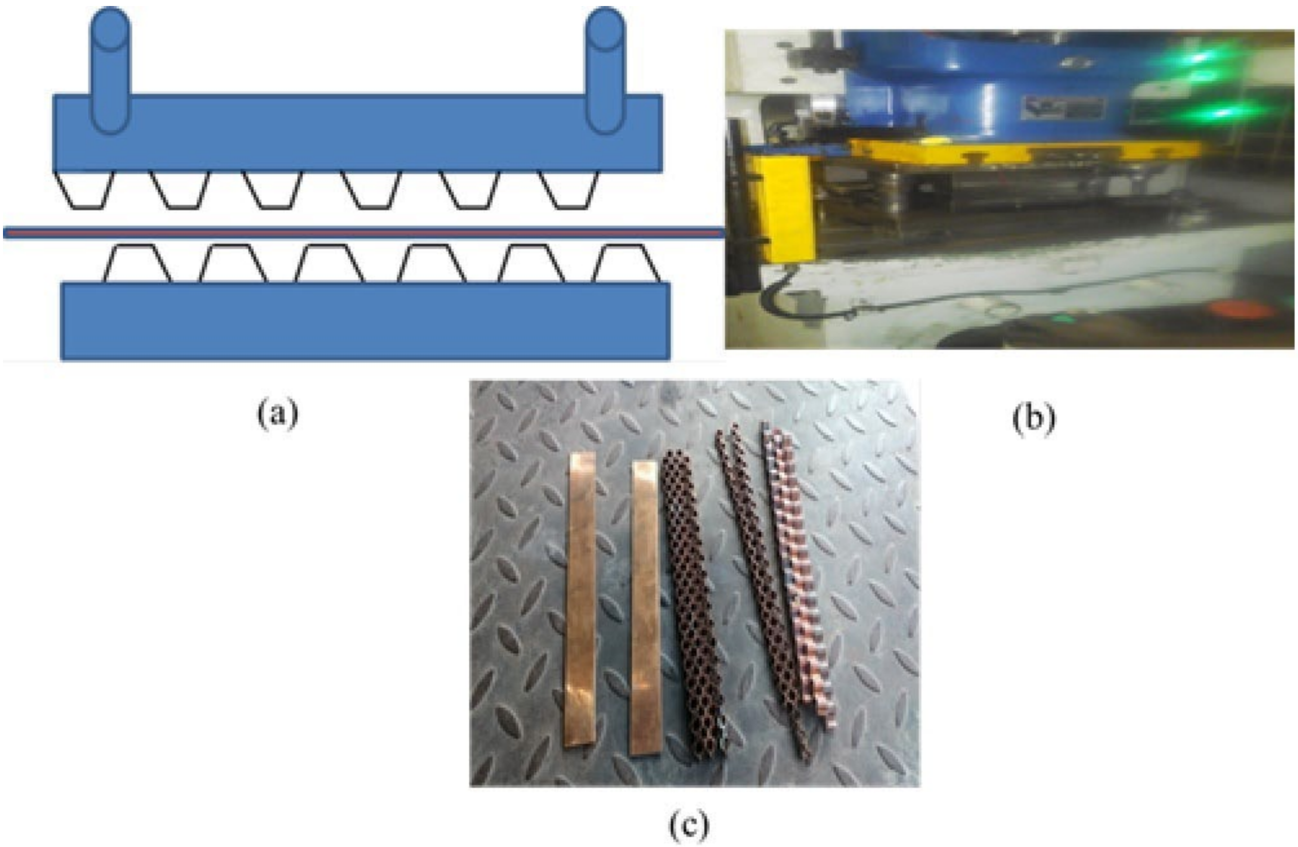

Fig. 1. Honeycomb core fabrication procedures a) Dies b) Power press c) Formed copper strips

TABLE 1

Specification of copper sandwich panels

Core thickness (mm)	Face and bottom sheets thickness (mm)	Sandwich thickness (mm)	Length (mm)
4	1	6.9	200
6	1	8.9	200
8	1	10.9	200

After the preparation of honeycomb core, it is bonded with copper face sheets of thickness 1mm using Cu filler by melting and depositing it at the interface using Oxy-acetylene flame. The oxy-acetylene torch is usually preferred because of its high heating rate. The melting temperature of the filler metals should be lower than the base metal. The molten filler metal should be able to flow into the narrow gaps between the two parts to be bonded by capillary action. The atoms of the filler material diffuse into the surface of the substrate to offer better adhesive strength.

2.2. Optical microscopic analysis of bonded joints

The joints were observed under optical microscope to study the microstructure and to ensure quality of the joint. The specimens were cut to desired dimensions using water jet cutting process. The joints were then polished using a set of emery sheets of grade ranges from 600 to 2000 in the order of decreasing grain size to get a well-prepared joint for observation. They were further polished in a rotary grinder polishing machine which uses 6.172 µm size Al_2O_3 powder to achieve highly reflective surface for better results. The specimen was placed in the mount present in the microscope and the images of the joints were taken with scale.

2.3. Microstructural and elemental analysis of bonded joints with SEM and EDS

In depth micro structural and constituent element analysis was done using scanning electron microscopy (SEM) and Energy-dispersive Spectroscopic (EDS) techniques respectively for the brazed joints. ZEISS-scanning electron microscope was used for the purpose. A voltage of 20 kV was employed to accelerate the electron beam and a working distance of 10 mm was adopted. The specimens were finely polished and loaded in the mount. By utilizing low wavelength electron beam, the fine details of the microstructure present in the surface and the constituent elements were revealed.

2.4.Three-point flexural testing

The main aim of the flexural test is to evaluate the mechanical properties such as young's modulus, flexural stiffness and shear strength of the sandwich panels. The test was performed as per ASTM C393-00. The three-point tests were performed on the copper sandwich beams of different thickness in TINIUS OLSEN universal testing machine (UTM model- H100KU) at the ambient temperature. Five specimens were tested in each category. The diameter of the supporting roller is 10mm.The load is applied at the mid-span through another roller. The three-point flexural test setup is shown in Fig. 2. The specimens were loaded at a constant speed rate of 5 mm/min. The applied load and deflection were monitored and recorded until the failure of the specimen.

3. Result and discussion

3.1. Microstructural analysis of joints

The optical microscopic was used to observe and characterize any changes in the micro structure in the brazed joints. For better bond strength the filler material must diffuse into the surface of the substrate. Fig. 3 shows the continuous joint obtained using brazing technique. It was evident that there is a change in the surface of the substrate near the joint which shows a different microstructure structure. Diffusion of atoms from the filler material into the substrates might be the reason for this change in the microstructure. No sign of separation was observed due to the formation of interphase layers and thus

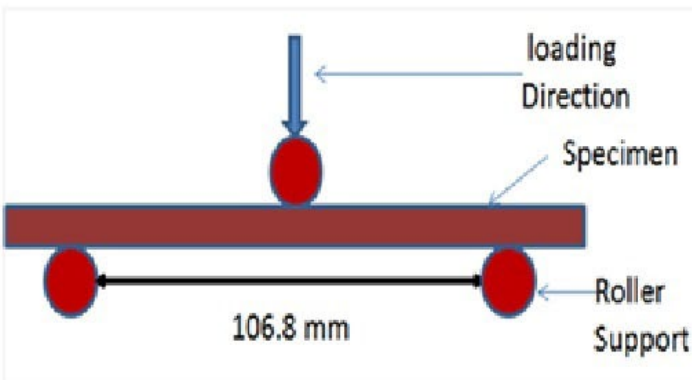

Fig. 2.Three-point flexural test configuration

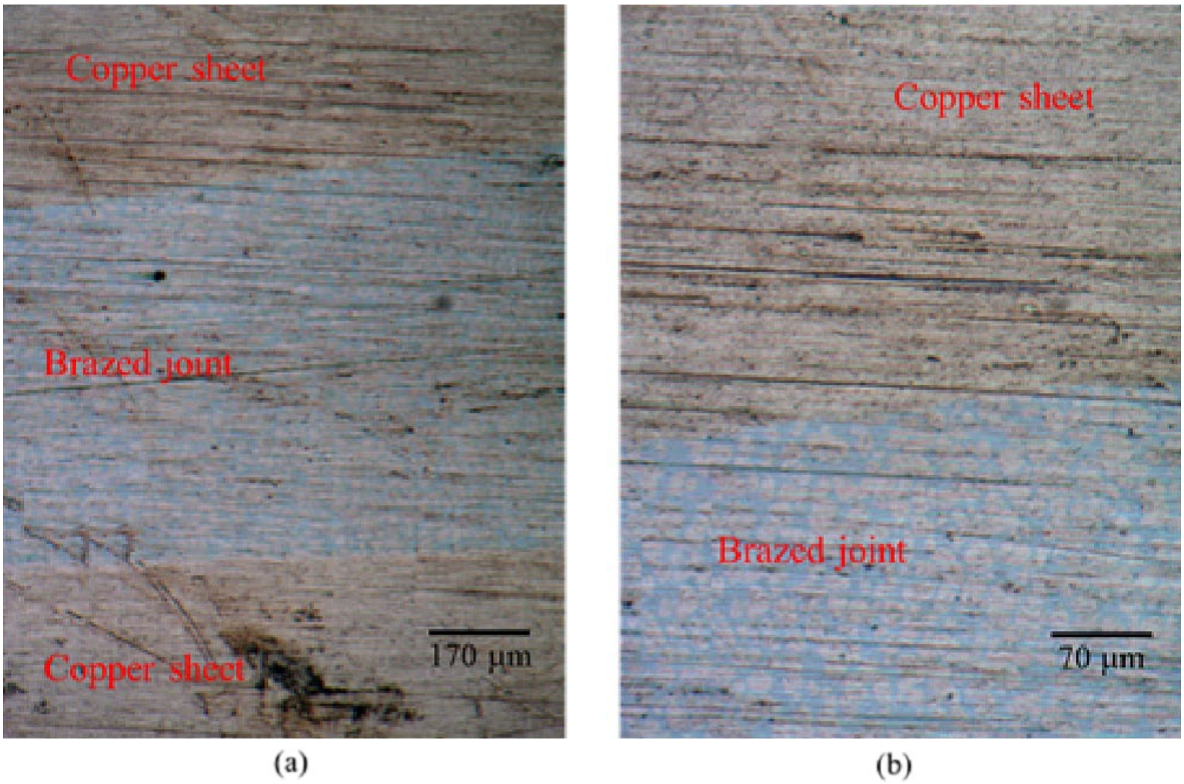

Fig. 3. Optical Microscopic Images of Brazed Joints (a) Interface area 40× (b) Interface area 100×

resulted in strong continuous joint. For detailed analysis of the joint regarding the microstructure Scanning Electron Microscope (SEM) was employed.

The interfacial joints were further examined with electron beam in SEM to reveal the bonding mechanism between the Cu-Zn filler and the copper substrate. From the images obtained from SEM analysis it can be seen that the filler material evenly spread out over the substrate as shown in Fig. 4. The Zn element in the filler has low melting point and hence it tends to evaporate at brazing temperatures above 800°C which is evident from the voids and pores present in the joint as shown in Fig. 4 [26]. Zn is having good thermal properties; high heat capacity and heat conductivity. At the same the Zn can be malleable with elastic properties while increase in heat. In future scope the research can be conducted with Al and the same can be compared for investigation. There is no inter metallic layer formed between the filler and the substrate, instead complete diffusion of molecules can be witnessed at the joint and there by establishing good bonding between filler and substrate as seen in Fig. 4. Further to reveal the constituents present in the joint and the substrate, EDS analysis was done on the joint and the substrate. The results showed the co-existence of copper and zinc elements in the joint surfaces as shown in Fig. 5. Various constituent elements present in the joint are given in TABLE 2.

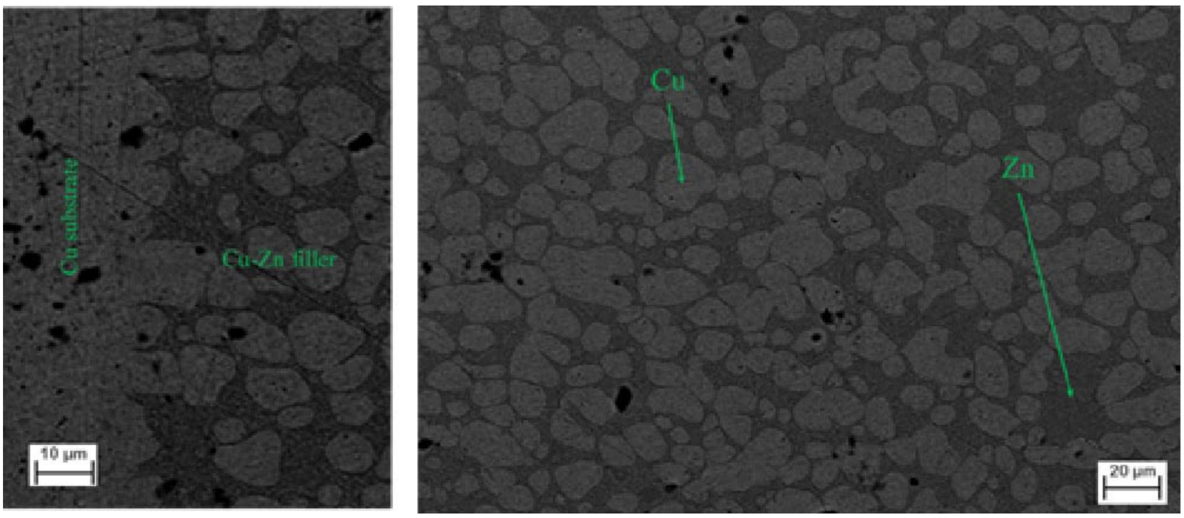

Fig. 4. SEM analysis of the joint

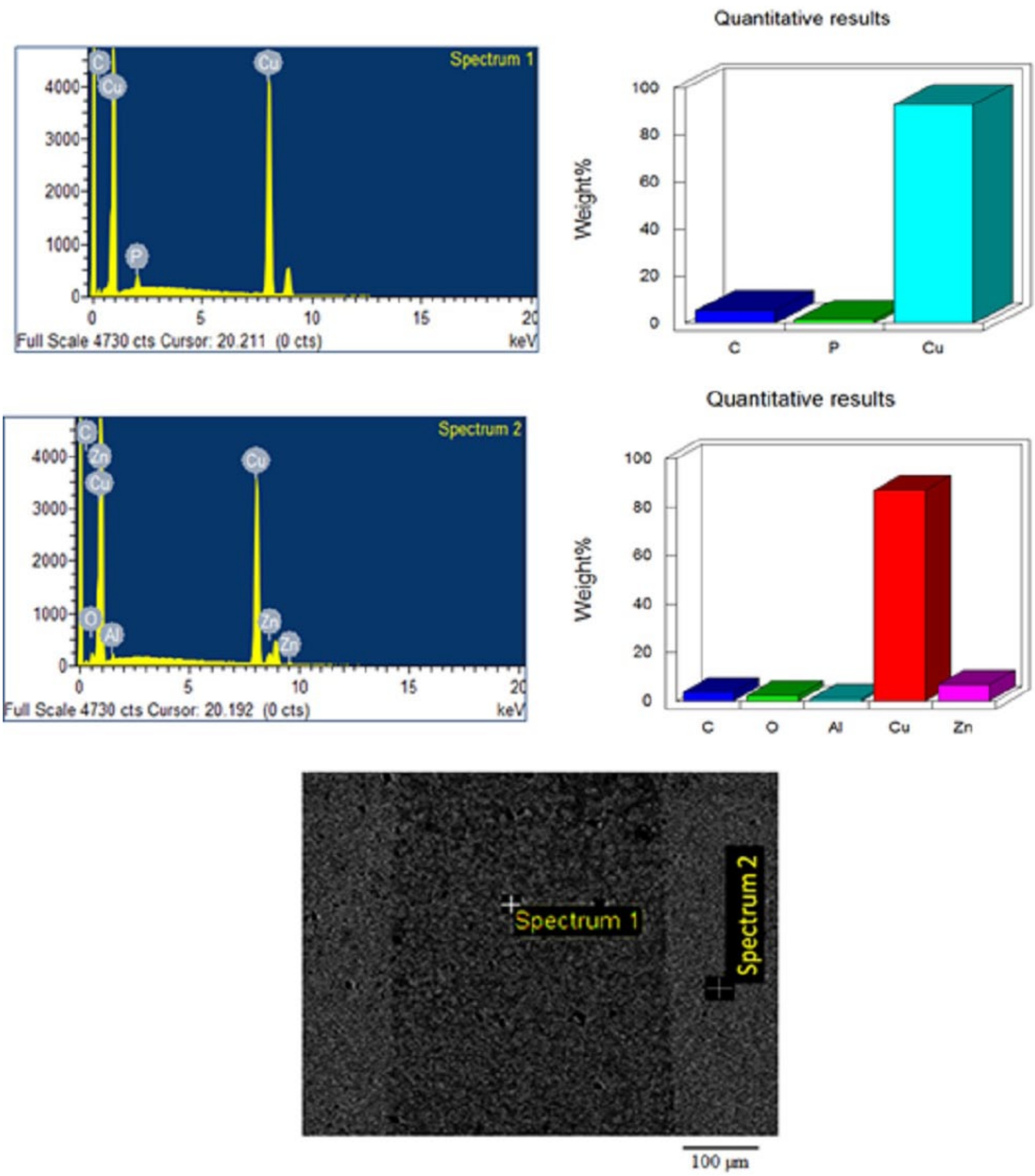

Fig. 5. EDS analysis of the joint

TABLE 2

Elemental breakdown at the joint

Element	Intensity	Weight%	Atomic%
C	0.3045	3.40	14.83
O	1.0131	1.99	6.49
Al	0.3928	0.85	1.65
Cu	0.9807	87.11	71.71
Zn	0.9830	6.65	5.32

3.2. Three-point test flexural test

Three-point tests were carried out on copper sandwich panels to evaluate the flexural properties and to characterize the materials used in the panel. Fig. 6(a) shows the Displacement vs Load curve of the three-point test. There is a linear elastic region in the curve where no permanent failures were observed. After that the plastic region begins due to permanent failures such as yielding of the honey comb core and face sheet where the load still increases due to core densification phenomenon but at a lower rate until it reaches the peak load. From there the curve shows a gradual decrease in the load as shown from the point 1 to 2 due to local buckling of the top face sheet. There are sudden load drops in the curve at the points 2 and 3 due to the debonding of the core from the face sheet occurred on the top face sheet highlighted as 2 and 3 in the specimen. During debonding the joint between the core and the face sheet failed and thus reduced the panel stiffness abruptly which led to the sudden load drop. Similar kinds of failures were reported in 8.9 mm and 6.9 mm thickness specimens. The peak load and

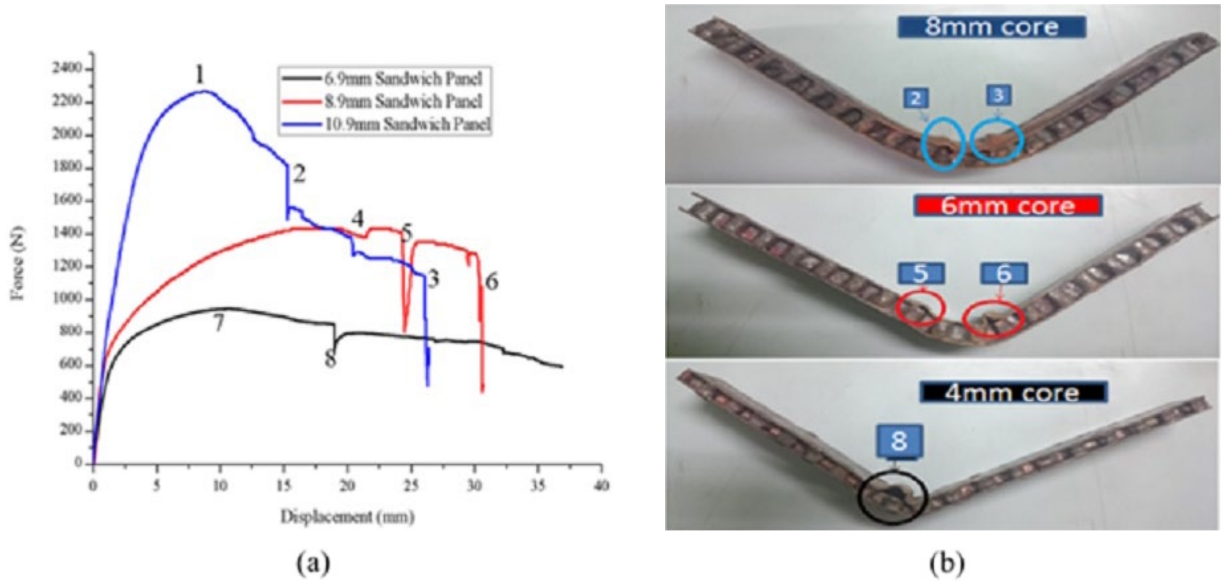

Fig. 6. Three-point bend test (a) Load displacement curve and (b) Observed failures

deflection at peak load values for different specimens are given in TABLE 3. Since the deflection and the bending moment are maximum at the mid-span the face sheet buckling failure occurs very close to the loading point.

TABLE 3

Peak load and deflection values of different sandwich panels

Thickness of copper sandwich composites (mm)	Peak load (N)	Mids. span deflection (mm)
6.9	934	10.94
8.9	1430	19.6
10.9	2270	8.96

It was observed that the time to reach the peak load value highly depended on the sandwich thickness. The specimen having higher thickness attained the peak load quickly due to the high load carrying capacity of the specimen. Also, since displacement control mode of test is adopted for this work, the loading rate is higher in thicker specimens compared to the thinner ones and hence attained the peak load quickly and led to earlier failure. Load resistance capability of the panels depends on the core thickness with 41.14% and 158.74% increase in peak load was reported for 6 mm and 8 mm sandwich core when compared to 4 mm core. All the failures were observed on the top face sheet. Wrinkling was seen near to the loaded point [21]. Thus as a whole the Copper sandwich composite panels exhibited high flexural properties and no other failures like core shear and core crushing were identified, as a result of the efficiency of the joint established between core and face sheet by the joining process that have been used in this work which mainly focused on reducing the mismatch between face sheets and honeycomb core and better flow of filler material between the joints.

3.3. Energy absorption capability of sandwich panels

The copper honeycomb core as well as the whole sandwich panels with face sheets was subjected to three-point bending test, and the stress strain curve obtained showed the elastic, stiffness

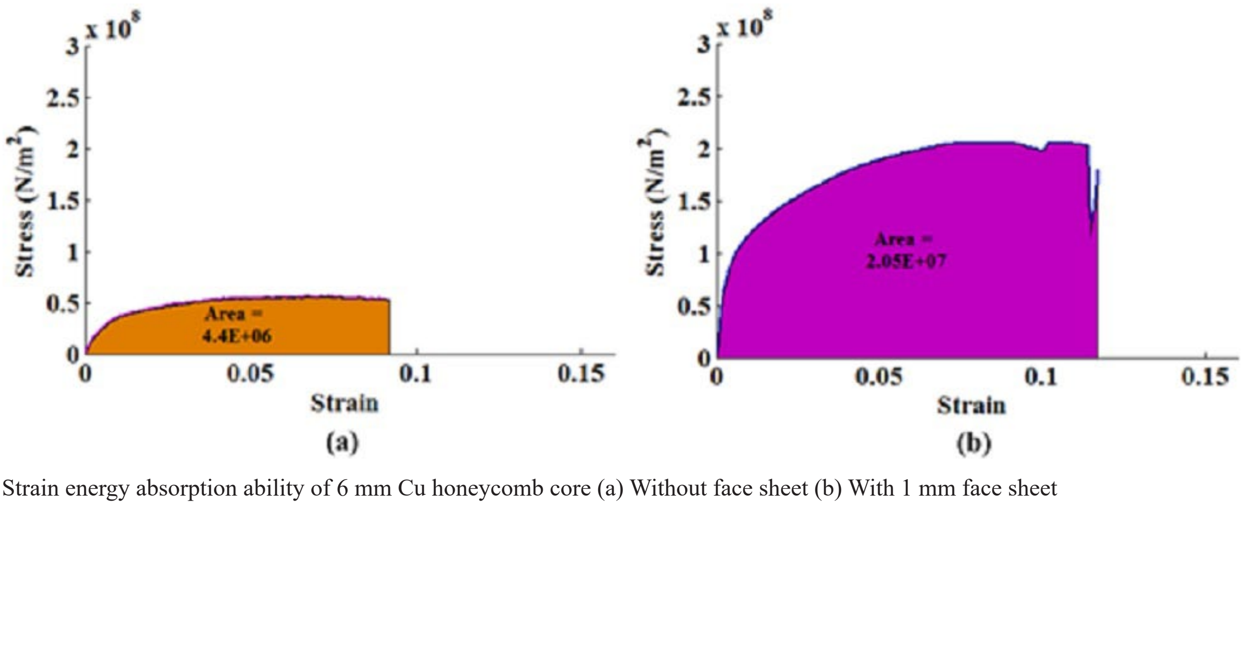

Fig. 7. Strain energy absorption ability of 6 mm Cu honeycomb core (a) Without face sheet (b) With 1 mm face sheet

and toughness properties of the structures. The strain energy absorption ability of the material was determined by integrating the area under stress-strain curve. Higher the area, higher is the strain energy absorption and it depends on the stiffness as well as the ductility of the structure. For a material to be tough, it should possess both rigidity and ductility. The stress-strain curves of 6 mm honeycomb core without face sheets and 6 mm honeycomb core with 1 mm face sheets are shown in Fig. 7(a) and 7(b). It can be observed clearly that addition of face sheet, contributed much to bending stiffness by effectively resisting the maximum compressive and tensile stresses at the top and bottom of the specimen respectively. Moreover, good bonding at the joints provided additional shear resistance and also constrains the yielding or distortion of the honey comb core and thus resulted in better flexural stiffness and strain energy absorption ability.

Fig. 8 shows the flexural loading response curve of 6 mm honeycomb core with and without face sheets in which it can be clearly seen that the load carrying capacity highly increased due to the augmentation of the face sheets and the bond efficiency. The flexural stiffness and the elastic limit found to be increased enormously. It can also be seen that there were no sudden load drops observed in the case of honeycomb core alone since the only failure occurred was core yielding. No other failures like face sheet buckling, debonding and wrinkling were reported as there are no face sheets included in the structure. But when face sheets are included, the above-mentioned failure came into picture along with core yielding and it can be identified and confirmed by the huge load drops in the response curve.

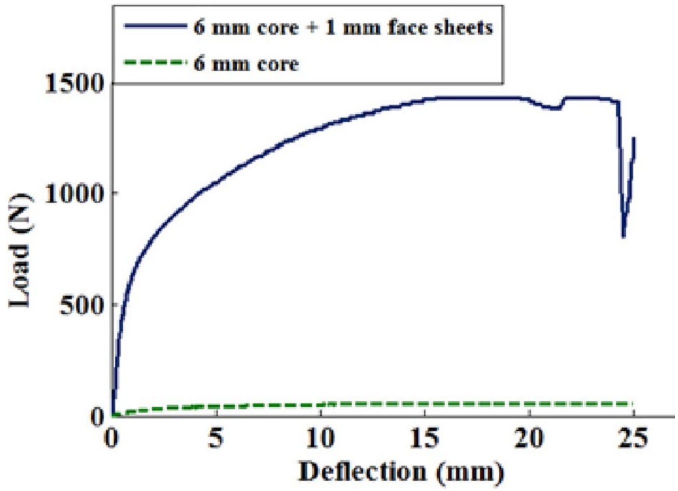

Fig. 8. Comparison of flexural loading response curve for 6 mm honeycomb core with and without face sheets

Fig. 9 shows the strain energy associated with sandwich panels having different core heights subjected to identical deflection. The area under the stress-strain curve gives the strain energy density of the structure. It is directly related to the toughness of the structure which is the amount of energy absorbed before failure [23]. From the results it was observed that the toughness depends on the thickness of sandwich panels. Higher the core height, higher was the elastic and plastic regions which increase the energy absorption ability of the sandwich panel. Sandwich panels with taller cores, exhibit core densification phenomenon

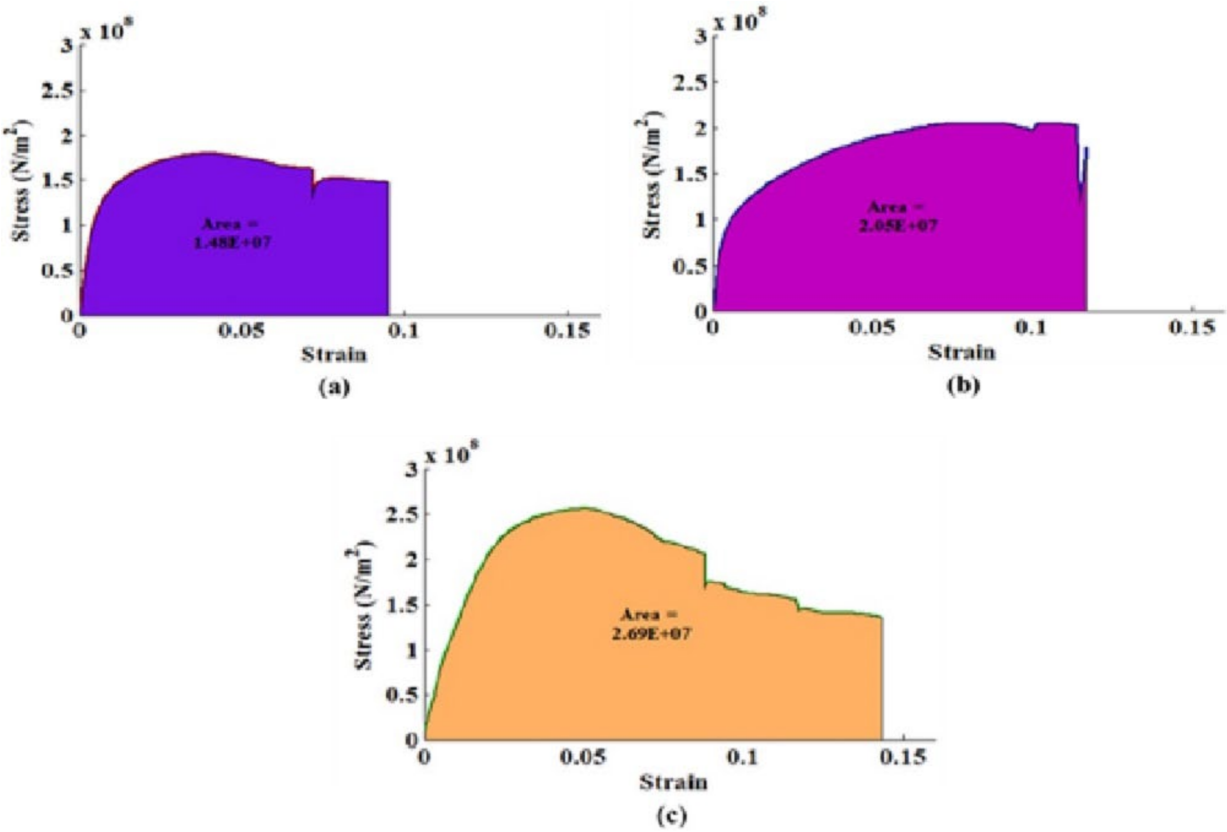

Fig. 9. Comparison of strain energy absorption ability of sandwich panels with different core height

to a higher extend which ultimately results in higher strain energy absorption ability. Due to the above-mentioned factors the sandwich with thicker core had higher toughness as determined from the area under the stress-strain curve. Toughness is an important material property which determines the ability of the material to withstand high stress and high strain without fracture. Fig. 10 shows the flexural response curve of sandwich panels with different core heights subjected to identical deflection. It is very clear that, increase in thickness (in terms of load bearing area) will have less stress intensity as shown in Fig. 10. In addition, the material buckling and core formation are also controlled with increase in thickness. On other hand there is also a chance for weak bond of metal with increase in thickness. Increase in the core thickness is associated with increase in total strain and thus involves higher extent of core crushing and face sheet yielding which results in high strain energy absorption.

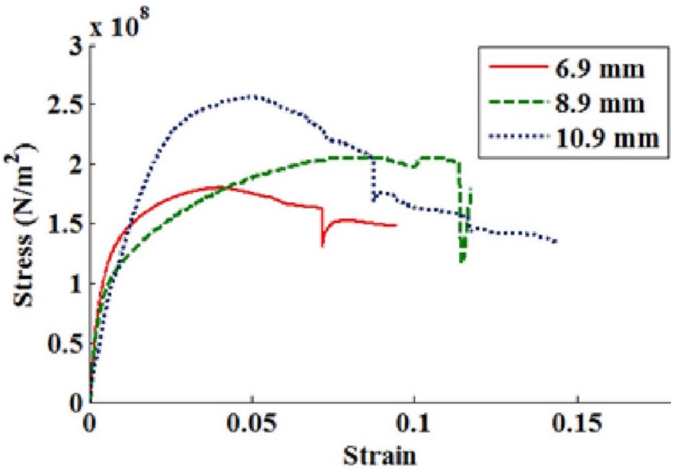

Fig. 10. Flexural response curve of sandwich panel with different core height

3.4. Relation between Flexural stiffness and thickness of sandwich panels

Fig. 11 shows the variation in flexural stiffness with thickness of copper sandwich composite panels. More or less linear variation of flexural stiffness with respect to thickness was reported. The stiffness highly depends on the height of the core even though the thickness of the face sheet was maintained constant due to the effective distribution of material mass and thereby possesses high second-moment of area and subsequent increase in bending resistance.

3.5. Density variation with core height in copper sandwich panels

Low density is inevitable for sandwich panels to be used in aerospace and automotive applications due to weight and space constraints. An increase in the height of copper sandwich core always decreased the sandwich density as shown in Fig. 12 with

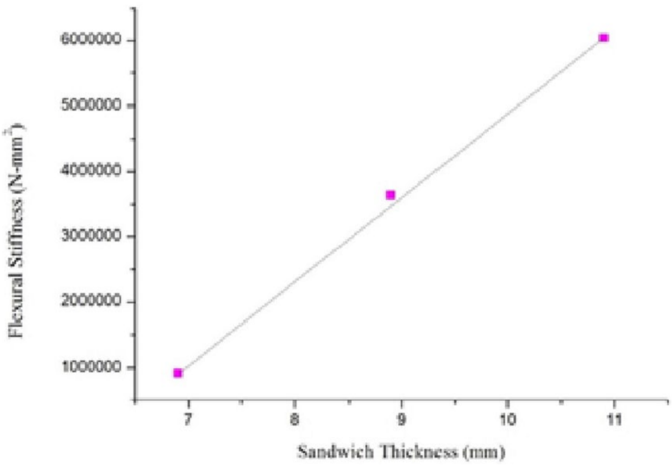

Fig. 11. Variation of Flexural stiffness with thickness of sandwich panel

10.9 mm sandwich composite panel has comparatively lower density of 2928.1033 kg/m^3. This is due to the increase in the volume of porous voids of the honeycomb cell. The increase in porous volume didn't have negative impact on the flexural stiffness since the core normally resists the shear which is generally meager compared to the bending stress induced. Moreover the high second moment of area of 10.9 mm sandwich panel provided high bending stiffness though. For 10.9 mm panel there is a decrease in density by 16.87% and an increase in flexural strength by 43% were reported.

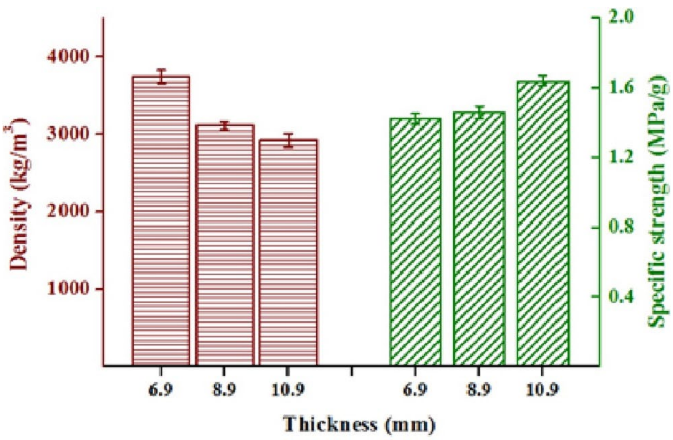

Fig. 12. Effect of sandwich thickness on density and specific flexural strength of copper honeycomb sandwich panels

3.6. Failure Mode map of copper sandwich panel

The failure mode characteristics of the sandwich panels depend on the radius of the loading pin, the relative density of the panel, material properties of the face sheet and the core [12]. The three common types of failures occur in the sandwich skin are Face yielding, Intra cell dimpling and Face wrinkling whereas the major failures that occur in the core are core indentation and core shear failure. The shear properties depend on modulus of core material and core height while flexural properties of the panel mainly depend on the modulus of the face sheet its thickness and the core height because the maximum bending stress acts on the face sheets. The stress resistance behavior depends on the sandwich panel fabrication method and yield strength of the material [25]. The following failure equations have been proposed [24] for the face sheet and core failure of the sandwich panels.

$$\frac{\rho_c}{\rho_s} = \left[\frac{\sigma_{yf}}{0.57E_f^{1/3}E_s^{2/3}}\right]^{3/2} \tag{2}$$

$$\frac{t_c}{L} = 0.25\left(\frac{\rho_c}{\rho_s}\right)^{3/2} \tag{3}$$

$$\frac{t_c}{L} = 1.411\times10^{-3}\left(\frac{\rho_c}{\rho_s}\right)^{1/6} \tag{4}$$

Where, ρ_c, ρ_s, t_c, L, σ_{yf}, E_c, E_s and σ_{yf} are density of core, density of sandwich, thickness of core, span length, yield stress in face sheet, young's modulus of face sheet and young's modulus of sandwich respectively.

The 2-D failure mode map was constructed by using dimensionless parameters such as relative density (ρ_c/ρ_s), ratio of core thickness to span length (t_c/L). The failure map is divided into three regions as shown in Fig. 13 by the failure mechanism Equations (2), (3) & (4). The failure mode map is drawn using statistical and graphic tools of MATLAB by program scripts. The respective values for the panels used in this work are mapped into the graph as in Figure 13 and with the help of this graph, the type of failure that may occur in the sandwich panels with specific dimensions and properties can be easily predicted. The Failure mode map is very much useful for sandwich composite designing purpose.

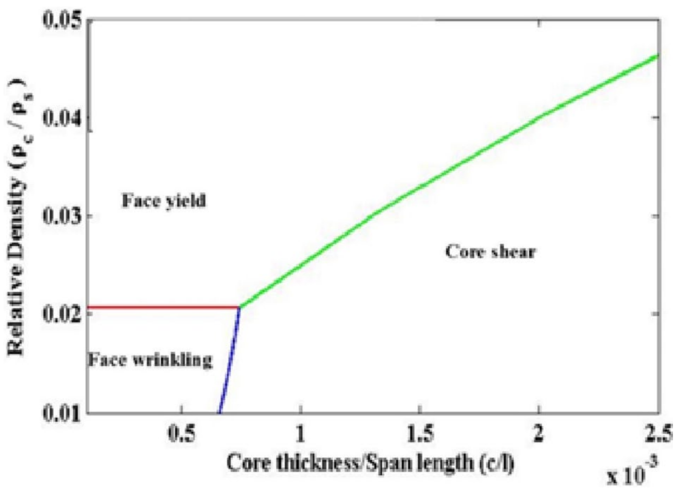

Fig. 13. Failure mode map for the copper sandwich panel

From the Fig. 14 it is shown that the failure theoretically predicted to occur on the sandwich panels is the yielding of the face sheet which is comparable with the dominant failure occurred during experimental testing. The reason for this failure was tensile stress acting on the bottom face sheet. No core failure was observed since the wall of the honeycomb core is thick enough to resist the meager shear stress developed in the panel.

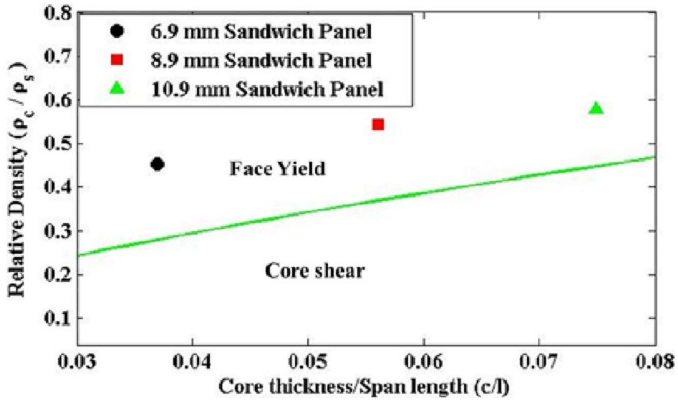

Fig. 14. Failure modes from experimental value

4. Conclusions

Copper sandwich composites were prepared by brazing technique. By using three-point tests some valuable results were obtained and failure mechanisms were observed. The honeycomb sandwich panels fabricated using this technique offered better flexural properties. The key findings and observations of this work is listed below:

- Gradual increase in the height of the honeycomb core of copper sandwich panel resulted in enormous increase in the flexural strength with 43% improvement for 10.9 mm core compared to 6.9 mm core.
- Increases in the core height of sandwich panel allow large plastic deformation before failure and thus increased the energy absorbing capacity and sandwich stiffness while decreasing the density. An increase of 81.75% in strain energy was reported for 10.9 mm thick panel compared to 6.9 mm.
- The type of failures that would occur in metallic sandwich panels with joints made using brazing technique was characterized. It was observed that the dominant failure was face sheet yielding which was also confirmed from the theoretical prediction using failure mode map.
- The failure mode map constructed with the failure mechanisms are useful for design purpose and to predict the type of failure that would occur in the sandwich structure.

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