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Mechanical and Metallurgical Properties of Aluminium and Copper Sheets Joined by Cold Pressure Welding

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Cold pressure welding is a special welding method that has been used in applications such as assembly of various parts at an increasing rate in recent years. In the present paper, cold pressure welding was applied to commercial purity aluminium and copper sheets as lap welding and a 150 metric ton hydraulic press was used for the process. As the surface roughness and the weld deformation ratia of aluminium sheets increased, tensile strength of the joints also increased. Purchased specimens with original roughness had the lowest weld deformation as-is and it was not possible to join these sheets at 30% weld deformations. Fatigue tests showed that joined sheets resisted against low fluctuating tensile stresses. Hardness increases due to local hardening at the interface as a result of cold deformation. Also EDX (Energy Dispersive X-ray) measurements clearly show that Al-Cu joints contain an intermetallic compound layer at the interface which does not affect the joint strength to a great extent. Results showed that the cold pressure welding technique in lap form resulted in strong Al-Al joints and the intermetallic layer formed in Al-Cu joints did not affect the joint strength to a great extent.

Keywords: cold pressure welding, metallography, mechanical properties, surface roughness, deformation ratio

0 INTRODUCTION

Cold pressure welding can be applied by bringing surfaces of virgin metal specimens into close contact. Cold pressure welding takes place due to the breakdown of the surface layers caused by bulk plastic deformation. It is a solid phase welding process that can be performed on a large number of possible metal combinations.

Cold pressure welding has particularly been applied within the last fifty years, due to the fact that the process can be carried out easily at room temperature without using complex and expensive equipment. Cold pressure welding also has the advantage of being applicable to metal pairs that cannot be joined with either melt welding methods or to those metal pairs that pose utmost difficulty with respect to melt welding.

Cold pressure welding is used to join aluminium cables, various types of kitchen furniture, electrolysis cells, and communication lines. It is also used to join wires and rods and in production of heat exchangers as coolers.

The important variables of the method are; surface preparation before processing, deformation, properties of the welding material or material pairs and pressure. Thus, one of the most important aspects of cold pressure welding is the properties of the surface before welding. The most commonly used method for surface preparation is cleaning the metal surfaces with a solving agent and brushing them with a wire brush. Wire brushing results in the formation of a hard brittle layer that prevents the metal from getting dirty (from grease, contaminant and oxide). It has been found that bonding occurs as a result of the cracking of this layer with the corresponding contact of metals [1]. Heating or chemical cleaning methods may also be applied. Deformation is the most important process variable. There is a minimum deformation – surface spread out or a reduction value for each material during cold pressure welding.

Mohamed et al. [2] investigated the mechanism of pressure welding in aluminium, copper, silver and gold. Bay [3] examined the bonding mechanism of cold pressure welding and mechanisms producing metallic bonds in cold welding [4]. Tabata et al. [5] investigated cold pressure welding of aluminium and copper by

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butt upsetting. Bond criterion in cold pressure welding of aluminium was examined [6]. Unal et al. [7] investigated the effects of process parameters on the welding strength in the cold pressure welding of aluminium. Altan et al. [8] obtained the surface roughness depending on welding strength in the cold pressure welding of aluminium. Li et al. [9] examined interfacial energy and the match of cold pressure welded Ag/Ni and Al/Cu. Li et al. [10] investigated the interfacial bonding state on different metals Ag, Ni in cold pressure welding. Krishna et al. [11] directed process parameter optimization to obtain high weld strength in the cold solid state in joining sintered steel and copper powder. Sahin et al. joined plastically deformed steels by friction welding [12]. Tylecote informed about pressure welding practice [13]. Sahin et al. investigated the application of cold pressure welding to aluminium and copper sheets [14]. Iordachescu et al. obtained the FEM Model of Butt Cold Welding [15]. Kim et al. described fabrication of organic light-emitting devices by low-pressure cold welding [16]. Okumura et al. developed the composite materials fabricated from multi-layered 5052 aluminium alloy foils and titanium foils by cold pressure welding [17]. A titanium-flake reinforced aluminium-matrix composite was prepared from multilayered foils by cold pressure welding [18]. Kim et al. investigated micro patterning of organic electronic devices by cold-welding [19]. Dariel et al. Studied acid-assisted consolidation of powder compacts [20]. Zhang et al. made a fractographic investigation of weld formation for cold welding [21]. Kuzin studied optimization of technological parameters for cold pressure welding of thin sheets of AD1M aluminium [22].

In the present paper, aluminium and copper sheets were joined by cold pressure welding, namely, lap welding. A 150 metric ton hydraulic press was used for the welding process. Before welding, a wire-brushing process was applied in order to prepare the aluminium and copper sheets, their roughness was determined using a surface roughness equipment and they were joined at different deformation ratia. The effects of deformation ratia and surface roughness on tensile strength of welded joints were investigated. Tensile tests and fatigue tests were carried out, hardness variations and micro-structures of the joints were examined. The joints were examined using EDX (Energy Dispersive X-ray) analysis in order to have an insight into the phases occurring during welding at the interface. Soundness of the joints was also investigated using non-destructive techniques radiographic inspection technique so as to evaluate the occurrence of defects.

1 COLD PRESSURE WELDING

1.1. Process Characteristics

Extent of deformation is one of the most important factors in cold pressure welding. Supposing that the basic parameter in cold pressure welding is the degree of deformation normally expressed as the reduction R or the surface expansion X of the bonding surface, plastic deformation of the metal pair is necessary in order to obtain a bonding.

In butt-welding, the experimentally measured extension (deformation) R is given by

$$R = \frac{A - A_0}{A_0} \tag{1}$$

where A_0 is the original cross – sectional area and A is the extended area after processing. True fractional metallic area revealed at a certain extension R is then:

$$\frac{\Delta A}{A} = \frac{R}{R+1} \tag{2}$$

This Equation, which is valid for butt cold pressure welding, is given by

$$R = \frac{h - h_0}{h_0} \tag{3}$$

for lap welding where h_0 is the original thickness of the sheet and h is the instantaneous thickness at deformation ratio R [2] and [3].

On the other hand, Equation 2 is also valid for lap welding. A specific threshold surface extension or reduction (minimum welding deformation) is required for bond establishment at the atomic level. This deformation depends on metal–metal pairs, joining shape and thickness and surface preparation. It should also be noted that welding strength increases as deformation increases. However, too many plastic deformations also cause a decrease in weld strength. Surface preparation before welding influences weld strength to a great extent. The most widely used surface pre-preparation technique is removing the grease and brushing with a wire brush. Nickel coating of metal surfaces before processing is known to produce effective results. Also, application of normal pressure on the welding surface affects weld strength in a positive manner [2], [3], [7] and [8].

1.2. Bond Formation Mechanism

Microstructural examination of SEM microphotographs was used to develop an understanding of the mechanisms underlying bond formation on the wire brushed surfaces. Wire brushing during mechanical surface preparation forms a hard and brittle surface film at metal surface which is referred to as the cover layer. Observations have shown that bond formation is carried out by means of the stages given in Fig. 1.

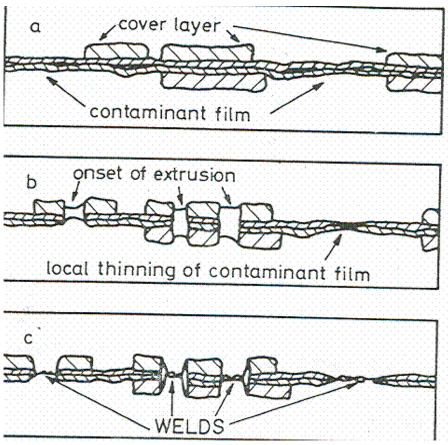


Fig. 1. *The bond formation mechanism in cold pressure welding [4]*

First the cover layer is fractured of by the effect of pressure (Fig. 1.a). Further increase in surface extension caused extrusion of metallic material through the crack in the cover layer (Fig.1.b). Finally, increase in deformation leads to real contact between metals resulting in the formation of a real bond (Fig. 1.c).

2 EXPERIMENTAL PROCEDURE

Aluminium and copper sheets (2.75 mm thickness) were joined using lap form of cold pressure welding. The properties of aluminium and copper materials used in the present study are given in Tables 1 and 2, respectively.

Table 1. *The chemical composition and the tensile strength of Aluminium material used in the experiments*

Chemical Composition	% 1.34 Fe, % 0.489 Si, % 0.439 Mg, % 0.913 Zn, % 0.107 Mn, % 0.0249 Cr, % 0.0135 Ti, % 0.005 Sn, % 0.0536 Pb, % 0.0179 Ni, % 0.003 Sb, % 1.12 Cu, % 95.47 Al
Tensile Strength	170 MPa
Surface Roughness	Arithmetical Average (Ra) = 0.30 μm

Table 2. *The chemical composition and the tensile strength of Copper material used in the experiments*

Chemical Composition	% 0.02920 Fe, % 0.00100 Si, % 0.00050 Mg, % 0.00100 Zn, % 0.00050 Mn, % 0.00100 S, % 0.00050 Bi, % 0.00108 Sn, % 0.00287 Pb, % 0.00596 Ni, % 0.00200 Sb, % 0.00230 P, % 0.00050 Al, % 99.95 Cu
Tensile Strength	360 MPa
Surface Roughness	Arithmetical Average (Ra) = 0.30 μm

The aluminium and copper sheets were 10x150 mm specimens and lap welding was applied in a single direction punch as shown in Fig. 2. Pressure needed for the process was applied using the 150 metric ton capacity press system (Figs. 2 and 3).

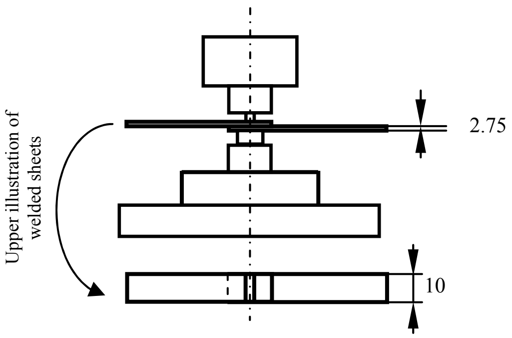


Fig. 2. *Schematic illustration of cold pressure welding*

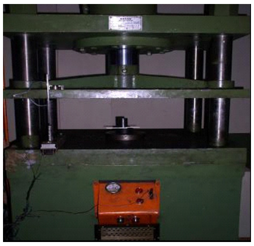


Fig. 3. *The hydraulic press*

All parts used in the experiments were cleaned using acetone oil and then they were brushed using a wire brush. A 60 mm diameter rotating steel wire-brush was used. Test surfaces were brushed at 510 r.p.m. wire brush rotational speed. The arithmetical average of surface roughness of the sheets prepared was used to determine the effect of surface roughness on weld strength. PRAZIS – RUG-03 surface roughness equipment was used to measure the surface roughness (Fig. 4). Arithmetic average surface roughness was found as Ra = 1, 3, 5 µm.

Fig. 4. *The equipment for surface roughness measurement*

Surfaces prepared were subjected to cold pressure welding shortly after the preparation. The application of welding for 10 minutes affected the weld strength greatly. Increasing the welding time to over 10 minutes caused the weld strength to diminish to a great extent. Extent of deformation was measured by determining reduction (R) over the total thickness of welded parts.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Preparation of the Metal Sheets

Effect of deformation ratio and surface roughness on cold pressure welding of commercial purity aluminium and copper was investigated using deformation ratios of 30%, 45%, 50%, 60% (3.85 mm, 3 mm, 2.75 mm, 2.2 mm, respectively) and an arithmetic average surface roughness Ra = 1, 3, 5 µm. Surface roughness was provided by a revolving brush, and the sheets were wiped with acetone after brushing.

3.2. Tensile Test Results

Cold pressure welding in lap form was applied to wire brushed metal sheets at different deformation ratios. Tensile tests using an INSTRON 8501 dynamic testing machine were applied on the cold pressure welded sheets to determine their weld strengths. Acceptable weld strength was obtained at a surface roughness of Ra = 5 µm and 60% deformation ratio. It was not possible to join the purchased specimens having original surface roughness as-it-is at 30% weld deformation, the lowest extent of deformation used in the present study. Figure 5 shows the variation of weld strength with deformation for different surface roughness values, while Figure 6 shows the variation of weld strength with surface roughness at different extents of deformations.

Acceptable weld strength in the aluminium joints was obtained at 60% deformation ratio and 5 µm surface roughness (Figures 5 and 6). Therefore further experiments to join copper sheets together and to join aluminium sheets to the copper sheets were performed only at 60% deformation ratio and a surface roughness of 5 µm (Figs. 5 and 6).

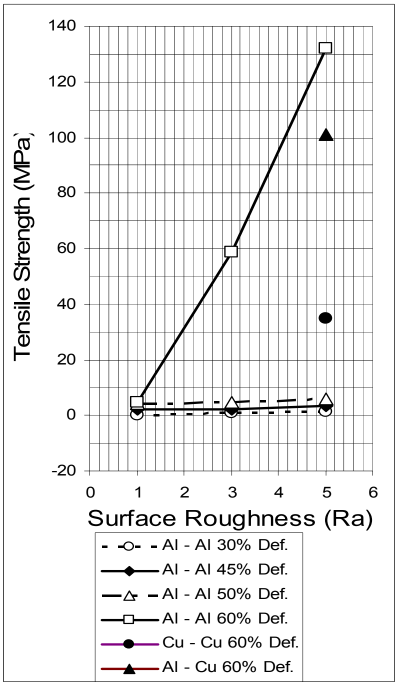


Fig. 5. *Relationship between tensile strength and surface roughness at different weld deformations*

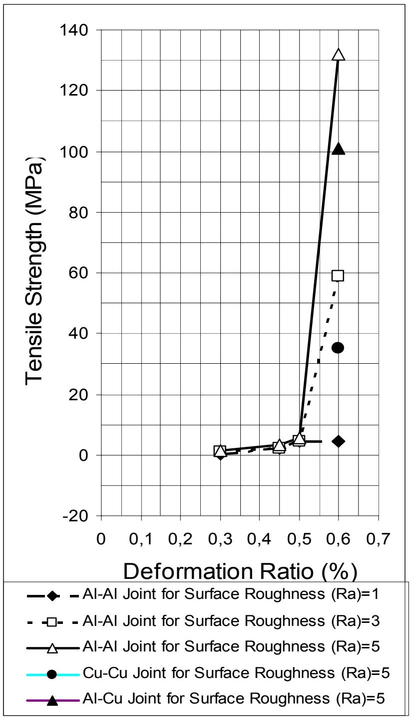


Fig. 6. *Relationship between tensile strength and weld deformation at different surface roughness*

The length of bond zones were found to increase with increasing deformation which further leads weld strength to increase. Weld strength also increases with surface roughness (Figs. 5 and 6).

3.3. Fatigue Test

Fatigue tests of cold-welded aluminium joints were conducted using an INSTRON 8501 hydraulic fatigue machine (Fig. 7). Tests were done at a frequency of 10 Hz Fatigue tests were applied to specimens that had the highest strength, namely to samples having a surface roughness of Ra = 5 µm and joined at 60% weld deformation. Dimensions of the specimens were set according to ASTM E-466 (Fig. 8).

Fig. 7. *INSTRON 8501 hydraulic fatigue machine*

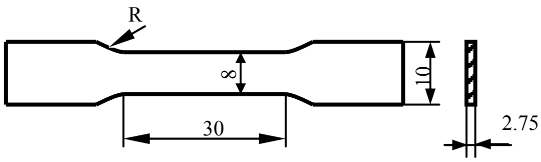


Fig. 8. *Dimensions of the specimens used in fatigue tests*

Welding interfaces were located in midsection of the fatigue specimen. Fatigue tests were conducted superimposing fluctuating tensile loads on a constant tensile load that can produce 40 MPa of tensile stress. When stress value in fatigue tests was increased, sheets joined were ruptured at the interface of the parts.

Fluctuating tensile stress amplitudes were varied between 10 MPa and 20 MPa and numbers of cycles to fracture were recorded. Sheets joined were capable of resisting fluctuating tensile stress (Fig. 9). Observations during fatigue tests showed that ruptures parts are usually detached from the welding interface. Joined sheets could not supply higher strength due to the defects (micro-cracks, inclusions or not fully bonded surfaces etc.) at the interface of the joints.

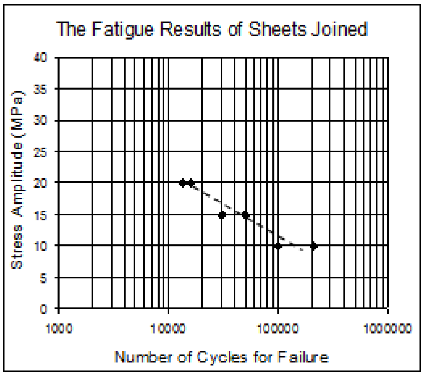


Fig. 9. *The fatigue test results,* σ_{mean} *= 20 MPa*

3.4. Results of Microstructural Examinations

Optical microscopy was used to study the microstructure of the welded interface both for aluminium joints and aluminium to copper joints that have an average surface roughness of Ra = 5 µm and welded at a 60% deformation ratio after etched in picral (Figures 10 to 13).

The vertical scratches owing to brushing are clearly visible on the fragments of the cover layer (Figs. 11 to 13). Scratch-brushing was carried out in longitudinal direction parallel to the direction of deformation. Extended areas of bonding regions and un-bonded regions of the cover layer are confined to isolated regions. Therefore, the bond fracture is ductile and occurs after numerous local necking [3].

3.5. EDX Analysis of Joints

Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis were performed to have an insight into the phases

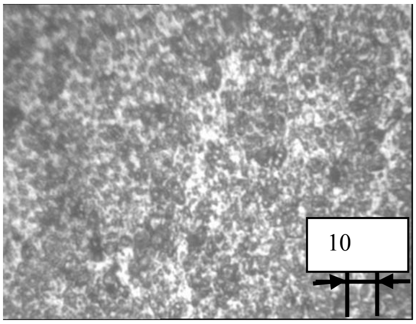


Fig. 10. *Microstructure of aluminium parts*

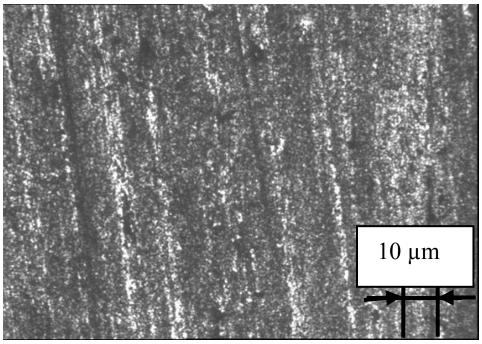


Fig. 11. *Microstructure at interface of joined aluminium parts having Ra = 5µm and 60% deformation*

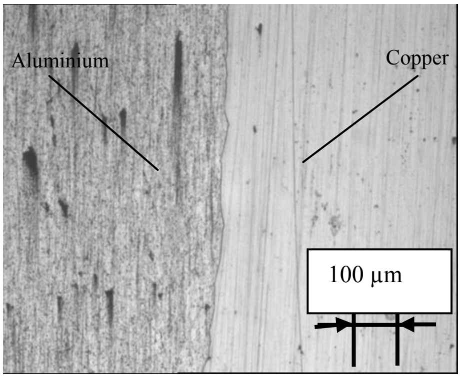


Fig. 12. *Microstructure at interface of welded aluminium to copper parts having Ra = 5µm and 60% deformation*

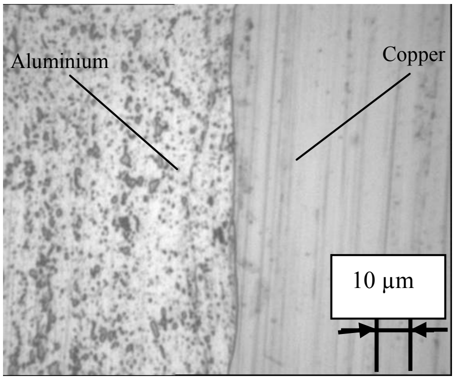


Fig. 13. *Microstructure at interface of welded aluminium to copper parts having Ra = 5µm and 60% deformation*

was utilized by means of software that allows piloting the beam and scanning along a surface or a line to obtain X-ray cartography or concentration profiles by elements, respectively.

Fig. 14 (a) shows EDX analysis points defined on the SEM microstructure at the interface region of the cold pressure welded Al-Al joints. Figure 14 (b) and (c) illustrate the EDX analysis results taken from point 3 of the SEM analysis results taken from point 3 of the SEM micrograph of the Al-Al joint and the respective EDS point analysis.

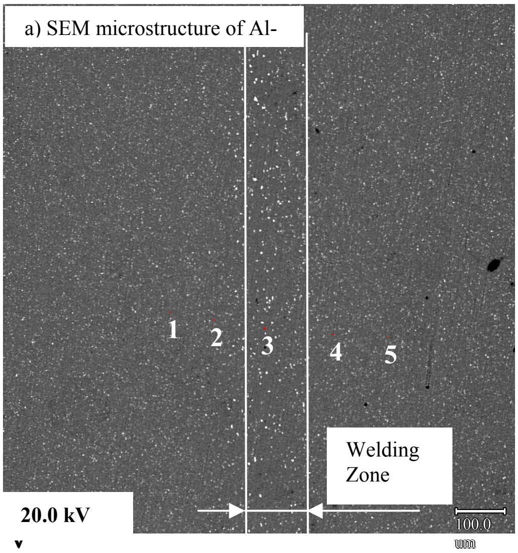


Fig. 14. a) *SEM microstructure of Al-Al joint*

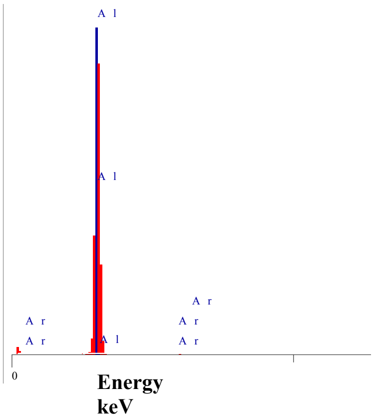


Fig. 14. b) *EDX analysis result taken from point 3 represented to SEM image*

Points	Elements	Line	Intensity (c/s)	Conclusion
1	Al Ar	Kα Kα	1852.48 28.12	96.940 wt. % 3.060 wt. % (100.000 wt. % Total)
2	Al Ar	Kα Kα	1537.79 17.99	97.614 wt. % 2.386 wt. % (100.000 wt. % Total)
3	Al Ar	Kα Kα	1404.12 14.93	97.824 wt. % 2.176 wt. % (100.000 wt. % Total)
4	Al Ar	Kα Kα	1378.65 19.41	97.151 wt. % 2.848 wt. % (100.000 wt. % Total)
5	Al	Kα	1495.16	100.000 wt. % (100.000 wt. % Total)

Fig. 14. c) *EDS point analysis results according to SEM microstructure*

Figure 15 (a) shows EDX analysis of the points defined on the SEM microstructure at the interface region of the cold pressure welded Al-Cu joints. Figures 15 (b), (c) and (d) illustrate the EDX analysis results of point 1 on the Al side, the point 3 on the Cu side of the SEM micrographs. The EDS results confirm that an intermetallic compound layer does not exist in Al-Al, whereas Al-Cu joints have an intermetallic compound such as Cu_3Al, Cu_4Al_3, CuAl and $CuAl_2$ which does not affect joint strength to a great extent [23] to [25]. This is well enough evidence that strong joints can be produced by cold pressure welding method.

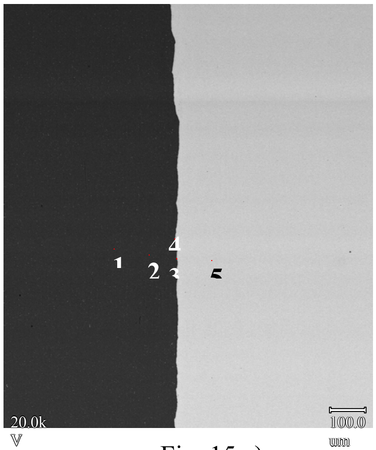
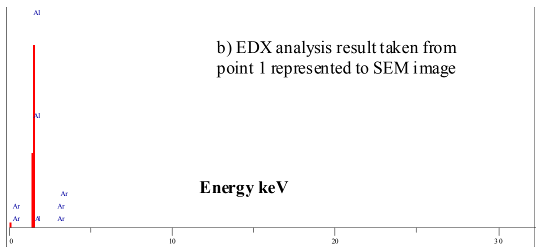
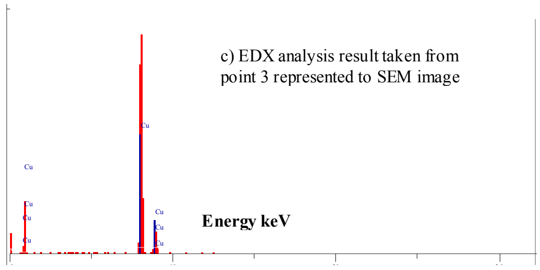


Fig. 15.a)





Points	Elements	Line	Intensity (c/s)	Conclusion
1	Al Ar	Kα Kα	1357.82 12.08	98.170 wt.% 1.830 wt.% (100.000 wt. % Total)
2	Al Ar	Kα Kα	1659.40 20.20	97.522 wt.% 2.478 wt.% (100.000 wt. % Total)
3	Cu	Kα	1134.00	100.000 wt. % (100.000 wt. % Total)
4	Cu	Kα	1188.01	100.000 wt. % (100.000 wt. % Total)
5	Cu	Kα	1205.98	100.000 wt. % (100.000 wt. % Total)

Fig. 15. *SEM microstructure of the cold pressure welded interface region between Al-Cu joints having Ra = 5µm and 60% deformation ratio and EDS analysis results*

3.6. Results of Hardness Examination

Hardness variations at the interface of joined parts were obtained by micro hardness tests under a load of 200 g. Measuring locations are given in Fig. 16. Hardness variations in vertical direction with respect to the weld-centre are shown in Fig. 17.

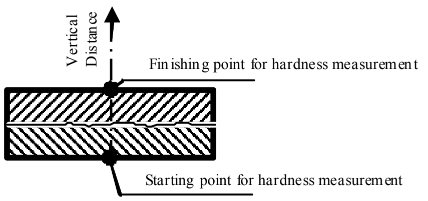


Fig. 16. *Hardness test orientations at cross-section of joined parts*

Hardness values are about the same at the interfaces of the parts having different surface oughness values and deformed at 60%. Hardness of aluminium material purchased is about 53 HV. Hardness of the joined parts is higher due to local hardening which is a result of cold deformation. The effect of the surface roughness on hardness variations is much less than that of the deformation ratio (Fig. 17). A similar result as to the increase in hardness due to local hardening is observed for the Al-Cu joint. Then, ductility is a mechanical property used to describe the extent to which materials can be deformed plastically without fracture. Aluminium is more ductile material than copper. It means that Al can be easily deformed according to Cu. Al sheet is plastically deformed in a greater extend than Cu when overall deformation ratio 60%. As a result, the hardness of a ductile material as aluminium is lower than that of less ductile material as copper [5] and [6].

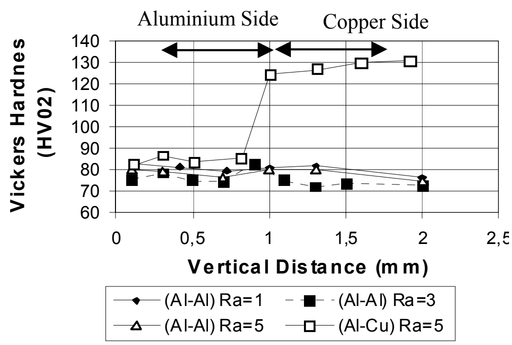


Fig. 17. *Hardness variations along the vertical direction*

3.7. Non-Destructive Evaluation by Radiographic Inspection

Inspection (NDI) is the examination of an object or material with technology that does not affect its future use. NDI can be used without destroying or damaging a product or material. Because it allows inspection without interfering with a product's final use, NDI provides an excellent balance between quality control and cost-effectiveness. NDI can and should be used in any phase of a product's design and manufacturing process, including materials selection, research and development, assembly, quality control and maintenance. Commonly used non-destructive inspection methods include liquid penetrant, magnetic particle, eddy current and radiographic inspection, ultrasonic inspection, tomography, and real-time radiography. Radiographic testing is one of the oldest methods of non-destructive testing and has been in use for approximately five decades. Radiography using X-rays is one of the NDT techniques used for imaging the joints to detect and locate defects. In the present study, Aluminium joints were evaluated by radiographic inspection using RIGAKU 200 kV test equipment. Figure 18 is an example of the radiographic patterns for an aluminium joint produced from sheets having a surface roughness of Ra = 5μm and welded at 60% deformation. As seen from the inspection figure, almost there are no defects in the joints. But, there can be very small weld defects (micro-cracks, inclusions or not fully bonded surfaces etc.) because the joined sheets do not resist against high static and dynamic loads.

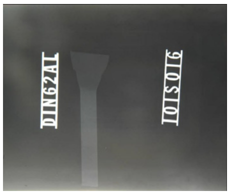


Fig. 18. *An example from radiographic patterns used in this work*

3.8. Statistical Analysis of Data

The basis of this approach is the assumption of a simplified linear model for the optimization parameter η given by $\eta = \beta_0+\beta_1 x_1+\beta_2 x_2+\ldots$, where x_1, x_2... are the factors which η depends on and β_0, β_1, β_2..., etc, represent the 'true' values of the corresponding unknowns. From the results of an experiment comprising a finite number of trials, one can arrive at sample estimates of the coefficients, β, which are then usually fitted into a linear regression equation of the type $y=b_0+b_1x_1+b_2x_2+\ldots$, where y is the response function and the b_s are the "estimated" values of the β_s. In simple terms, each coefficient represents the influence of the corresponding factor on the quality of the tensile strength expressed by the optimization parameter [12] and [13]. Parameter optimization was carried out using factorial design of experiments. In the present study; aluminium specimens obtained by machining was chosen as an example model. Deformation ratio and pre-upsetting surface roughness were chosen as the two factors. Then, the tensile strength data were subjected to statistical analysis to understand the influence of individual effects of the factors. The other parameters were kept constant. Regression equation was obtained from this analysis. Correlation coefficient was also obtained from the statistical analysis. Experimental results are given in Table 3.

Table 3. *Experimental results*

Trial No	Surface Roughness of Parts (Ra-μm) x_1	Deformation Ratio (%) x_2	Tensile Strength of Joined Parts (MPa) y
1	1	0.30	0.192
2	1	0.45	2.021
3	1	0.50	4.362
4	1	0.60	4.590
5	3	0.30	0.974
6	3	0.45	2.267
7	3	0.50	4.650
8	3	0.60	58.700
9	5	0.30	1.527
10	5	0.45	3.410
11	5	0.50	5.810
12	5	0.60	132.100

Optimum estimates of regression coefficients were obtained using the Fisher method ratio. The resulting equation is also given here:

$$y = -94{,}739 + 8{,}230 \cdot x_1 + 191{,}204 \cdot x_2 \qquad (4)$$

The correlation coefficient using Eq. (4) is about 0.70 in respect of tensile strength. Therefore, it is quantitatively shown that the effects of deformation ratia and surface roughness on the tensile strength are very significant, as expected.

4 CONCLUSIONS

- Cold pressure welding of the commercial purity aluminium and copper in lap form was successfully applied to Al-Al and Al-Cu joints.
- As the surface roughness and the weld

deformation ratia of aluminium sheets increased, tensile strength of the joints also increased.
- Purchased specimens with original roughness had the lowest weld deformation as-it-is and it was not possible to join these sheets at 30% weld deformations. However, it was possible to join these specimens at deformation ratios greater than 70 %.
- Micrographs of specimens having a surface roughness of 5 μm and deformed at 60% deformation ratio clearly reveal bond formation at the interface of joined parts.
- Hardness values of joints are about the same at interfaces of sheets having different surface roughness and produced at equal deformation. Hardness results in Al-Cu joints are similar to those of aluminium joints. Hardness increases due to local hardening at the interface as a result of cold deformation.
- Fatigue tests showed that joined sheets resisted against low fluctuating tensile stresses.
- EDX measurements clearly show that Al-Cu joints contain an intermetallic compound layer at the interface which does not affect the joint strength to a great extent.
- Even if radiographic testing showed no defects at the welded joint, there could be very small weld defects since the joined sheets do not resist against high static and dynamic loads.
- Tensile strength of joined parts can be expressed in terms of the process parameters by regression equation obtained by statistical analysis.

5 NOMENCLATURE

X Surface expansion of bonding surface (%)
R Reduction (%)- Deformation Ratio
A_0 Original cross-sectional area (mm)
A Extended area after process (mm)
h_0 Original thickness of sheet (mm)
h Instantaneous thickness at deformation (mm)
R_a Surface roughness (μm)

6 ACKNOWLEDGEMENTS

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