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SIMULTANEOUS PLASTIC DEFORMATION AND JOINING OF DISSIMILAR SINTERED P/M PREFORMS BY COLD EXTRUSION

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ABSTRACT

The present paper briefly describes the results obtained during investigation on a method to produce sound bimetallic tubes and transition joints between dissimilar metals by controlling the initial materials characteristics through powder metallurgy (P/M) and cold extrusion route. Simultaneous compression tests were carried out to obtain preliminary understanding on the simultaneous deformation of dissimilar sintered P/M preforms and also to generate plastic flow properties. These observations and data were used to optimize the process parameters for sound transition joining of dissimilar sintered P/M preform tubes and for co-extrusion of bimetallic tubes (steel-Cu and Cu-Al). Optimal post-joining heat treatment cycle was identified to enhance the weld strength of transition joints and bimetallic tubes. Significant information regarding the simultaneous deformation characteristics of dissimilar P/M preforms was inferred during compression and extrusion studies. Cold extrusion studies evinced the manufacturing flexibility and economy of current processing route.

***Keywords**:* powder metallurgy, bimetal, solid state joining, dissimilar metal joining, extrusion, simultaneous plastic deformation

1.INTRODUCTION

Products made of dissimilar materials are becoming increasingly important in industrial applications due to their numerous advantages. These include not only the technical advantages, such as desired product properties, but also the benefits in terms of production economics. Fabrication of dissimilar material combinations is, however, a difficult task due to the great differences in physical and chemical properties. Although the number of desired combinations for practical use is virtually unlimited, the number of bimetallic/dissimilar metal combinations actually in use is limited, mainly due to manufacturing difficulties. The production of bimetals/dissimilar metal joints through extrusion offers the most favourable conditions such as compressive deformation, large change of shape in one operation and the possibility of governing the deformation zone. In order to produce defect-free product (transition joints or bimetals) by extrusion, there must be homogeneous deformation of both the core and matrix/sleeve, i.e. both metals must simultaneously undergo the identical reduction. However, various microstructures and properties of simultaneously deformed metals make homogeneous flow quite non-viable. It is also known that the formation of defects in co-extrusion is caused by improper selection of process variables [1]. Several analytical and experimental investigations have been carried out on the fabrication of *wrought bimetal rod and wire by extrusion* [1-8]. These studies have shown that successful bimetal extrusion is sensitive to the combination of several process parameters. The review of literature on wrought bimetal extrusion revealed some limitations in the earlier investigations/technique and they are:

i) Very narrow processing zone to produce sound product and little flexibility in terms of tool / process parameter selection.

ii) The suggested low die included angle ($2\alpha \leq 30°$) for sound flow was different from the most commonly used dies in the industry (2α=90°).
iii) The analytical studies started with an assumption that the composite rods/tubes were bonded before extrusion, which is not true in actual extrusion.
iv) The number of stages required to produce the bimetal would be high if conventional extrusion was used. Although the use of hydrostatic extrusion extends the achievable extrusion strain, the equipment for high pressure could be quite expensive, and its maintenance could also complex and troublesome.
v) Very limited reports were available on bimetallic tube extrusion.
vi) No reference to the strength or any other property of the bimetal was found.

These limitations may cause some practical implications in the selection of suitable material combinations. The primary focus of current project will be an exploration to improve and optimize the process of solid state transition joining of dissimilar metal tubes and production of bimetallic tubes using sintered P/M preforms as initial materials. The expected merits of current strategy i.e. tailoring the initial materials characteristics through P/M route, are:

i) The consolidation of P/M preforms during deformation reduces the differential velocity (between core and sleeve) and thus should expected to aid sound flow during extrusion.
ii) High friction coefficients associated with P/M deformation are expected to enhance sound flow and widen the safe processing zone.
iii) Tailorable flow stress and strain hardening values should facilitate homogeneous deformation.
iv) Sound flow over a wide range of processing conditions will envisage greater manufacturing flexibility.
v) The tooling design for P/M extrusion is identical to the design most commonly used in industries. This aspect can be seen to reduce the tool / amortization cost.

The main objectives of the present investigation are to achieve (i) sound transition joining between dissimilar metal tubes (steel-Cu and Cu-Al) using sintered P/M preforms as initial materials through conventional cold extrusion (ii) sound bimetallic tubes by co-extrusion of dissimilar sintered P/M preforms. With these objectives, the present work is divided into four major parts: (1) preliminary study to understand the mechanism of simultaneous deformation of dissimilar sintered P/M preforms and to generate plastic flow properties during simultaneous plastic deformation; (2) optimization of process parameters for sound transition joining of dissimilar sintered P/M preform tubes and for co-extrusion of bimetallic tubes (steel-Cu and Cu-Al); (3) selection of post-joining heat treatment conditions for transition joints and bimetallic tubes to enhance the weld strength; and (4) evaluation of nano particles interlayer to supplement the quality of these dissimilar metal joints.

2.EXPERIMENTAL

Complete experimental details related to part 1 through part 4 are provided in [9-17, 19]. However, a brief description of the experiments conducted is presented here in this section. In the first part of work simple compression tests were carried out, using special laboratory test setups (a. pure upsetting, b. upsetting and free extrusion), to evaluate the ability of dissimilar sintered P/M preforms to undergo simultaneous deformation [9]. The influence of density ratio, volume ratio, type of deformation/stress-state and total strain on the strain experienced by the individual metals is studied to establish the conditions for sound flow during simultaneous deformation. Standard compression and ring-compression tests have been carried out to generate the plastic properties and interfacial friction coefficient during simultaneous deformation of sintered steel and copper P/M preforms. Finally an empirical relationship to estimate the flow stress to simultaneously deform dissimilar metal combination is established [10]. These data were fitted into appropriate equations for the estimation of force during extrusion.

It is shown in wrought bimetal extrusion that, the successful bimetal extrusion is very sensitive to process parameters. A small variation in the process parameters will drastically reduce the domain under which sound flow is ensured. The second part of current work concerns with the optimization of process parameters to produce a sound transition joint between steel-Cu and Cu-Al sintered P/M preforms by conventional cold extrusion. Process parameters such as density ratio, volume ratio, interfacial angle and strain, were optimized in terms of failure propensity, weld strength, extrusion force, etc., based on microstructural, microhardness and fractography studies [11,17]. Similarly, the influence of density ratio, physical volume ratio and extrusion strain on sound co-extrusion of steel-Cu and Cu-Al sintered P/M preform bimetallic tubes was intended to study in this part [11,17]. Difference in the strain experienced by two metals is evaluated to substantiate the sound flow during co-extrusion of dissimilar sintered P/M preforms.

In general, the surface expansion or stretching in P/M deformation would be relatively low compared to their wrought equivalents due to densification during deformation, which consumes part of the energy expended during deformation and reduces the efficacy of the deformation in causing surface expansion. The low stretching at the interface of the two metals may lead to lower weld strength, which is a decisive parameter to achieve high weld strength. Therefore, the use of a post-joining heat treatment may be beneficial in enhancing the weld strength of P/M preform joints. The post-joining heat treatment offers a possibility for improving the weld strength by causing inter diffusion and resultant metallurgical unification of metal pairs. But can also result in certain adverse effects like micro-cracks, micro-voids and intermetallic compound formation. Thus it becomes essential to characterize the joint interfaces in terms of intermetallics formation, inter-diffusion and diffusion induced porosity. The optimum heat treatment should improve the weld strength without causing these adversities. In the present project, the transition joints and bimetallic tubes were evaluated for their weld strength and interfacial microstructure through post-joining heat treatment at different conditions (temperature, time, Ni powder interlayer and Ni powder size) [12-14]. It is intended to enhance the weld strength and also to study the evolution of interdiffusion microstructures.

There would be a considerable advantage if the same physical, chemical and mechanical properties were maintained in the diffusion zone as in the base materials to be joined. This could possibly be achieved if the diffusion zone and other undesirable phases are avoided or reduced to the maximum possible extent. The use of nano particles as an interlayer may possibly preserve the properties of the base materials to be joined due to their enhanced diffusion. In the last part of the current project, dissimilar joints and bimetallic tubes were made with nano Ni particles as interlayer and then heat treated [19] to evaluate the strength and microstructural uniformity across the interface. Besides, a final attempt in enhancing the interface strength also has been made by increasing the extrusion strain (keeping all other parameters constant) and then heat treating with nano Ni particle interlayer.

3.RESULTS AND DISCUSSION

3.1 SIMULTANEOUS DEFORMATION BY SIMPLE COMPRESSION

The ability of dissimilar P/M preforms to undergo simultaneous deformation has been studied by using special laboratory tests [9]. The influence of density ratio, volume ratio, type of deformation and total strain on the strain experienced by individual metals was studied, to establish the conditions of sound flow during simultaneous deformation. The results indicated that, the difference in the strain experienced by each material increased with total strain, volume ratio and deviation from the unit density ratio (Fig. 1). Besides, identical strain could be attained in both materials at an intermediate density ratio. The type of deformation/test i.e. stress-state in the deformation zone, was also found to influence the deformation behaviour of each metal (Fig. 1a and 1b). Consolidation and metal matrix hardening mechanisms associated with P/M preform deformation would strongly affect the densification behavior of each metal and the onset of steady state deformation, depending on the process parameters (Fig. 2).

Simultaneous compression and ring-compression tests on dissimilar P/M preforms [10] revealed that the deformation and densification behaviour of individual materials varied depending on the local micromechanical interactions at metal-metal interface and the severity of interaction depended on the type of deformation/test (stress-state). The 'strain hardening exponent' during simultaneous deformation of dissimilar P/M preforms was found to be higher than those of individual materials indicating the enhanced densification/matrix hardening (Fig. 3). The high densification of P/M preforms during simultaneous compression deformation was attributed to the active frictional stresses, altered strain paths, differences in frictional shear stresses and their directions along the metal-metal interface. The enhanced densification at metal-metal interface compared to tool-metal interface is shown in Fig. 4.

In order to have a prior knowledge on (a) compatible flow and (b) failure propensity with the help of analytical equations, the composite/bimetal flow stress for iso-stress and iso-strain conditions were evolved and examined for good agreement with the experimental values (Fig. 5). The composite/bimetal flow stress for iso-stress and iso-strain conditions were calculated using the following equations:

Iso-stress: $\sigma_c = (\sigma_{f1} \times \sigma_{f2})^{1/2}$; Iso-strain $\sigma_c = \phi[A_1^* \times \sigma_{f1} + A_2^* \times \sigma_{f2}]$

where

σ_c is the composite flow stress/mean flow stress; ϕ is a correction factor (0.85)

σ_{f1} is flow stress/mean flow stress of material 1; A_1^* represents the fractional area of material 1;

σ_{f2} is the flow stress / mean flow stress of material 2; A_2^* the fractional area of material 2

The interfacial friction coefficients were found to be less than that of the same material when tested between hard tools. This was attributed to the active and reactive frictional stresses at the metal-metal interface. The high interfacial friction at density ratios above unity was expected to enhance the solid joining of these two dissimilar materials.

3.2 TRANSITION JOINING OF STEEL-CU AND CU-AL SINTERED P/M PREFORM TUBES

The correlation between process parameters and the failure propensity showed that, the consolidation of P/M preforms during simultaneous extrusion reduced the differential velocity (between the two metals) and a high friction at the interface aided the sound flow over a wide range of processing conditions [11]. For the range of process parameters studied the sound flow domain seemed to be large as shown in Fig. 6, where the failure propensity was very less. Typical successful joints are shown in Fig. 7. An optimal interfacial pressure existed for sound product depending on the process parameters, beyond which there would be difficulties in accommodating the non-uniformities in strain, stress, densification, etc., at the interface leading to failure. The combination of process parameters, which lead to excessive extrusion force and densification rate at the interface (Fig. 8), resulted in more non-uniform flow during extrusion. The shear test results had shown that DR:1.25, VR:1.25, IA: 50°, ε:1.00 were the optimal conditions for steel-Cu joining and DR:1.00, VR:1.25, IA: 60°, ε:1.15 for Cu-Al joining. The weld strength of the joints made under these conditions was found to be 60 MPa for steel-Cu joints and 22 MPa for Cu-Al joints. Though the theoretically predicted extrusion forces showed discrepancies in relation to the experimental extrusion forces, the theoretically calculated values enabled the evaluation of failure propensity.

3.3 POST-JOINING HEAT TREATMENT OF DISSIMILAR TRANSITION JOINTS

The post-joining heat treatment of transition joints between steel and Cu P/M preform tubes was carried out at different temperatures and time (with and without interlayer) [12-14]. During heat treatment the 'solute drag' effect and strain localization were found to influence the grain size near the interface and in turn the weld strength in steel-Cu joints (Fig. 9). Post-joining heat treatment without interlayer resulted in severe micro-void formation on steel side in steel-Cu joints (Fig. 10a) and different intermetallic compounds (near the interface) in Cu-Al joints (Fig. 10b), due to difference in the diffusivities of two metals. The strain localization and residual porosity in the joints further enhanced the void formation by acting as favourable nucleation sites. These observations were substantiated by concentration profiles across these joint interfaces.

Heat treatment with fine nickel powder (1μm) as an interlayer enhanced the weld strength, besides eliminating the micro-voids and intermetallic compounds. On the other hand, coarse interlayer particles reduced the weld strength by leaving physical discontinuities and residual particles at the interface (Fig. 10c). Heat treatment of the joints made with 1μm Ni powder, as interlayer, increased the strength by 45% in steel-Cu joints and 82% in Cu-Al joints, when compared to their strength in the as-extruded condition. The optimal heat treatment (with 1μm Ni interlayer) conditions thus identified were 950°C, 2 h and 600°C, 4 h for steel-Cu joints and Cu-Al joints, respectively.

3.4 BIMETALLIC TUBES BY CO-EXTRUSION OF SINTERED P/M PREFORMS

The co-extrusion of bimetallic tubes [15,16], using P/M preforms as initial materials, also showed that the consolidation of P/M preforms during deformation reduced the differential velocity and a high friction at the interface aided the sound flow over a wide range of processing conditions, through the accommodation of non-uniformities (near the interface) in the deformation by softer preform. Typical successful bimetallic tubes thus produced are shown in Fig. 11. In general, the hard core configuration increased the failure propensity (Table 1). However, tailoring the density ratio effectively changed the stress-state at the interface and eventually reduced the failure propensity. This revealed that, at appropriate density ratio it should be possible to extrude any material combination without failure thus opening out a wide safe processing zone. An additional advantage could be that, the same tooling can be used for variety of products.

3.5 STRAIN VARIATION DURING CO-EXTRUSION OF DISSIMILAR P/M PREFORMS

The strain variation during co-extrusion (bimetallic tubes and transition joints) of dissimilar P/M preforms was determined to substantiate the earlier observations of reduced failure propensity by using P/M preforms as initial materials [17]. In transition joints, the strain of harder metal was found to be higher than that of softer metal, i.e., $\varepsilon_{steel} > \varepsilon_{Cu}$ in steel-Cu joints and $\varepsilon_{Cu} > \varepsilon_{Al}$ in Cu-Al joints. In general, the softer metal accumulated more strain during co-extrusion. However, in the present case the flow of the softer metal (in the direction of extrusion) was restricted by the bottom hard metal during transition joining. At the same time, the harder metal was free to flow without any restriction, in the direction of extrusion. In essence, the present joint configuration was inhibited with triaxial constraints on the softer metal (by the tools and harder metal) leading to lower strain in the softer metal.

The results related to the co-extrusion of P/M bimetallic tubes showed that, the difference in strain between core and sleeve (Fig. 12) would be relatively less than wrought bimetal extrusion [18]. The strain difference was in the range of 10-30% only, for P/M preform extrusion as against 30-85% for wrought metals. The larger strain difference (depending on the process parameters) reduced the weld strength in both cases (bimetallic tubes and transition joints).

3.6 IMPROVED WELD STRENGTH BY MEANS OF NANO INTERLAYER PARTICLES

The post-joining heat treatment temperatures for the joints made with nano Ni interlayer were considerably lower, by up to 150°C for both systems, and holding time could be shorter [19]. For identical weld strength in transition joints, the use of nano interlayer powder reduced the heat treatment temperature to the order of 16% for steel-Cu joints and to 25% for Cu-Al joints. The heat treatment of bimetallic tubes with nanocrystalline Ni interlayer increased the weld strength above 100% in steel-Cu joints and ~ 100% in Cu-Al joints, when compared to their strength in the as-extruded condition. Maximum strength of 90 MPa was achieved in steel-Cu transition joints when heat treated at 800°C for 3 h. In Cu-Al joints 35 MPa strength was obtained at 450°C, 3 h. Bimetallic tubes with soft core and high volume ratio, extruded at high strain, ensured highest weld strength (Fig. 13).

The joints thus obtained had additional advantages of preserving the quality of the dissimilar metal joints (steel-Cu and Cu-Al) in terms of similar physical, chemical and mechanical properties across the interface i.e., very thin diffusion zone and preserving the base metal properties. The thin diffusion zone was confirmed by microhardness, EDX (Fig. 14) and electrical resistivity (Table 2) studies on these joints. The application of nano particle interlayer greatly reduced the resistivity, indicating the absence of physical discontinuities and minimum diffusion zone at the interface.

4.CONCLUSIONS

The simultaneous compression deformation of dissimilar P/M materials revealed that the parameters such as density ratio, volume ratio, total strain and stress-state (type of deformation) affected the strain experienced by each metal. The deformation behaviour of individual material, during simultaneous deformation, was strongly influenced by the local micromechanical interactions at the metal-metal interface. The high strain hardening exponent and low interfacial friction during simultaneous deformation were due to active frictional stresses, altered strain paths, differences in frictional shear stresses and their directions along the metal-metal interface. These tests also showed that the higher density ratios would enhance the solid state joining and it was supported by the actual extrusion studies.

Based on the results obtained during transition joining and co-extrusion of bimetallic tubes using sintered P/M preforms as starting material, it could be concluded that the sound flow domain would be large in case of P/M processing as opposed to dissimilar wrought metal processing. The combination of process parameters, which lead to excessive extrusion force and densification rate at the interface eventually caused heterogeneous flow during co-extrusion. Though the hard core configuration increased the failure propensity, controlling the density ratio eliminated this failure also. The present investigation showed that at some density ratio it should be possible to extrude different material combinations without failure, i.e., ensuring a wide safe processing zone, with greater manufacturing flexibility.

Post-joining heat treatment studies revealed micro-voids and intermetallic compounds near the interface of steel-Cu and Cu-Al joints respectively, when the interlayer was absent. The strain localization and the residual porosity enhanced the formation of voids and intermetallics. Finer Ni powder as an interlayer facilitated in achieving highest weld strength for both the joints by eliminating above adverse effects. Considerable reduction in heat treatment temperature and time were achieved with nano particles interlayer, besides, preserving the quality of dissimilar metal joints (steel-Cu and Cu-Al) in terms of similar physical, chemical and mechanical properties across the interface.

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TABLES

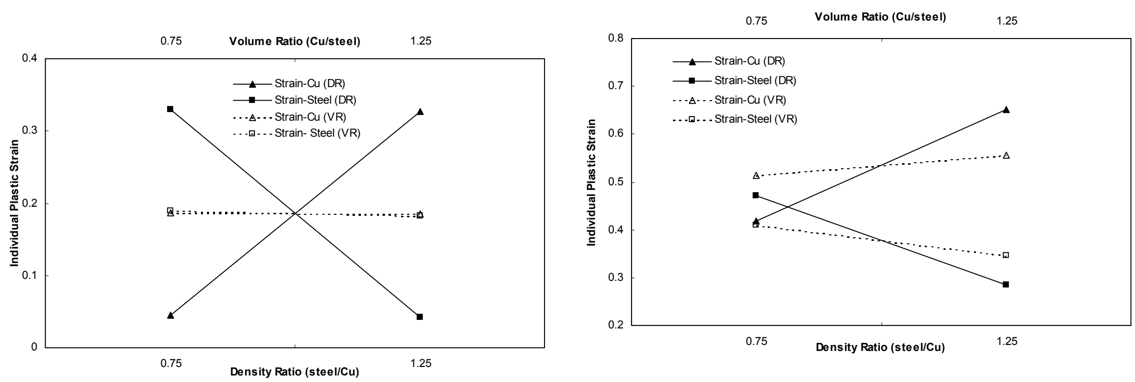
Table 1 Failure modes during co-extrusion of dissimilar sintered P/M preform tubes.

Strain	Soft Core		Hard Core	
	VR-0.75	VR-1.25	VR-0.75	VR-1.25
Steel-Cu Tubes				
0.85	✓	✓	✓	SF
1	✓	✓	✓	✓
1.15	✓	SF	CF	✓
Cu-Al Tubes				
0.85	✓	✓	✓	SF
1	✓	✓	✓	SF
1.15	✓	SF	CF	✓

Table 2 Results of electrical resistivity measurements on transition joints.

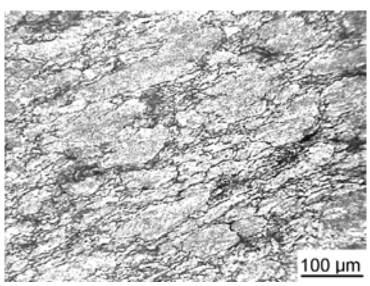
System	Condition	Resistivity, Ω-cm
Steel-Cu	without interlayer	0.39
	with 1 μm Ni interlayer	0.29
	with nanocrystalline Ni interlayer	0.15
Cu-Al	without interlayer	0.29
	with 1 μm Ni interlayer	0.21
	with nanocrystalline Ni interlayer	0.08

FIGURES

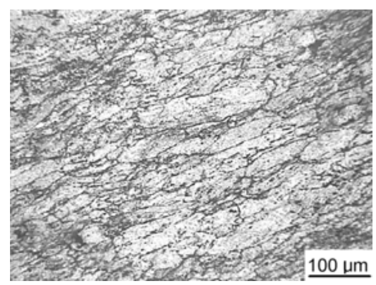


(a) (b)

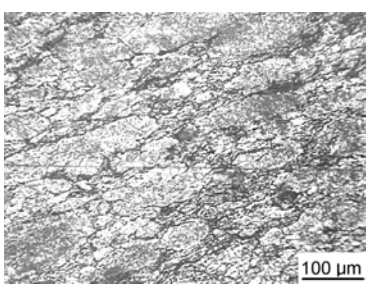
Fig. 1 Effect of process parameters on the individual strain (a) Pure upsetting (b) Upsetting and free extrusion.



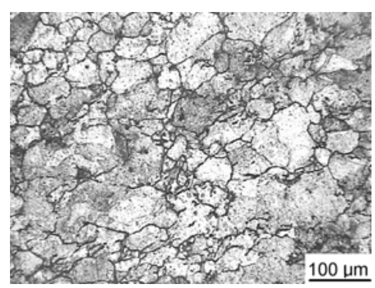
(a) DR:0.75, VR:0.75, ε_t=0.4



(b) DR:0.75, VR:0.75, ε_t=0.4

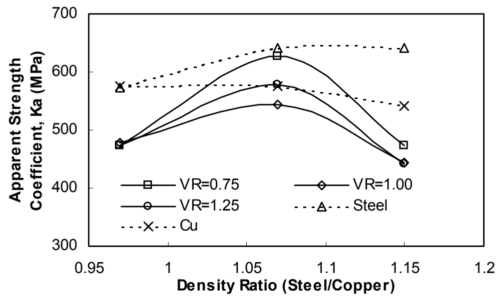


(c) DR:1.25, VR:1.25, ε_t=0.4

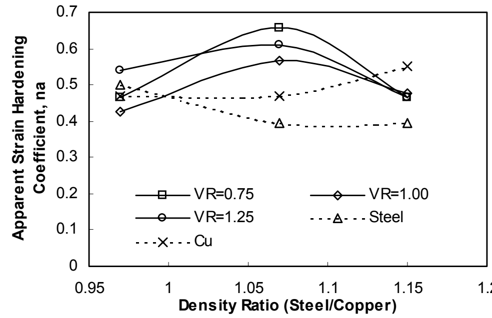


(d) DR:1.25, VR:1.25, ε_t=0.4

Fig. 2 Microstructures of P/M preforms deformed during Test 2 (upsetting & free extrusion) (a) & (c) copper (b) & (d) steel.

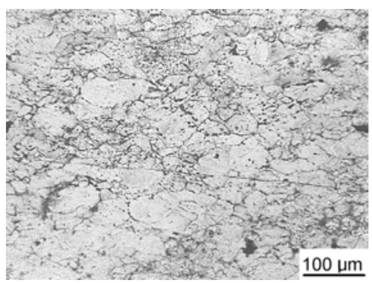


(a)

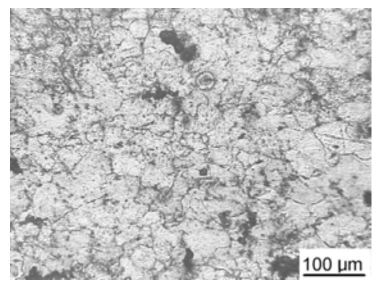


(b)

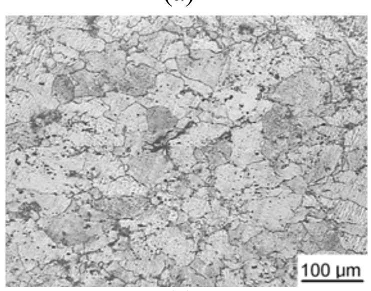
Fig. 3 Flow constants determined during simultaneous deformation of steel-Cu P/M preforms under iso-stress condition, (a) for apparent strength coefficient, (b) for apparent strain hardening exponent.



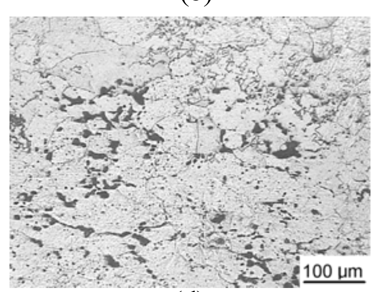
(a)



(b)

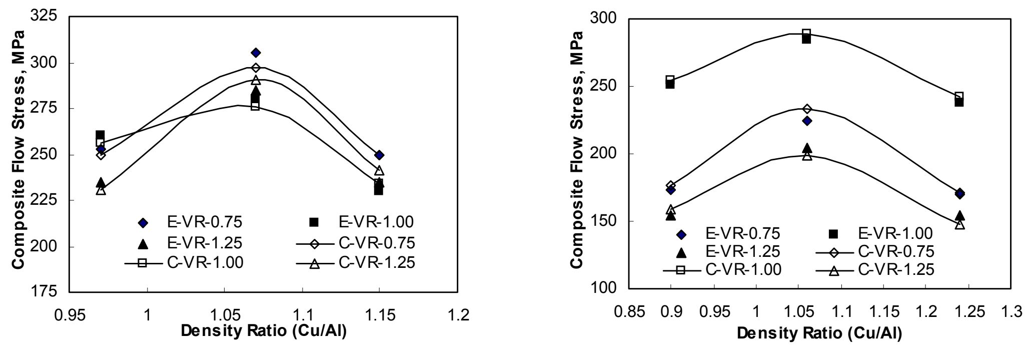


(c)



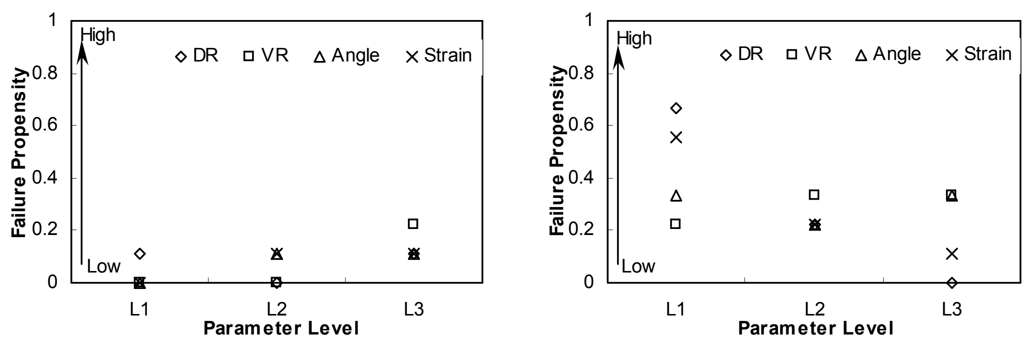
(d)

Fig. 4 Microstructural variation in simultaneously deformed steel P/M preforms, VR-0.75 (a) M/M interface, DR-0.97 (b) T/M interface, DR-0.97 (c) M/M interface, DR-1.15 (d) T/M interface, DR-1.15.



(a) (b)

Fig. 5 Comparison between calculated and experimental flow stress values for simultaneous deformation of Cu and Al P/M preforms (a) under iso-stress condition (b) under iso-strain condition [E-experimental, C-calculated].

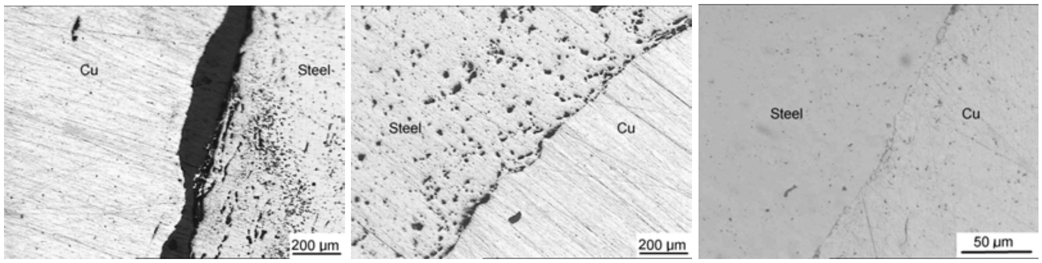


(a) (b)

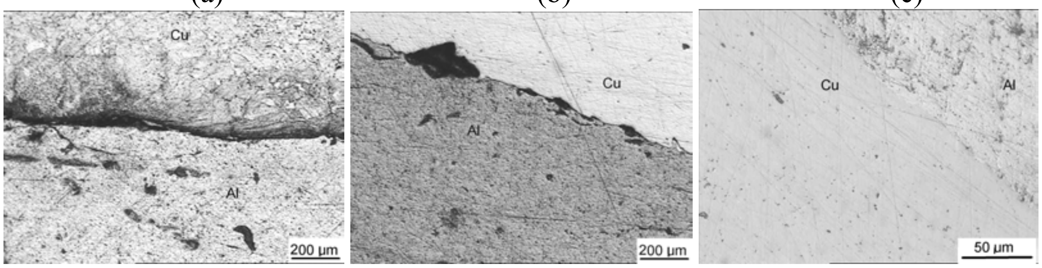
Fig. 6 Failure propensity during transition joining of dissimilar P/M preforms (a) steel-Cu (b) Cu-Al ['0' for sound extrusion, '1' failure of extrude; L1, L2, L3 = 0.75,1.00,1.25 for DR and VR, 50°, 60°, 70° for interfacial angle, 0.85, 1.00, 1.15 for strain].

(a) (b)

Fig. 7 Successful transition joints made by cold extrusion of P/M preforms (a) steel-Cu (b) Cu-Al.

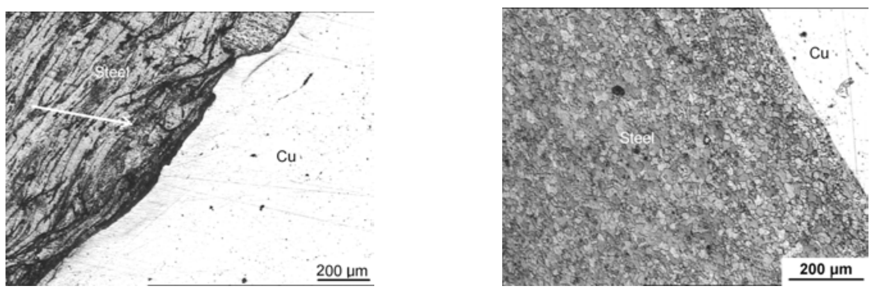


(a) (b) (c)



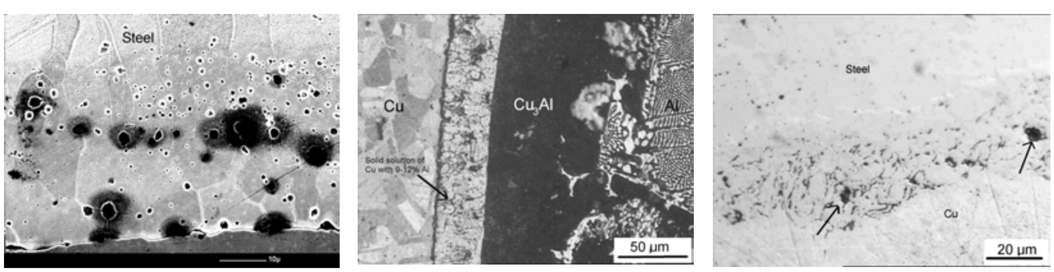
(d) (e) (f)

Fig. 8 Interface microstructures of the joints (a) steel-Cu, DR-0.75, VR-1.00, IA-60°, ε-1.15 (b) steel-Cu, DR-1.00, VR-1.00, IA-50°, ε-1.15 (c) steel-Cu, DR-1.25, VR-1.25, IA-50°, ε-1.0 (d) Cu-Al, DR-0.75, VR-1.00, IA-50°, ε-1.0 (e) Cu-Al, DR-1.00, VR-1.00, IA-70°, ε-1.0 (f) Cu-Al, DR-1.00, VR-0.75, IA-60°, ε-1.15.



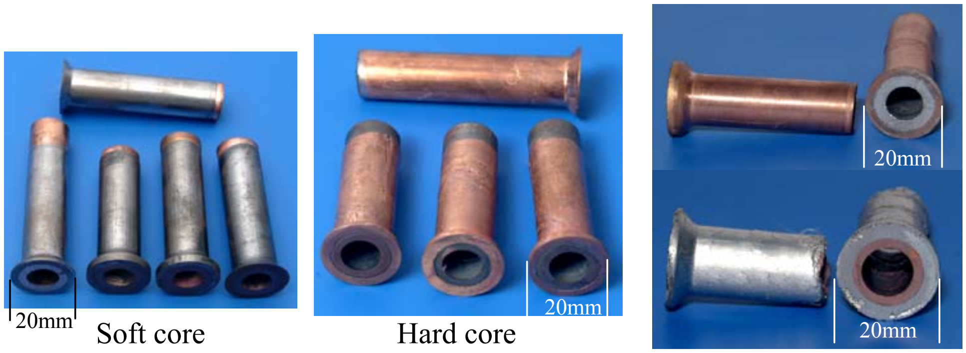
(a) (b)

Fig. 9 Strain localization (arrows) and the resultant microstructure of steel-Cu joints (a) before heat treatment (b) after heat treatment.



(a) steel-Cu joints (b) Cu-Al joints (c) steel-Cu joints

Fig. 10 Microstructures near the bond region of joints made without interlayer (a) diffusion induced micro-voids, 950°C, 6h (b) intermetallic compounds, 600°C, 4h (c) residual particles at the interface (Ni 100µm).



(a) (b)

Fig. 11 Typical sound bimetallic tubes produced by co-extrusion of dissimilar P/M preforms (a) steel-Cu (b) Cu-Al.

Remarks: ✓-sound, CF-core fracture, SF-sleeve fracture, DR = 1.25 for steel-Cu, 1.00 for Cu-Al.

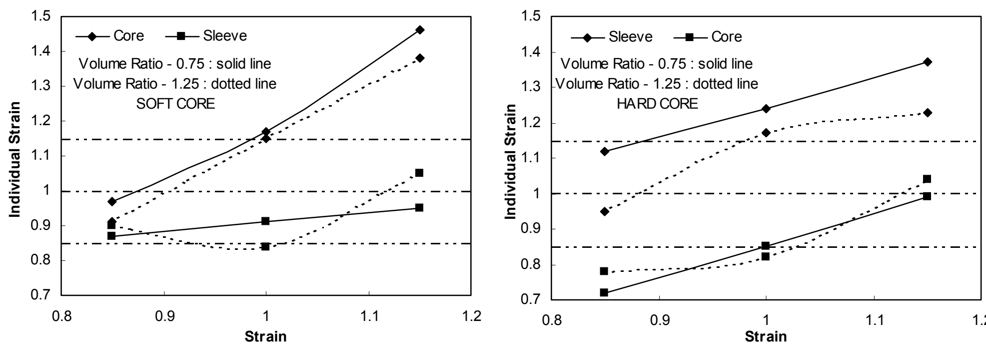
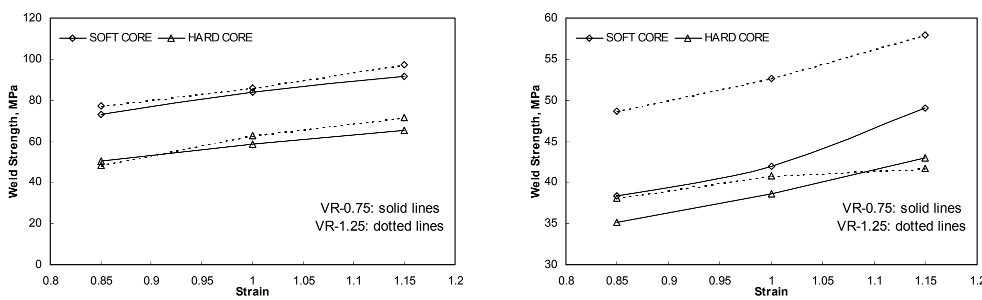
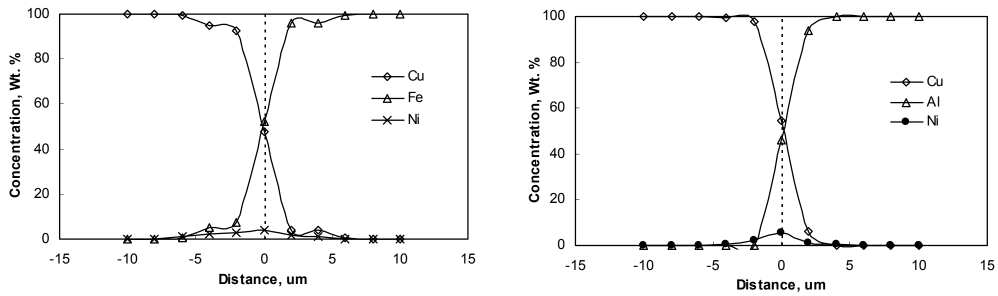


Fig. 12 Core and sleeve strains during steel-Cu bimetallic tube extrusion.



(a) (b)

Fig. 13 Weld strength of heat treated bimetallic tubes made with nano Ni interlayer (a) steel-Cu (b) Cu-Al.



(a) (b)

Fig. 14 Concentration profile of Fe, Cu and Ni in transition joints made with nano Ni interlayer (a) steel-Cu, 800°C, 3h (b) Cu-Al, 450°C, 3h.