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A Review on Welding Processes for Dissimilar Materials

[1]Sakthieswaran N, [1]Gopinath R, [2]Priyanka M, [2]Shiny Brintha G, [2]Karthiga Devi P

[1]*Assistant Professor, Department of Civil Engineering, Regional Centre Of Anna University, Tirunelveli, Tamil Nadu, India.*
[2]*PG scholar, Department of Civil Engineering, Regional Centre Of Anna University, Tirunelveli, Tamil Nadu, India.*

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ABSTRACT
An exclusive survey on literatures closed to bonding of dissimilar materials, super-plastic forming carried out for lap and butt joints of work pieces is done to implement innovative and challenging new works and to help the reader able to get extended ideas about the characteristics of materials under the application of processed welding methods . Innovative investigations and experiments are necessary to implement the idea in structural engineering aspects.

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INTRODUCTION

In this present scenario, joining of different materials is worth necessary. Welding process has wider applications in all fields such as structural joints, military, aerospace, piping, tanks, shafts, tubes, automobiles, communication devices than bolted, rivet and screwed connections. The tensile strength is reduced considerably due to stress concentrations, rigidity is reduced due to loose fitting and nuts are likely to loosen endangering the safety under vibrations.

Welding is a material (or) metal joining process in which two or more parts are joined together, at their contacting surfaces. In some process, filler material is added to facilitate coalescence. Welding method is the most suitable and practicing in joining of two different materials. This is advantageous as it is possible to achieve 100% efficiency, possess airtight and anti-leak connections with good appearance. This does not have the problem of mismatching of holes and alterations in existing connections can be easily made and thus grabs the preferred place in joining of materials.

Classification of welding processes:

Review of literatures showed that many researchers have concentrated on different welding techniques to make joints of materials and have made study on its joint strength characteristics. Generally, welding process is broadly categorized in to fusion and solid state welding techniques. In the traditional fusion method, coalescence is accomplished by melting the two parts to be bonded and may or may not use filler material. From the review, it is understood that, in fusion welding method, coalescence of work pieces produced by heating them in which melting of surface occurs whereas in solid state welding, coalescence of work pieces produced by application of heat and pressure without melting any of joint components.

The gas welding technique, processed by heating the work-pieces with an oxyfuel gas flame has the disadvantage that the flame directed by torch and filler rod should be often coated flux to clean surfaces and prevent oxidation. Arc welding is further categorized to consumable and non-consumable electrodes. Shielded metal arc welding has limited applications of joining steels, cast iron and stainless steel. Gas tungsten arc welding produces high quality welds but this is a slower and more costly than consumable electrode arc welding processes. Though weld quality, penetration control and no limitations in materials can be obtained by plasma arc welding, the equipment cost is too high and has limited access in some joints. Electron beam welding technique is disadvantageous as it generate X-rays and its equipment cost is high whereas in laser beam welding, no x-rays generated but LBW is not capable of the deep welds. As well, under solid state welding techniques, Forge welding, in which the components are heated and then forged by hammering or similar means. Forge welding is the oldest and crude method and its quality depends on the skill of the welder.

Cold welding which has its application limited to sealing of heat sensitive containers, wire stocks etc. Roll welding, in which coalescence caused by sufficient pressure by means of rolls with or without external heat. Hot

Corresponding Author: Priyanka M, Shiny Brintha G, PG scholar, Department of Civil Engineering, Regional Centre Of Anna University, Tirunelveli, Tamil Nadu, India.
E-mail: cjrcautvl@gmail.com +91 9715908675

pressure welding, in the process of diffusion welding, bonding mechanism is obtained usually in a controlled atmosphere but the time required can range from seconds to hours. This has its applications in joining high strength and refractory metals in industries.

Explosion welding, in which rapid coalescence of metallic surfaces caused by the energy of a detonated explosive. In this method, time is too short that no diffusion occurs within it but when processed for long time, leak tight joints promoting discontinuity and crevices can be obtained. Ultrasonic welding is limited to lap joints on soft material. Frictional welding is the widely used technique mainly for butt joints and now also used in joining of polymers and composites. Resistance welding can be worked out with operator skills lower than what is required for other methods but with high capital investment.

Selection of welding method:

Most of the fusion welding techniques possess slight negative aspects such as micro-structural defects, melting and solidification of base materials and possess high distortion and an exit hole is produced when the tool is withdrawn. Using the melting welding methods, different zones come out depending on the composition and properties of the materials under process.

Solid state welding techniques overcome the above said problem and possess more advantages such as good dimensional stability and joints obtained without melting of base metals. The essential factors for a successful SSW are clean surface and close contact to permit bonding.

Amongst the category of solid state welding, diffusion and friction stir welding possesses good mechanical properties, weld appearance, less distortion and avoids toxic fumes and shielding issues. Therefore, an exclusive survey on literatures closed to diffusion bonding, combined super-plastic forming with diffusion bonding and friction stir welding carried out for lap and butt joints of work pieces of dissimilar base metals is done to implement innovative and challenging new works and to help the reader able to get extended ideas about the characteristics of materials under the application of above said welding methods.

Diffusion bonding:

The bond and shear strength of the joining materials can be improved by modifying the process parameters of diffusion bonding technique. This advantageous method is processed by preparing the surfaces, then placing in the chamber, and removing samples under room temperature. Finally the welded joints carried out by any method of welding are evaluated for its microstructure by SEM, TEM, XRD, EDS and EPMA and tensile test to evaluate the bond strength characteristics by UTM and hardness by micro-hardness tester.

(Kenevisi *et al*., 2013) dealt about diffusion bonding of Al7075 and Ti – Al – 4v with Cu and Sn – 4Ag – 3.5Bi as interlayer at a temperature of 500^0C under a pressure of 2MPa. This report also showed that $TiAl_3$ and TiAl inter-metallics formed and increase in bonding time showed increase in strength upto 60min and showed decrease in strength at 75min. (Sabetghadam *et al*., 2010) reported that diffusion bonded of 410SS and Cu with Ni interlayer under 12MPa bonding pressure with temperature range of 800 – 950^0C heat rate 30^0C/min and vacuum of 10^{-4}torr for 1hr bonding time showed maximum hardness of 432HV and shear strength of 145MPa. This work also showed that diffusion zone at Cu – Ni was larger than at Ni – Cu interfaces, shear strength was reduced, if the temperature is lowered and the thickness of reaction layer is increased by raising the bonding temperature. (Barrena *et al*., 2010) studied the interfacial microstructure and mechanical strength of WC – Co/90MnCrV8 cold work tool steel diffusion bonded joint with Cu/Ni electroplated interlayer and in their work they carried the process at a temperature range of 825 – 875^0C with heating and cooling rate of 10^0C/min under a pressure of 5 MPa for holding time of 30 – 60min. From their work, they have concluded that increasing bonding time and temperature, both diffusion process and generation of reaction layers are promoted whereas shear strength decreases. (Rahman *et al*., 2010) studied the strength and microstructures of diffusion bonded commercially pure Ti using Ag and Cu inter-layers and without any inter layers. Their study showed that formation of inter metallics could not be avoided using Ag even for longer bond period whereas using Cu interlayer, this was eliminated and joint strength has reached 98% of strength of base metal. Only 75% of strength of parent metal was observed when no interlayer is used which shows higher strength than when Ag is used as interlayer. (Mahendran *et al*., 2010) studied about the process parameters of diffusion bonding on bond characteristics of Mg – Cu dissimilar joints. Their work indicated that goods bond with maximum shear strength, bond strength and hardness was obtained at 500^0C, 16MPa and bonding time of 40mins. In their work, they also developed an empirical relation to obtain the thickness and hardness using process parameters. The interface structure of diffusion bonded duplex stainless steel and medium carbon steel couple was well established in a wok by (Bulnet *et al*., 2009) in their work they carried the process at a temperature range of 750 – 900^0C under 8MPa with holding time of 30min. Their result showed that bond showing maximum shear strength of 767MPa was obtained at 900^0C and also indicated that there was formation of $Cr_{23}C_6$ and ferrite on stainless steel and carbon steel sides respectively and also resulted that thickness of carbide layer increases with increase in bonding temperature. (Ravishankar *et al*., 2009) established a work on diffusion bonding of SU263 showing maximum hardness and shear strength merely equal to parent metal at a temperature of 1323K for 24hrs bonding time under pressure of 0.9 0f its YS. Their study also showed about the phase composition formed during bonding and empirical relation developed. Their work also extended to compare with Pilling's model for super plastic materials and observed with 7%deviation. Microstructure and mechanical properties of diffusion bonded joints between tungsten(W) and F82H steel using a Ti interlayer is well established in a work by (Zhihong *et al*., 2009)In their work the bond showed maximum shear strength at a bonding temperature of 900^0C beyond which it decreases. The bonding pressure and holding time was 10MPa and 60min respectively. Their work also indicated that the width of diffusion layer increases with increase in temperature and the fracture was at Ti/F82H interface under shear test. (Mahendran *et al*., 2009) worked to develop diffusion bonding windows for joining AZ31B Mg – AA2024 Al alloys to act as reference maps for selecting parameters to get good quality bonds. 30 joints at different process parameters was made and resulted that no bond was obtained at temperature below 400^0C and melting of Mg was observed at temperature above 475^0C and also indicated that no bond and melting of Mg was observed under pressure lower than 5MPa and greater than 20MPa respectively and also showed that holding time greater than 90min caused Mg alloy to melt. In their work, they observed bond showing maximum shear strength at 425^0C under 20MPa for 45minutes. (Elrefaey *et al*., 2009) established a paper on diffusion bonding of Ti to low carbon steel(AISI – 1008) with Cu-Ni-2Ni as interlayer to prevent migration of atom. Their work reported that bonding was not attained below 800^0C and bonding was good at 850^0C under a pressure of 3MPa with vacuum of 2 x 10^{-5}Pa for 30 – 180minutes. The formation of inter metallics are TiCu, Ti_2Cu, $TiCu_2$, Cu_4Ti and fracture was observed at inter metallics under test. The effect of Zn alloy interlayer and without any interlayer on interface microstructure and strength of diffusion bonded Mg – Al joints is very well established in a work by (2008)Zhao *et al*. Their work resulted that specimens bonded at 447^0C with heat rate of 110^0/3s without interlayer produces harmful inter metallic compounds with thickness greater than 5mm and showed shear strength of 41.3MPa whereas the bonded specimens with Zn interlayer at 360^0C with heat rate of 90^0C/3s produces inter metallics with less than 5mm thickness and showed twice the shear strength than the specimens without interlayer. (Wang *et al*., 2008) studied the microstructure and XRD analysis in the interface zone of Mg/Al diffusion bonding at a temperature range of 470 – 480^0C under pressure of 0.08 – 0.1MPa for 40 – 60min. In their work, they inferred that a new compound was formed at the interface. It is also inferred that increase in temperature accelerates formation of Mg_3Al_2 results for improving joint strength and crack resistance. The fracture observed at mid diffusion region was coarse and dark gray with metallic shine whereas in Mg side was flat and silvery white. (Ho-Sung *et al*., 2007) made a study on diffusion bonding of super plastic Ti-6Al-4v ELI grade at temperature of 1073 – 1223K under pressure of 3MPa for 1hour holding time. It is also inferred that good bonding was observed at relatively lower temperature and pressure lower than those of conventional Ti-6Al-4V and microstructure bonded at 1173K exhibits oxygen enriched alpha phase at bonded interface. The interfacial microstructure and mechanical properties of diffusion bonded Ti-steel joints using Ni as interlayer is very well established in a work by (Kundu *et al*., 2006)The joints were made at 800 – 950^0C under 3MPa pressure and observed that $TiNi_3$, Ti Ni, Ti_2Ni were formed at Ni-Ti interface. It also indicated that SS-Ni side was free from inter metallics up to 900^0C whereas beyond this phase mixtures were formed leading to decrease in bond strength. Diffusion bonding behaviour of a super-plastic AZ31 magnesium alloy processed by hot rolling is dealt by (Hidetoshi *et al*., 2003) the alloy behaved as super plastic manner at 523 and 573K under 15 – 30MPa for 2hours and successfully bonded at these temperatures. The lap shear strength beyond 0.8, no bond line was micro structural observation and increasing temperature and pressure increases strength. (Ren *et al*., 2002) studied the microstructure characteristics in the interface zone of Ti/Al diffusion bonding processed at 640^0C under 24MPa for 90min. Inter metallics such as $TiAl_3$, Ti Al and Ti_3Al were observed. It also inferred that the width of inter metallics can be reduced by controlling the process parameters. (Hidetoshi *et al*., 2003) dealt with diffusion bonding in super plastic magnesium alloys processed under 2 – 10Mpa showed super plastic behaviour at 673 – 723K. Their work also inferred that strength decreases with the presence of voids and longer bonding time or pressure needed to improve the bond quality. No bond line was observed in micro structural studies and proved the possibility of fabricating Mg products using SPF/DB. Characterization of transition joints of commercially pure Ti to 304 SS is very well established in a work by (Ghosh *et al*., 2002)In their work, the process was carried at a range of 850 – 950^0C under 3MPa with vacuum of 10^{-4}mbar for 60minutes. They resulted that Ti traversed a minimum distance in SS whereas Fe, Cr and Ni traversed comparatively larger distance in Ti side. This work also inferred that width of IL increases with increases in temperature and brittle phases reduces strength and ductility of joints. The bond showing maximum strength of 217MPa with small amount of strain and finer size of IMC was attained at 850^0C. (Orhan *et al*., 2001) studied diffusion bonding of a micro duplex SS to Ti-6Al-4V. The materials were processed at a range of 800 – 880^0C under 2 - 3.5MPa for 15 – 30min. It was noticed in their work that there was a noticeable shift in bond interface towards Ti-6Al-4V with no void formation. This work also indicated that the formation of Fe-Cr-Ti inter metallic is more important than σ – phase and increase in temperature and time, the width of IL region increases. A study on interface structure and formation mechanism of diffusion bonded joints of SiC ceramic to Ti-Al based alloy is handled by (Liu *et al*., 2000) In their work, the materials were processed at 1473 – 1573K under 35MPa for 15 – 240 min. It was observed that three stages of reactions involving for the process and was inferred that increase in temperature and processing time width of reaction layer increases. (Huang *et al*., 1999) studied diffusion bonding of super plastic 7075 Al alloy which was processed at 490 – 530^{0}C under 1-5.7MPa for 30 – 360 min. It was observed that the re-crystallisation in the bond region eliminated the interfaces leading to high bond strength. It was also inferred that increase in temperature increases strength up to a certain range and beyond that strength decreases. As well increase in holding time increase grain growth and bond strength. Low pressure diffusion bonding of SAE 316 SS by inserting a super plastic interlayer was studied by (Yeh *et al*., 1995) the material was processed at 1300K under pressure range of 4.2 – 7MPa for 30min. It was observed and confirmed that using super-plastic interlayer improves bond strength. As well, increase in surface roughness shows increased tensile strength. A report on effect of interlayer chemistry on the diffusion welding of cobalt base wear resistant surfaces on Ti alloy was established by (Wisbey *et al*., 1996) their work investigated the possibility of cladding Ti with conventional wear resistant alloys by diffusion bonding and materials were processed at 900^{0}C under 20MPa for 1hour. The joints without any interlayer's showed high strength but brittle fracture occurred along a region containing TiC at the joint interface. Combinations of molybdenum/Ni, Cr/vanadium and Ti/Ni produced β- layer about 8µm, 13µm and 7µm respectively. The combination of tantalum and Ni interlayer's showed best results though Ni_3Ta inter metallic formed and concluded that interfaces can be tailored to the application in terms of strength and toughness. (Urena *et al*., 1996) studied TEM characterisation of diffusion bonding of super plastic 8090Al-Li alloy which dealt about the grain boundary interface migration and local recrystallization. In their work, the alloys were processed at 530±5^{0}C for 2hours. This paper showed that when no interlayer is used, recrystallization occurs forming new grains and losing smoothness at the bond interface whereas process with interlayer eliminates the oxide film and improved the quality of joint.

Friction stir welding:

Friction stir welding is also a method under solid state welding process in which the relative motion between the tool and the work pieces produces heat which makes the material of two edges being joined by plastic atomic diffusion. The principle is the conversion of mechanical energy to thermal energy to form the weld without application of heat. The process parameters are rotational speed, axial pressure, welding speed, time and the type of pin, shoulder and tilt angle of the rotating tool. Weld joints without melting of base metals are obtained by inserting the pin such that the shoulder rubs the surface which generates frictional heat. It is advised that the maximum temperature allowed is 80% of melting point of the materials. As said before, many researchers have concentrated in this method. The influences of rotational and welding speeds on micro-structural and mechanical properties of friction stir welded Al5083 and commercially pure copper sheet lap joints was studied by (Bisadi *et al*., 2013). They carried the work with H13 tool with tilt angle of 3.5^0 and 0.4mm shoulder penetration. The good weld was obtained at rotational speed, weld speed and axial force was 1500rpm, 118mm/min and 2709N respectively. Their work also indicated that increase in rotational and welding speed increases the process temperature whereas increase in temperature causes cavity due to difference in melting point and contraction coefficient of materials resulting low quality welds. Al_2Cu is the main IMC at fracture areas. The ultimate tensile stress of Cu and Al observed was 78% and 74% of the parent material. (Chen *et al*., 2012) studied the interface characteristics of FSW lap joints of Ti/Al dissimilar alloys. This combination was investigated for having reduced mass and cost and showing greater strength. The tool used in their work was concave shoulder of 15mm dia., cone-threaded pin 4mm dia. and tilt angle of 2^0. The weld showed good quality at 1500 rpm, 60mm/min and 2.8KN of rotating speed, weld speed and axial force respectively. It also indicated that the joint showed maximum hardness of 502HV and increase in the weld speed showed groove like cracks. (Izzatual *et al*., 2012) reported on the effects of GMAW or MIG processes on different welding parameters, carried their work with three different voltages, speed and current and investigated the penetration depth and hardness. From their work it was very well understood that increase in weld current reduces hardness and depth of penetration. It is also understood that the size of grain boundaries varies according to the process parameters. (Hui-Chi *et al*., 2011) presented a paper on gap-free fibre laser welding of Zn coated steel on Al alloy for light-weight automotive applications in which the investigation of weld appearance and improvement of corrosion resistance was worked out. Their work resulted that the welds showed greater shear strength and less inter-metallic phases obtained when N_2 gas was used as shielding gas. Microstructure characteristics and mechanical properties of AA/SS lap joints fabricated by MIG welding brazing process has been reported by (Hongtao *et al*., 2011). They have done the joint with 4043 Al-Si filler material and the aluminized coating had limited effect of promoting the appearance of weld surface and obvious micro-cracks were found between the compound layer and the SS side. It was observed three zones such as reaction zone consisting of Cr, Ni and Si, fusion zone with molten filler wire and AA base and another zinc rich zone. The maximum tensile strength was 193.6MPa. The effects of FSW process parameters on appearance and strength of polypropylene composite welds was reported by (Payganeh *et al*., 2011). In this worked out the joints on two stages, one for investigating appearance, with different pin geometires at 500rpm, 112mm/min 1^0 tilt angle and another for tensile stress, with selected tool with varying rotating speed, weld speed and tilt angle. They concluded that the tool with taper pin with groove proved best for appearance and best joint was attained at 630rev/min, 8-20mm/min and with the tilt angle of 1-2^0. This work also indicated that increasing linear speed decrease the tensile strength and improper tilt angle may cause tunnel and crack like defects. (Ahmed *et al*., 2010) reported on evaluation of parameters of FSW for AA6351 alloy. Four combinations of feed rate and rotational speed was carried and investigated for its tensile strength and hardness. The improper alignment of weld metals showed maximum hardness and tensile strength of 85 and 160MPa whereas when the metals are properly aligned in line showed 90.2 and 274MPa respectively. The maximum results were observed at 1350rpm with feed rate of 115mm/min without use of any filler materials indicating high surface finish. This paper also reported that maximum tensile strength was observed with lower weld speed. (Balasubramaian *et al*., 2008) established empirical relationships that can be effectively used to predict FSW parameters for welding of five different Al alloys to produce defect free welds. In his paper, he predicted that rotational speed is directly proportional to yield strength, hardness and indirectly proportional to elongation. He also proposed that welding speed is directly proportional to elongation and inversely proportional to yield strength and hardness and also empirically predicted that weld pitch is inversely proportional to yield strength and directly proportional to hardness and ductility. The Tensile deformation and fracture behaviour of FSW Al alloy2024 is very well understood from the work by (Srivatsan *et al*., 2007). In their work, they have studied the behaviour of welded and un-welded counterparts under two FSW panel, one with low and other with high ductility. Onion rings on the surface are the evidence of the FSW phenomenon. The YS and UTS of the weldment were lower than the un-welded and FSW samples fail at lower strain than the un-welded counterparts. This work resulted that the tensile fracture of un-welded was by shear at 45^0 to far-field stress axis whereas the FSW samples revealed brittle and macroscopic failure at 90^0 to the far-field stress axis. A comparison between FSW and TIG welding techniques was reported by (Squillace *et al*., 2004) in a work with results from polarisation curve and EIS test. TIG welded joints showed general decay whereas FSW joints showed slight decay of mechanical properties.TIG with lower speed showed wider grains in the direction of heat source whereas same with higher speed showed fine grained through the thickness of the weld. This work also resulted that TIG joints showed evident pitting tendency whereas it was less evident in HAZ weld bead of joints by FSW. The micro-structural, tensile and fatigue properties of linear friction welded AA2024 was examined by (Fabio *et al*., 2012) and resulted with three zones namely weld centre, TMAZ and HAZ with ultra-fine, severe plastic deformation and without modifications respectively. Their work on the analysis of fracture surfaces evidenced the presence of cleavage between TMAZ and weld centre. Amorphization by friction welding between 5052AA and 304SS was worked out by (Fukumoto *et al*., 2000). Their work was done with rotational speed of 40/s with friction pressure 50MPa for 2s and investigated on the weld interface by TEM resulting that amorphous phase produced by complex process of MA and SSR at high temperatures. AA1050 and AISI 304 SS processed by rotary friction welding process in a study by Eder *et al*., (2010). In their work, they resulted that the strength of the joint varies with friction time and the other process parameters. They also analysed by EDX at the interface and it was observed that inter-diffusion occurs between the main chemical components of the materials involved. (Hidekazu *et al*., 2003) studied the mechanical properties of friction surfaced AA5052 and observed that the circular pattern appeared on the surface of deposit by rotation of consumable rod. It is also observed from their work that the width of the deposit increased with increasing processing pressure and decrease in rotational speed and the tensile strength of the deposit increased with increasing friction pressure. An experimental study on joining plastically deformed Al materials with friction welding method was carried out by (Mumin *et al*., 2008). In their work, the alloys, as purchased were joined and process parameters were obtained and then the Al5083 were prepared as square cross section and then one pass was applied by pressing die. It was observed from this study that the tensile strength of the two forms is compared and it also resulted that the tensile strength increases with process time and pressure. The weld strength of the joints was observed similar to the strength of material after deformation. (Hiizu *et al*., 2008) evaluated the tensile and fatigue strength of commercial pure Al and tough copper friction welded joints by deformation heat input. It was observed in their work that joints having stable tensile strength at the weld interface with long processing time. And it was also observed that the fracture was observed at the weld interface under testing. (Ahmadi *et al*., 2012) studied the effect of pin profile on quality of friction stir lap welds in CFRP composite. In this work, friction stir welding was carried on with four different pin profile and observed that the profile with threaded cylindrical conical performed well resulting with good surface appearance and high tensile strength. Friction stir welding of glass Fibre Reinforced Polymer composites was established in the international conference by (Czigany *et al*., 2011)They observed that this method performed well with the matrices and also observed that the flexural strength of the seams produced exceeded than those produced on non-reinforced sheets by 27%. Their work also resulted that increase in fibre length increases the joint strength.

Conclusion:

From this study on literatures closed to diffusion bonding, combined super-plastic forming with diffusion bonding and friction stir welding carried out for lap and butt joints of work pieces of dissimilar base metals, it is very well observed that

1. Articles lacking in application of welding with Cu/Ag, Al/Ti combinations and innovative paper on some other new combinations can be done for the development study of material technology.

2. New research needed for the challenging ideas in structural engineering aspects such as diffusion and friction stir welding techniques on glass, carbon and hybrid fibre reinforced polymer structural sections for trusses, lattice towers, bridges etc.

3. Development of new steel application such as small and medium scale fabrication depends on matching development of the welding sector. It is a challenge to establish a cost effective welding practices in steel intensive construction sector in India.

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