Review of Direct Metal Bonding for Microelectronic Interconnections

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***Abstract--*Microelectronic interconnections require advanced joining techniques. Direct metal bonding methods, which include thercomsonic and thermocompression bonding, offer remarkable advantages over soldering and adhesives joining. These processes are reviewed in this paper. The progress made in this area is outlined. Some work concerned with the bonding modeling is also presented. This model is based on the joint interface mechanics resulting from compression. Both bump and substrate deformation are taken into account. The improved understanding of the relationship between the deformation and bonding formation may provide more accurate joint evaluation criterion.**

I. INTRODUCTION

There are three main joining technologies currently being used for microelectronics packaging:

1) Soldering

Solder-bumped chip is bonded on a solder pre-coated pads on the substrate through reflow process. Strong and reliable connection will be formed along with underfill resin.

2) Adhesives

Adhesives include ICA (Isotropic Conductive Adhesive), ACA (Anisotropic Conductive Adhesive) and NCA (Non Conductive Adhesive). They are very different from metallurgical solders, and have the following advantages:

- Low temperature processing capability
- High density interconnection
- Low cost and environmentally friendly
- Flexible and simple

3) Direct metal bonding

It is a method of joining two flat, clean and smooth surfaces under ambient condition without an intermediate layer (glue) between them, including thermosonic and thermocompression bonding.

Although soldering offers high yield and reliable connections, it requires complex and often environmentally unsound processes. Solder joining is not suitable for the pitches less than 50μm, as the micro-solder joints may not be able to support the mechanical and electrical loading. The detrimental effect due to intermetallic growth is likely to be amplified in microjoints. Alternative joining process using adhesives are limited by their lower reliability and relatively poor conductive. Direct metal bonding is a promising candidate for solving all the above problems. Metallurgical joints are highly reliable and can be applied to fine pitch interconnections with little or no melting during the process. In this paper, the review of present development of direct metal bonding would be given.

II. THERMOSONIC BONDING

Thermosonic bonding was previously applied mainly for wire bonding. This process uses a combination of heat, pressure and ultrasonic energy to form a bond between the bump and metallization on the joining surface. Thermosonic bonding has been attracting increasing interests in recent years. For example, in Toshiba, Japan, die with Au bumps was thermosonic bonded to glass substrates with Al pads for LCD applications. Compared with the soldering technology, it is simpler, faster and more cost-effective. No special pad treatment or bumping process is necessary because the bumps can be formed using a regular wire bonding machine or plating on a package substrate. The bonding characteristics of gold was studied with precise control of mechanical and environmental variables [1]. It was concluded that for contaminated surfaces, plastic deformation under normal loads only (without tangential loads) is ineffective in contaminant displacement. Thermosonic bonding may be the best solution.

A typical bonding system is shown in Fig. 1. Its major elements are a power generator, piezoelectric transducer, bonding tool and substrate holder [2]. The ultrasonic waves are generated in the piezoelectric tansducer and are transmitted to the horn as longitudinal waves. Then they are converted into the cyclic shear movements of the metal bumps against the substrate.

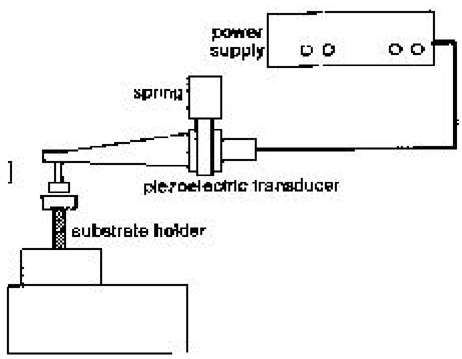


Fig. 1. Flip chip thermosonic bonder

A lot of work has been done on thermosonic bonding of gold to gold. The effect of ultrasonic power, bonding time, temperature and force was studied thoroughly [3]. The pull-off gold bumps were formed using a wire bonder with 25 μm gold wire. The resulting bumps were about 75 μm in diameter and 50 μm in height. The substrate was 1mm thick alumina, with a layer of gold produced by paste printing and co-firing. The thickness of printed gold layer was about 10μm. Reliable bonding was achieved in a wide range of conditions. The shear force was more than 10 g /bump (23 MPa) when bonding temperatures was higher than 50^{o}C, using bonding force higher than 50g / bump (115 MPa) and a bonding time longer than 1s. It was found that higher temperature (the maximum investigated temperature is 150^{o}C due to the limit of the die bonder) always produced better joints. Longer bonding time was also beneficial, but there was little advantage in increasing bonding time over 2 seconds. Higher bonding force helped to increase the contact area and improve the joint shear strength. However, too high bonding force would limit the relative motion between bump and substrate and degrade the joint shear strength.

Thermosonic bonding of gold was also investigated for microwave flip-chip applications [4], fabrication of miniaturized surface acoustic wave filters [5], assembly of vertical cavity surface emitting laser and a VLSI chip [6]. Reliable joints were produced at a bonding temperature below 200 ^{o}C, with bonding pressure ranged from 45 MPa to 136 MPa, and a bonding time less than 1 second.

High-frequency ultrasonics was utilized to improve the bondability of difficult substrates [7]. The bonding qualities were compared between the joints bonded at nominally 60 kHz and bonded at 100 kHz. There appeared to be no advantages in using 100 kHz on Al+1% metallization, while it was beneficial to apply 100 kHz on pure aluminum. In the transition from rigid to soft substrates with gold metallization, the 60 kHz system produced more consistent bonds than the 100 kHz system.

A saturated interfacial phenomena for thermosonic bonding of gold wires onto copper pad was reported [8]. Increasing the preheat temperature increased the number of metallic bonds and the energy transfer at the interface. However, excessive preheat temperature could cause damage to the weld because of excessive energy at the interface and greater oxidization. After the establishment of maximum atomic bonds, any type of further energy input would degrade the bonding.

In spite of its appealing features, application of thermosonic bonding to flip chip assembly is challenging. One of the major problems is the non-planar contact between the bump and the substrate. A small planarity angle between the bonding tool and stage can result in a non-uniform ultrasonic energy distribution. This problem might result from two sources:

1) The structural deformation of the bonding tool [9]. A transverse bonding system (Fig. 2) could bend with a large bonding force and has a planarity problem. It cannot be used for high I/O assembly. By using a longitudinal bonding system (the ultrasonic horn is mounted vertically instead of horizontally, as shown by Fig. 3), the force and vibration were transmitted to the chip along the axis of the horn and the bending deformation associated with transverse bonding system was eliminated. There was no apparent damage because the impact stress was low due to the low ultrasonic vibration amplitude.

2) The machining and assembly variations. A self-planarization concept was developed [10]. A layer of soft polymer was placed between the bonding tool and the chip to smooth the non-planar contact. Young's modulus and thickness of the polymer layer were found to be important. A polymer thickness of 350 um and Young's modulus of 2GPa were recommended. Although the polymer layer could assure a uniform ultrasonic energy distribution, it also reduced the energy transmission efficiency.

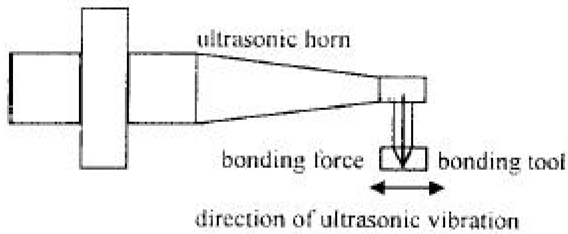


Fig. 2. Transverse bonding

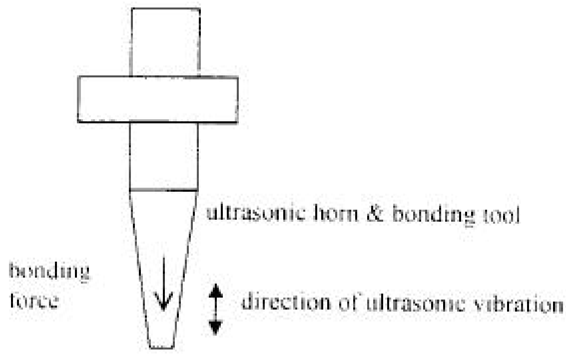


Fig. 3. longitudinal bonding

Many approaches were made to explain the physical and chemical processes during thermosonic bonding. Experimental evidence was presented against early concept of interfacial rubbing causing a high temperature rise during the bonding. It was believed the effect of ultrasonic energy was more than that of an equivalent superimposed stress and was manifested as a unique softening phenomenon at the interface [11]. The interfacial rubbing concept may arose from earlier misinterpretations based upon bonds being made with non-optimized bonding conditions. For instance, ultrasonic bonds made with low clamping force have been shown to generate excessive heat due to interfacial sliding and may indeed be thermocompression bonding.

The ultrasonic softening of metals has been studied [12]. It was found either ultrasound or heat (both under a compressive load) can independently cause equivalent deformations. However, many differences exist between the two types of excitation. For example, the energy density required to produce a given elongation in aluminum by ultrasound is about 10^7 times less than the energy density required to produce an equivalent elongation using heat. The softening effect was ascribed to the preferential absorption of acoustic energy at dislocations. This frees the dislocations from their pinned positions, allowing the metal to deform under relatively low compressive load. The flow of the softened metal under compressive load (interfacial shear) breaks up and sweeps aside the oxide and other interfacial contaminants. Bonding begins at the perimeter where flow is the greatest. As shown by the patterns (Fig. 4) of partially bonded material exposed by peeling underdeveloped bonds [13, 14], there was bonding near the periphery and no bonding in a central zone.

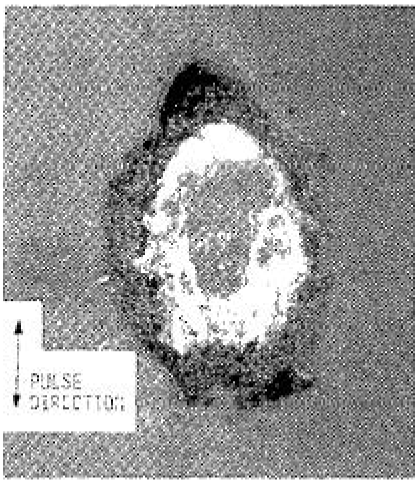
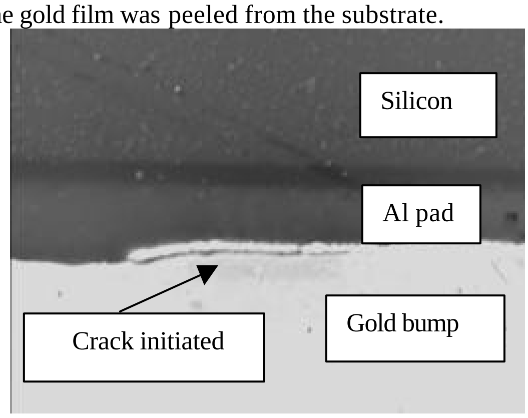


Fig. 4. Bonded region defined by aluminum (light colored region) when wire is peeled from silicon surface

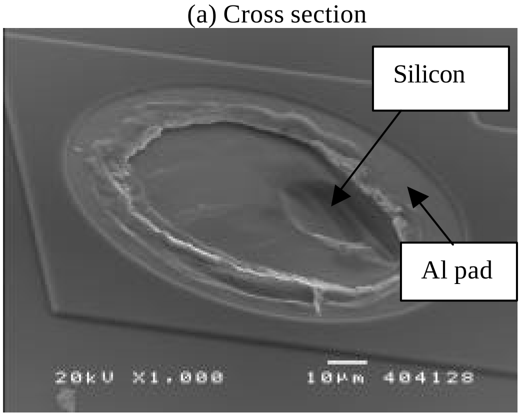
To better understand the effect of the ultrasonic energy on the bonding results, A finite element model was built to characterize the tool vibration as a function of length and mass for thermosonic flip chip bonding process [2]. It was used to estimate the energy level propagated into the bonding tool corresponding to different lengths and masses. The model can give a guideline for selecting the tool length for a better yield.

The in-situ and in-process monitoring of thermosonic bonding was reported. Ultrasonic vibrations were measured in-situ using integrated piezoresistors [15]. The wave form of such microsensor signals was investigated in terms of friction. A model of friction during thermosonic ball bonding was put forward. This model interpreted the oscillation in terms of alternate periods of sticking and sliding during bond formation. The in-situ temperature during ball bonding was measured by the integrated aluminum microsensor [16]. The microsensor signal revealed information about different phases during bonding. Bonding force optimization was feasible by analyzing the microsensor signal.

In thermosonic bonding, higher ultrasonic power does not always produce better joints. Damage due to the excessive ultrasonic energy was observed both in the bump and in substrate. As shown by Fig. 5 (a), crack was found in the root part of gold bump. Under this bonding condition, fracture initiated from the interface between gold bump and aluminum pad, and propagated into silicon chip (Fig. 5 (b)). In Fig. 6 (a), when bonded with higher ultrasonic energy output, the gold film was peeled from the substrate.

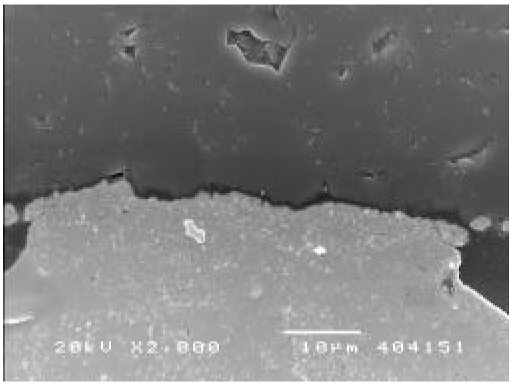


(a) Cross section

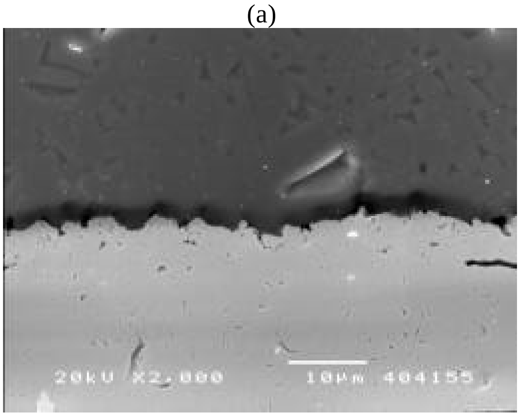


(b) Fractography

Fig. 5 Thermosonic bonding of gold to gold. Bonding pressure: 112MPa, temperature: 100^{o}C, time: 1s, ultrasonic power: 0.25W



(a)



(b)

Fig. 6 Cross section of thermosonic bonding of gold to gold

(a) Bonding pressure: 56 MPa, temperature: 100^{o}C, time: 1s, ultrasonic power: 0.25W

(b) Bonding pressure: 168 MPa, temperature: 100^{o}C, time: 1s, ultrasonic power: 0.1W

III. THERMOCOMPRESSION BONDING

Although thermosonic bonding is an attractive choice, there are distinct disadvantages. For example, it is difficult to control the ultrasonic energy tranmission. Another potential problem is silicon cratering, which result from excessive ultrasonic vibration.

In thermocompression bonding, pressure and heat are simultaneous applied. Unlike thermosonic bonding, there is no input of ultrasonic energy. Thermocompression has been a standard packaging technique in microelectronics. While several materials are bondable under modest temperature and pressure, bonding is easier to achieve in some materials than others. Gold is most preferred, not only for the oxidation and corrosion resistance, but also for the low yield point.

The times, temperatures and deformations required to achieve comparable bonding between gold plated copper leads and thin film gold were determined [17]. The results were interpreted in terms of the overcoming of an energy barrier by a thermally activated process. Increased deformation not only reduced the temperatures and times, but also reduced the apparent activation energy.

The effect of surface contamination on thermocompression bonding of gold to gold-chromium metallization was studied. The process was found to be highly temperature dependent when organic films were present [18]. UV radiation was effective in the removal of organic contaminants from gold films. For bonds where metallic bond interfaces were discontinuous, post-heat treatment resulted in their growth. A ½ hour, 150^{o}C heat treatment could significantly increase the joint strength. The kinetics of thermocompression bonding was studied for contaminated gold metallization [19]. It was found that the bonding could be divided into two stages: the first stage occurred within a fraction of a second and resulted from the mechanical disruption of barrier films by shear displacements at the faying surface. The second stage involved the growth of the metal-metal interfaces by a sintering phenomenon. Under high external loads, the rate of second stage growth exhibited little temperature dependence, indicative of a stress-assisted process.

To evaluate the contribution of plastic flow to the gold-gold thermocompression bonding, the deformation properties of gold was studied. The temperature dependence of flow stress was determined [20]. When deformed at 300 ^{o}C or above, work hardening was negligible after deformations of about 10%. Dispersion of surface contaminants and exposure of fresh metal were promoted.

The effect of the substrate structure was investigated. The thermocompression bondability of thick-film gold was compared to that of thin-film gold [21]. The thick films were either as-fired or mechanically burnished prior to bonding. The average Au films after firing was 0.48 mil with a range of 0.4 to 0.61 mil. The thin-film test vehicle was a tri-metal system Ti / Pd / Au (with nominal thickness of 200nm, 200nm, 1.3μm respectively). Although it was possible to get acceptable bonding quality for the thick-film, the bondability window was significantly smaller than that for thin-film gold. The large difference in bondability was ascribed to the more surface contaminants and rougher, less dense structure of thick films.

When larger arrays of bonds became desirable, studies on bump-lead bonds began. Experiments were performed on a 328-lead TAB (tape automated bonding) device (gold bump on 4-mil pitch) [22]. The effects of thermocompression bonding parameters on the bump-pad adhesion were experimentally determined. A consistent increase in the bump strength was observed. Pressure and duration were found to be the most significant parameters that affect bump-pad adhesion. A very large array bonding technique was also reported [23]. This technique extended Au-Au thermocompression bonding from single or tens of connections, to thousands or tens of thousands of connections over a large area in a single joining cycle. Bond yields of 99.97% for metal / polyimide thin film arrays containing nearly 60,000 contacts to pads on a 127 mm ceramic substrate was achieved. Using a semi-isostatic lamination fixture, uniform pressure and temperature distributions were applied to non-planar substrates to insure good bonding without inducing substrate damage.

Apart from the die-level thermocompression process, a wafer-level bonding of gold was described [24]. The bonding was carried under the temperature of 300 ^{o}C, with a bonding pressure of 7MPa was applied for 10 min. Surface segregation of Si on the Au surface at the bonding temperature was observed. The presence of Si at the Au bonding surface hampered the bonding. A 150 nm SiO_2 barrier layer was shown to be sufficient in preventing Si from reaching the surface. The critical strain energy release rate for the bonds ranged between 22 to 67 J / m^2 and was not shown to be strongly associated with the gold bond layer thickness in the thickness range studied (0.23 to 1.4 μm).

In thermocompression bonding used in TAB, the gold to aluminum interface is one of the most difficult bonds that can be formed because of the thin aluminum oxide layer. The usual bonding temperature is higher than 500^{o}C, which would result in the formation of various gold-aluminum intermetallics, and might lead to the failure of the joints. To reduce the bonding temperature, a laser-processed gold-plated balltape was used [25]. Such bumped tape structure could be bonded at a temperature of 350 ^{o}C. Thick plating of soft gold on balltape did not provide any advantages over the balltape with the standard thickness. For the bonding of aluminum bumps to gold plated copper beam in TAB, in order to reduce the commonly observed large deformation when using pure Al bump, bumps were fabricated by adding a small amount of an alloying element to the Al matrix [26]. The harder bumps were bonded with a less bump deformation and a higher pull strength. The bump structure is shown schematically in Fig. 7. It consists of metals evaporated sequentially: 50 nm titanium adhesion layer, 12 to 18 μm aluminum body, and followed by a capping layer of 0.5 μm Ti / 1.0 μm Cu /0.2 – 05 μm Au.

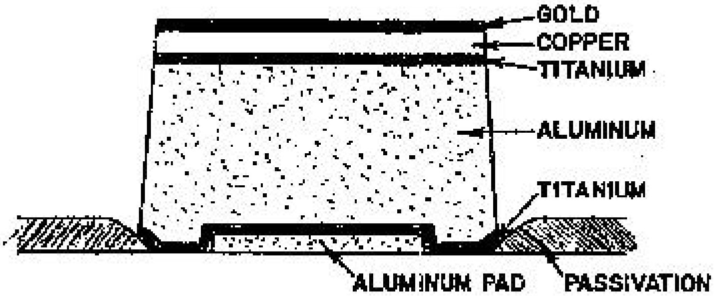


Fig. 7. Schematic of an aluminum bump structure

Based on the joint interface mechanics resulting from joint bump compression, a finite element model was created to provide predictions of bond formation [27]. This model computed distributions of stresses / strains at the interface of a joint. The evaluation criterion was defined to be the change in the differential area at the bonding interface, as shown mathematically as follows:

$$\Delta A = e_{xx} + e_{yy} \geq (e_{xx} + e_{yy})_{crit}$$

For a joint to be formed, the sum of the strains in the plane of the joint interface should be greater than some critical value (minimum required for bonding). In the case of a cylindrical joint, the radial, circumferential and total strains are plotted in Fig. 8 for a 0.2 aspect ratio bump (90 μm diameter and 18 μm high). For a critical strain value of 0.016 (determined from experimental data), the bonded zone predicted from this figure was confirmed by the SEM photograph.

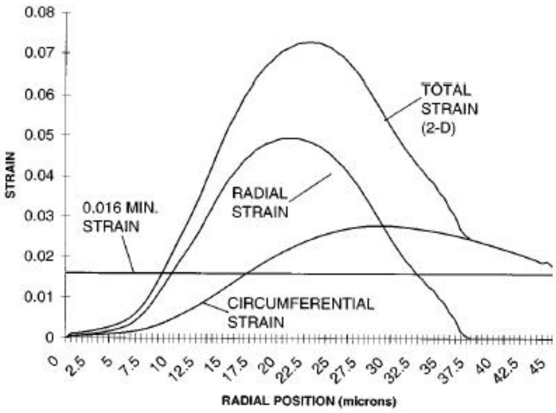
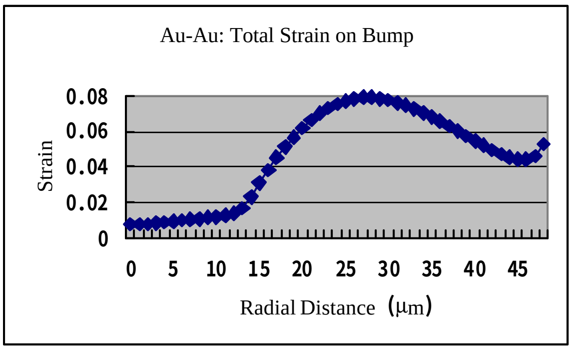


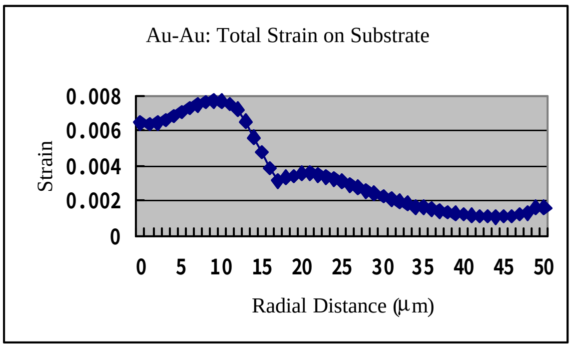
Fig. 8. Radial, circumferential and total strain for 0.2 aspect ratio bump

IV. COMPRESSION MODELING

The above model allowed for the comparison of the effects of various joint design and manufacturing process parameters on the bond joint mechanics, and the resulting probable bond joint quality. However, this model only considered the strain in bump, the strain in substrate was not taken into account. If the strain has to reach some critical to break up surface contamination and oxide layers to “activate” the bump for bonding, it should also meet the similar requirement for the substrate. For a simulated bonding of gold bump to gold pad, the strain distribution calculated by finite element method is shown in Fig. 9. The gold bump is with a diameter of 100µm and a height of 40 µm. A circular gold pad is chosen over the usual square one to maintain axisymmetry in modeling. The gold pad diameter is 200 µm, thickness is 10 µm. The distribution of strain is much different between the bump and pad. Considering the strain evaluation criterion, the unbonded region should be the central region for bump, yet the outer region for substrate. The strain value in substrate is much lower than in bump. It seems as if any part of substrate is activated for bonding, the whole bump area should also be activated. A different joint evaluation criterion has to be developed.



(a) Strain in bump



(b) Strain in substrate

Fig. 9. Strain distribution versus radial position

V. CONCLUSIONS

Direct metal bonding is of great interest for microelectronic interconnections. A lot of effort has been put on the study of the influence of bonding parameters, optimizing the bonding process and building joint quality evaluation model. Future work to realize joining at room temperature and to understand the bonding mechanism still represents a considerable challenge. There is also a need to develop appropriate mechanical testing procedures. Such procedures should take into account of the unique features of the joints and demonstrate the consistency of the joint quality.

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