THE ULTRASONIC WEDGE BONDING MECHANISM: TWO THEORIES CONVERGE

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Abstract

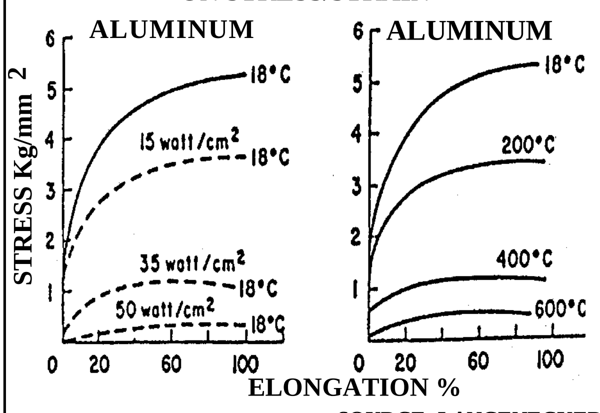
The basis for our understanding of the ultrasonic bonding mechanism was first presented by B. Langenecker[1]. This paper will explain Langenecker's contribution, with a description of the ultrasonic wirebonding mechanism based on his theory. Descriptions of the mechanisms that occur at the bonding interface will also be included. Recently a new theory has been presented by K. Otsuka that significantly adds to Langenecker's work. This paper will also cover Dr. Otsuka's contribution and describe mechanisms for both 60KHz and 120 KHz wedge bonding based on a modified theory. Dr. Otsuka emphasizes dislocation theory, the effects of strain rate on material behavior, and provides a better explanation of how new metal surfaces are exposed and where oxides and contamination are trapped. His theories explain the significant differences between wedge bonding with 60KHz and 120 KHz ultrasonics and add significantly to our understanding of the process.

Key words: wirebonding, ultrasonics, welding

THE EFFECT OF ULTRASONICS ON DEFORMATION

Figure 1 shows a graph of stress vs strain for aluminum in uniaxial tension. The righthand graph shows the effect of increasing the testing temperature on the strength. As temperature increases, less stress is required to produce equivalent deformation. Yield stress, the stress level where plastic deformation begins, and Young's Modulus, the slope of the elastic portion of the stress-strain curve, are also reduced. In the lefthand graph, increasing ultrasonic energy results in similar behavior; however, there are significant differences. Material deformed at higher temperatures recrystallizes dynamically and has an annealed grain structure. Ultrasonically deformed material is not recrystallized and has a work hardened grain structure. Low stress deformation, induced by ultrasonics, is termed ultrasonic softening.

FIGURE 1. THE EFFECT OF ULTRASONICS ON STRESS/STRAIN



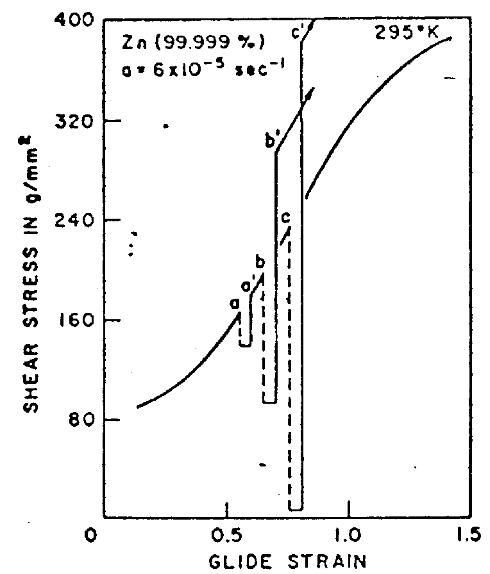
SOURCE: LANGENECKER

Langenecker states that ultrasonic energy is absorbed preferentially at dislocations (defects) in the crystal lattice increasing both the density and mobility of dislocations. The movement of dislocations within the lattice enables a material to deform.

STRAIN HARDENING AND SOFTENING

Figure 2 is a stress strain curve for zinc. When ultrasonic energy is turned on (a) and then off (a') at a low level (5 W/mm^2), the material shows the ultrasonic softening effect. When the ultrasonic amplitude is increased, as at points b and c, the material shows the ultrasonic softening. When the ultrasonic energy is turned off, as at points b' and c', the material behaves as if additional deformation had occurred, termed ultrasonic hardening. Hardness is a measure of a material's resistance to deformation. Both ultrasonic softening and hardening occur during wirebonding. Hardening of the bond pad metallization during first pass bonding often makes attempts to rework failed wirebonds unsuccessful.

FIGURE 2. ULTRASONIC STRAIN HARDENING AND SOFTENING **(SOURCE:LANGENECKER)**



SEGMENT	POWER W/mm^2	STRAIN	
		SOFTEN	HARDEN
a-a'	**5**	**YES**	**NO**
b-b'	**15**	**YES**	**YES**
c-c'	**25**	**YES**	**YES**

TEMPERATURE RISE STUDIES

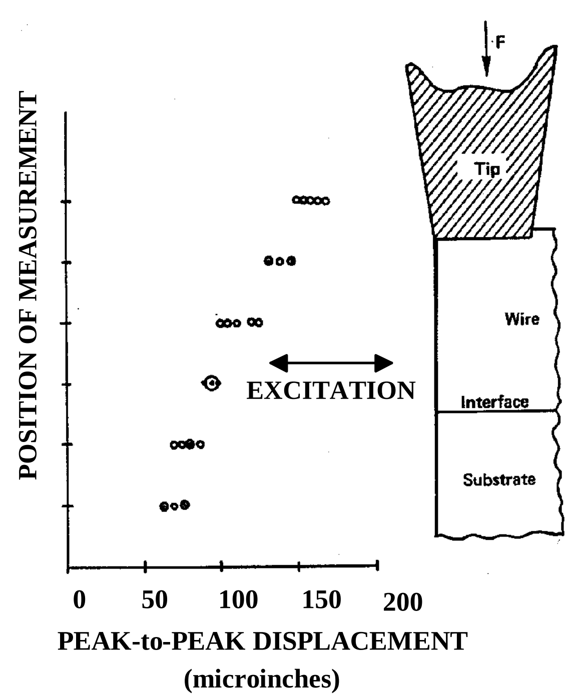
Ultrasonically-induced deformation is efficient, requiring less energy than for equivalent thermal deformation. Estimated energy density is approximately 10^7 times lower for ultrasonically than for thermally deformed aluminum[2]. Internal heating from ultrasonics is low. Joshi, bonding directly on fine wire thermocouples ground flat and plated with gold, determined that there was less than an 80^0 C temperature rise in high quality bonds[3]. In samples bonded with low clamping force (force reduced to 50% of high quality bond levels), temperature rise was greater, but it never exceeded 120^o C. The additional temperature increase in poorly clamped bonds was attributed to interfacial movement under the tool and was associated with low quality bonds.

Both Harman (Al wedge) and Joshi (Au ball bonding) have demonstrated ultrasonic bonding at liquid nitrogen temperature. Harman pointed out that no nitrogen bubbles, signifying localized hot spots, were seen and concluded that, at maximum, a 100^o C temperature rise was possible. The demonstration of high quality bonds produced at liquid nitrogen temperatures proves that high temperature, either from machine heaters or generated by the ultrasonics, is not the dominant requirement for high quality bonds. However, it does have a significant effect on the strength and quality of the weld.

INTERFACIAL MOTION STUDIES

Several researchers[2,3,4] have studied interfacial movements during bonding and have concluded that movement between the wire-to-substrate

FIGURE 3. INTERFACIAL MOVEMENT MEASUREMENTS BY LASER INTERFEROMETER (SOURCE: K. JOSHI).



interface quickly (<2mS) reaches a constant value and is continuous (not changing) across the interface. Lack of relative motion between interfaces implies that fretting, shearing, and scrubbing mechanisms are not active. Joshi, bonding on soft, epoxy substrates, found no relative motion at any of the interfaces. Harman, bonding on rigid, silicon substrates, found relative motion between the tool and the wire, but concluded that relative motion at the wire/ substrate interface was not required for bond formation. Winchell and Berg, bonding on silicon, observed groove-like patterns in the periphery of the bond. The distances between peaks and ridges of the grooves were of the same magnitude as the ultrasonic amplitude. They concluded that not only was there no relative motion between the wire and the substrate, but also that the peaks and valleys were positive evidence that no shear, fretting, or scrubbing flow had occurred. If they had, the surface would have been smooth and shear erosion of the groove peaks would have been apparent.

ULTRASONIC ENHANCEMENT OF DIFFUSION

Diffusion is the flux of atoms of one element (the solute) through another (the solvent). It is described by a set of equations, Fick's Laws. The flux is a function of four variables that control the process. Figure 4 lists the variables and the effect of each on the diffusion rate[5]. A trend is positive when increasing the variable results in a larger response. Increasing ultrasonic energy enhances diffusion[6]. Faster diffusion results in better intermetallic phase formation and stronger bonds.

FIGURE 4. DIFFUSION VARIABLES

VARIABLE	RESPONSE TREND
CONCENTRATION	POSITIVE
TIME	POSITIVE
TEMPERATURE	POSITIVE
LATTICE VIBRATION FREQUENCY	POSITIVE

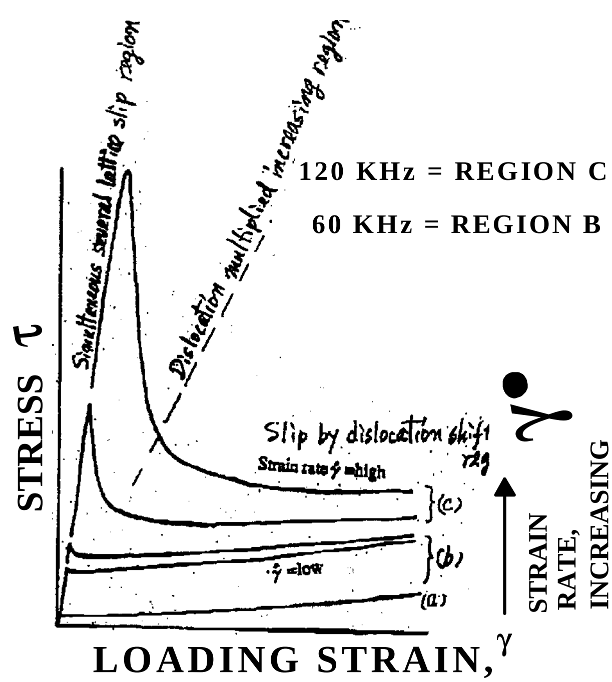
SUMMARY OF THE BONDING MECHANISM AFTER LANGENECKER

Figure 5 summarizes a theory of ultrasonic bonding after Langenecker. Ultrasonic energy lowers the yield strength of the wire or ball, resulting in a large deformation from a minimum bond force. As deformation occurs, the oxide layer fractures and is swept aside. The newly-exposed metal surfaces, in contact from the deformation, form ultrasonically-enhanced diffusion bonds. As time and temperature are increased, additional diffusion results in phase changes, from the lower gold content phases to the phases with higher gold concentrations.

FIGURE 5. BONDING THEORY SUMMARY (AFTER LANGENECKER)

- Ultrasonic energy causes a reduction in yield strength and increases the mobility and density of dislocations. Easy slip mechanisms occur within the lattice.
- Bond force is required to yield and deform the wire.
- Plastic flow at the wire-pad interface breaks the brittle oxide layer and sweeps aside the oxide, exposing new metal surfaces.
- Contact and diffusion at the new metal surfaces result in bond formation.

FIGURE 6. THE EFFECT OF STRAIN RATE (SOURCE: K. OTSUKA)



DISLOCATION THEORY

Dislocations are point defects within the crystal lattice. The movement and density of dislocations are the basis of theories explaining the mechanisms for metallic deformation. The movement of dislocations allows atomic planes to slip over each other when a load is applied, causing deformation. The rate of loading (strain rate) has a significant effect on the onset of deformation (yield strength). At high strain rates, the yield strength may be many times higher than at low strain rates.

Ultrasonic loads are applied at a very high strain rate (at 60 KHz the load is applied in 1.7×10^{-5} sec). Figure 6[7] is a stress strain curve showing the effects of very high strain rates. At these rates (region C), deformation occurs with entire lattice planes slipping simultaneously. At lower strain rates (regions A and B), deformation occurs by individual defect movement. In Figure 6, the high strain rate attributable to 120KHz bonding puts the deformation in the "Dislocation multiplied increasing region (C)". In contrast, 60 KHz bonding occurs in the B, or "Slip by dislocation shifting region".

Figure 7 describes the stages of bonding. At 60 KHz, the material initially is softened. As deformation occurs, the material hardens and energy is transmitted through the wire into the wire/bond pad interface. At 120KHz, the soft wire initially behaves like a harder material because of the high strain rate. Whole planes in the lattice shift simultaneously. Energy is transmitted directly to the wire/bond pad interface, with very little deformation. For wedge bonding applications, it has been well documented that bonds produced with high frequency (120 KHz) ultrasonics develop full strength with less deformation than is required to produce equivalent bonds with normal (60 KHz) ultrasonics. The equivalent data for ball bonding applications is still unclear.

Dr. Otsuka has predicted that 120KHz bonding will provide the best bonding for COB, flex circuit, DUROID, and soft substrate applications.

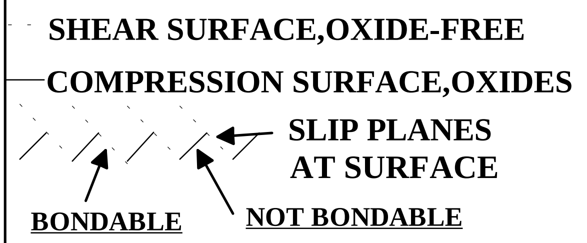
FIG 7. STAGES OF BONDING

STAGE	60 KHz	120KHZ
0	DEFORMATION RESULTING IN STRAIN HARDENING	HIGH STRAIN RATE HARDENING WITH SLIGHT DEFORMATION
1	SLIP	
2	COUPLE FORMATION WITH ULTRASONIC ENHANCED DIFFUSION	
3	BOND AREA INCREASE	

SLIP SURFACES

As deformation proceeds, slip planes intersect the opposing material surface. At the surface, a new area, free of oxides and contamination, is exposed. Figure 8 shows this process. Oxides remain on the old compression surface. New metal is exposed on the shear surface. When new metal surfaces are in contact, diffusion bonding takes place. Ultrasonics enhances the speed of diffusion bonding.

Figure 8 SLIP BOUNDARIES



SUMMARY OF THE BONDING MECHANISM AFTER OTSUKA

Figure 9 summarizes a theory of ultrasonic bonding after Otsuka. For 60 KHz bonding, the ultrasonic energy lowers the yield strength of the wire or ball, resulting in a large deformation from a minimum bond force. Deformation allows both of the opposing interfacial surfaces to mate. As deformation occurs, the material strain hardens. The mated surfaces of the hardened material slip, generating new oxide and contamination-free surface areas. Oxides and contamination are trapped on the old compression surfaces. The newly-exposed shear surfaces, in contact from the deformation, form ultrasonically-enhanced diffusion bonds. For gold ball or wedge bonding, as time and temperature are increased, additional diffusion results in phase changes, from the lower gold content phases to the phases with higher gold concentrations.

For 120 KHz bonding the mechanism is similar except that the strain rate is so high that the material is initially strain rate hardened. The hardened material efficiently transfers energy across the wire-bond pad interface. Very little initial deformation

Figure 9. THEORY SUMMARY
(AFTER OTSUKA)

FOR 60 KHz BONDING

- **Ultrasonic softening occurs as in Langenecker . The strain rate is in the "slip by dislocation shifting region". As deformation occurs, the material strain hardens. When the hardened material transmits energy to the wire-pad interface, slip planes shift at the interface, opening up new metal surfaces. Diffusion bonding, enhanced by ultrasonics, occurs at the newly exposed metal surfaces.**

FOR 120 KHz BONDING

- **The strain rate is in the "simultaneous several lattice slip" region. The material behaves as a hard material transmitting energy to the wire-pad interface. Slip planes shift at the interface, opening up new metal surfaces. Diffusion bonding, enhanced by ultrasonics, occurs at the newly exposed metal surfaces.**

is required to mate the surfaces and cause them to slip. Once the mated surfaces have slipped the diffusion bonding mechanism is the same as at 60 KHz.

CONCLUSION

The theories of Otsuka and Langenecker are consistent with each other and with accepted metallurgical theories. Together they explain the mechanism for ultrasonically enhanced bonding. As our experience with high frequency bonding grows, we will see confirmation of Dr. Otsuka's theories regarding soft substrates, hard and soft wires, and lower temperature bonding.

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