1. Literature survey: Ultrasonic welding

1.1. Welding process

Ultrasonic welding (UW) is a 'solid-state' welding process that can be used to join similar or dissimilar materials, by applying high frequency vibration and normal pressure to the weld interface. In this thesis, the focus will mainly be on joining of dissimilar materials more specifically on joining copper to aluminium. The major advantage of this method is the low heat input at the weld interface. Because of the cold welding technique, UW can be used to join thin foils to thick sheets and the properties related to the heat at the weld interface are less significant. So welds such as aluminium to copper, aluminium to steel, etc. can be made. [2]

This joining process has some variations based on the type of weld produced. These are spot, ring, line and continuous seam welding. In this thesis, spot welding will be used. Typical components of an ultrasonic welding system are given in Figure 1.1.

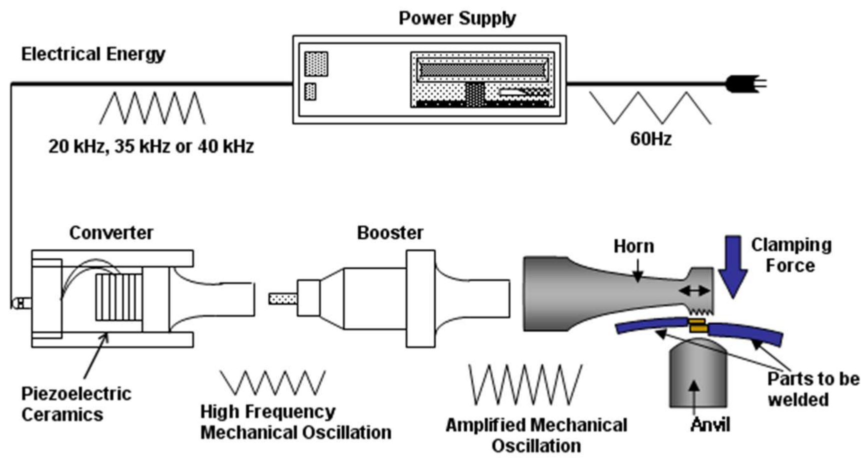


Figure 1.1: frequency transformation UW [10]

The ultrasonic welding equipment consists of a power supply, converter, booster, coupling, sonotrode, welding tip and anvil.

First of all, the user provides the correct clamp force to clamp the sheets together between the sonotrode tip and the anvil. This force is perpendicular to the weld interface. After the clamp force has been set, the power supply provides the conversion of the net frequency (50-60 Hz) into high frequency (20-40 kHz) that is needed for the welding process. The piezoelectric ceramics of the converter, mostly made of lead zirconate titanate, use that voltage with high frequency to make high frequent mechanical displacements, the ultrasonic vibration. A next step in the process is to change the amplitude of the vibration. This is done by the booster. From there on, as a result of the coupling system, the vibrations will be transferred to the sonotrode.

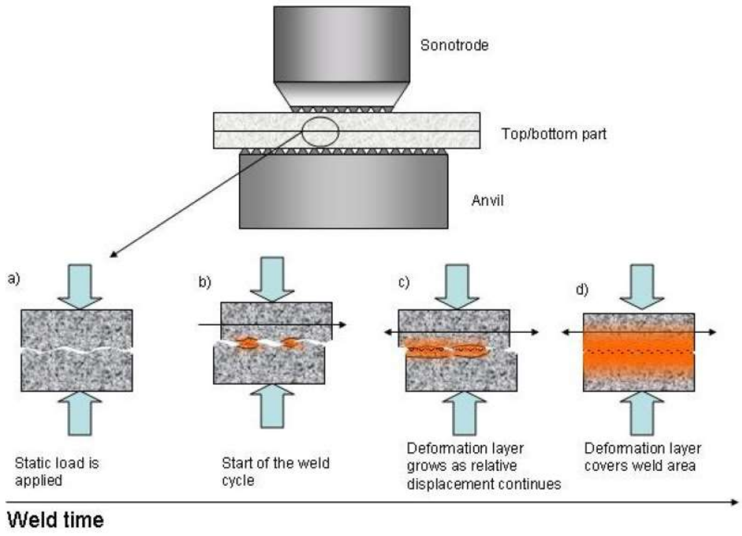


Figure 1.2: weld development at the interface [13]

When the ultrasonic vibration arrived at the tip of the sonotrode (the component that directly contacts the upper sheet), the texture of it will grip the upper sheet with the help of the clamping force (as can be seen in Figure 1.2). Because of that, the sonotrode and the upper sheet will vibrate with the same phase and amplitude. If not, the sonotrode will be welded to the upper sheet. As a result of the vibration of the upper sheet with respect to the bottom sheet (which is fixed), slippage occurs. As a result of this friction, the oxides and contaminants layer will be dispersed and brings about metal to metal contact. Then they become plastic so the upper sheet can bind with the bottom sheet. [2]

The components that are mentioned above are similar for all UW systems. Yet, as said earlier, there is a variety of UW processes: spot, seam and torsion welding. In this thesis, the focus will be on ultrasonic spot welding. The most used systems for ultrasonic spot welding are the lateral-drive and the wedge-reed ultrasonic welding systems. They are illustrated in Figure 1.3.

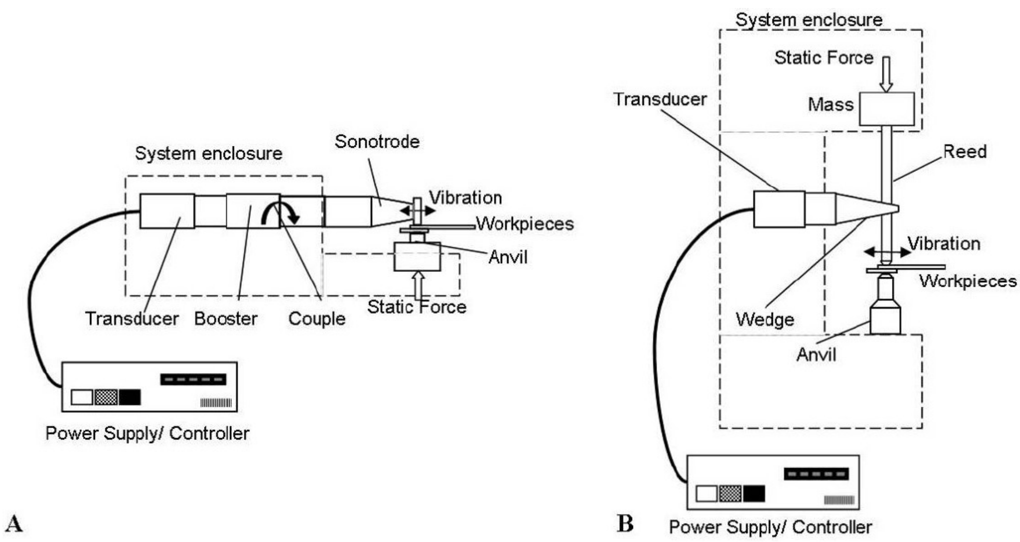


Figure 1.3: lateral drive (A) and wedge reed (B) ultrasonic spot welding systems [4]

Lateral-drive ultrasonic spot welding is a system which uses a lateral sonotrode. The clamping force will be created by a bending moment applied to the sonotrode or because of the anvil that can move up and down. Due to the clamping force and the ultrasonic vibration at the sonotrode tip, the sheets can be welded together as earlier mentioned. This system is illustrated in Figure 1.3A.

The other system, wedge-reed ultrasonic spot welding, is very similar. The difference here is that the ultrasonic vibrations will be firstly transferred through a wedge and a reed, before reaching the sonotrode tip. In this process, the clamping force can be applied in two different ways. When the reed can move, it's done with a force at the top of the reed. Otherwise, the anvil will move up and down to produce the clamping force. Finally, the usual UW bending method is being used. [4]

The geometry of the sonotrode is of importance on the weld shape and quality. As you can see in Figure 1.4 any application can have different sonotrode shapes, dimensions and texture to grip sheets. For example line welds need narrow, elongated shapes, ring welds have circular, elliptical, square shapes and continuous seam welds use resonant disks. Many sonotrodes have more than one side which they can use to weld. It is obvious that the 'teeth' of the sonotrode are very important for the accuracy of the welding cyclus. In this thesis spot welds were made.

Figure 1.4: different sonotrodes/shapes [11]

Another important part of the UW system is the anvil. The anvil has the important function to fix the bottom sheet, so this sheet can't move while welding. The contact surface of such an anvil is most of the time flat. As a result, the bottom sheet doesn't have damage when clamping force is applied. A flat anvil has one disadvantage, slip can occur between anvil and bottom sheet which can cause a weld between these two surfaces. So when this happens, an anvil with serrated surface can be used. [2]

There have already been several studies on welding sheets with UW. The material combinations found in the literature are mentioned in Table 1.1. The different parameters are the sheet thickness, the power range of the system, the pressure force, the welding time and the vibration amplitude. Also the numbers of publications in the bibliography are mentioned.

Material combination	Thickness (mm)	Power range of machine (kW)	Static pressure (MPa)	Welding time (s)	Vibration amplitude (µm)	Source Nr.
Al-Al	0,01 - 2,5	2-3	0,14-0,20 tot 60	0,005-2	10-100	[3],[4],[6],[10],[11]
Al-Cu	Al 1 Cu 1	3	0,5	0,1-1	12	[4],[18],[19]
Al-Stainless steel	Al 0,3 SS 0,05	2,4	0,2-0,4	0,1-0,5	30-60	[5]
Al-Mg	1	2,5	≈35	0,3-1	10	[7],[12]
Mg-Mg	2	2	0,414	<0,5	30-60	[9]
Cu-Cu	0,2	2,5	0,2-0,3	2-2,5	40-50	[8],[13]
Al-Zn	Al 0,05 Zn 0,25	3		1	10	[14]

Table 1.1: investigated material combinations UW

Besides a specific material combination can be welded, it's important that every parameter will be chosen correctly. This ensures the best weld quality. The important parameters of UW are the welding time, the pressure force and the thickness of the upper sheet. These parameters will be used in the DOE-study, so a certain set of parameters ensures that the weld has the best possible weld quality.

1.2. Parameters

1.2.1. Welding time

The welding time of UW processes is very short. It is in the range of several milliseconds to a few seconds. This parameter is important, because overdone welding time ensures the sonotrode penetrate deep into the material and this will damage or even cause expulsion of the material at the weld interface (as can be seen on Figure 1.8). On the other hand, too short welding time may cause that there were unbounded places so the weld line is only partially bonded. Which has a high influence on the weld strength.

The weld time is also related to the power and welding energy as can be seen in the relation below. When a specified energy is needed by a given maximum power, the control system changes the weld time in order to meet this energy. If the energy level is reached, the cycle is completed. So the time can been determined by the power and energy level, given by the relation:

$$E = P \times t \quad [7]$$

With:

E : energy [J]

P : power [W]

t : time [s]

1.2.2. Vibration amplitude

The vibration amplitude is of big importance. This parameter is related to the system's power as well as the gain provided by the booster/sonotrode. In some systems, the vibration amplitude can be changed by the user. Other, similarly the machine of this thesis, have a permanently set amplitude.

The amplitude varies by system, because of the design and different energy settings. Nevertheless, the vibration amplitude has typical values between 10 – 100 micron. Although micron doesn't sound much, there will be a huge amount of stress. Because the sonotrode vibrates at a very high frequency (≈20 000 Hz) for a second. [3],[7]

1.2.3. Frequency

Most of the time, an ultrasonic welding machine has a nominal frequency. In almost all the cases, the frequency is around 20 kHz. However, it is possible to have a UW system which has a frequency somewhere between 15 and 75 kHz.

In UW, the frequency converter output must constantly match with the operating frequency of the welding system. So, adjustment of the frequency converter output is necessary to have a good performance and is automatically done. Imagine, there will still be a deviation of a few hundred Hertz, the vibration amplification will be eliminated and because of that the amplitude at the sonotrode will reduce significantly. [2],[13]

1.2.4. Clamping force

The clamping force on the welding tip results in the static pressure applied at the weld interface. The function of the clamping force is to clamp the two worksheets together, between the sonotrode and the anvil. The size of this clamping force can be different and in almost all the applications, it's a parameter that is set by the user.

The need of a well-set clamping force is important. Because from other thesis', too high clamping force ensure surface deformation. But insufficient clamping force can create tip slippage which causes surface damage and heating.

By UW it's important to have a sufficient welded area. Because of that, research to the relation between the energy density (welding pressure divided by the pressurization area) and the rate of welded area with different parameters are being carried out (corresponds to the welding pressure and required duration). The results of A1050-H24 (0,3 mm)/A5052 can be seen in Figure 1.5. The legend shows the true joint of the pressurization area. As can be seen on the figure, when the energy density (required duration) increases, a smaller welding pressure is needed for a sufficient area. But pay attention, when the values of the two parameters are too big, the welded sheets will break or have cracks and hence will be a defective product. So the perfect combination is needed to have a good welding rate/area. [15]

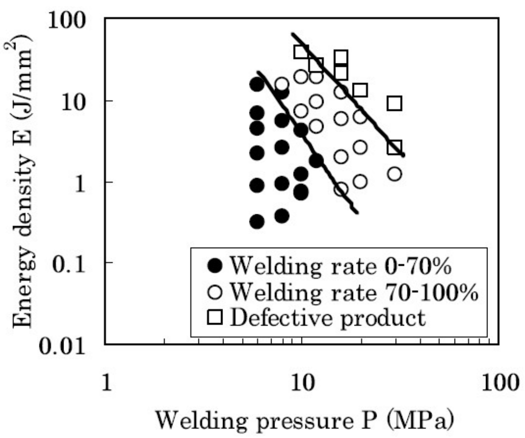


Figure 1.5: relation between energy density E and welding pressure P [15]

In conclusion, the welding pressure and energy density have a big influence on the welded strength. As a result, a relation was introduced:

$$E = KP^n \quad [6],[15]$$

With:

E_d : energy density [J/mm²]

P_r : welding pressure [MPa]

K,n: material bonded coefficients

1.2.5. **Sheet thickness**

For UW, there are some limitations on the thickness of the sheet that is in contact with the welding tip of the sonotrode. The limitation depends on the delivered power of the machine, the tool geometry and the material that is used. The bottom plate has not really a limit, because it's stuck on the anvil.

The limited thickness is obviously not the same for all the materials, as a result of the different material properties. In Figure 1.6 can be seen which thickness of a particular type of material can be welded with a specific machine power.

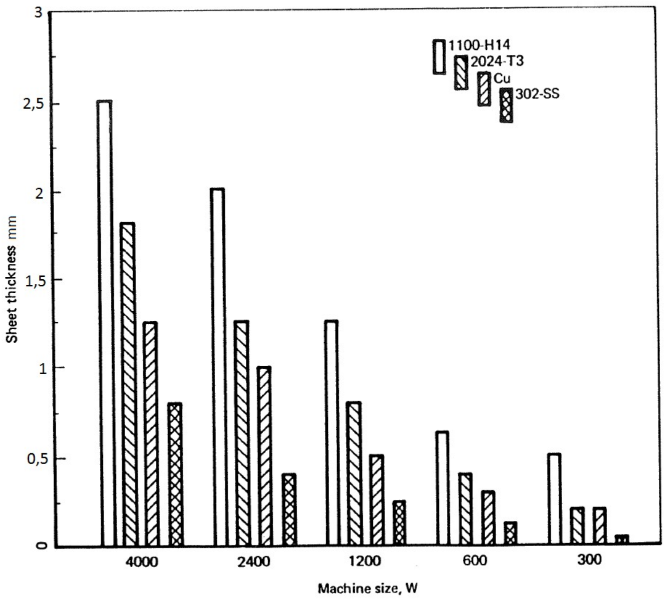


Figure 1.6: relation between the sheet thickness and the power of the machine [2]

1.3. Material combinations

Before the experiments can start, information concerning the current knowledge of the material combination was searched. In this thesis, the combination Aluminium to copper will be examined. Previous researchers have already examined which combinations are possible to weld. The results are shown in Figure 1.7. The combinations which are indicated with black dots have been welded in the past, and the combinations with blank spaces are either not weldable or not tried. As indicated in yellow on the image, the combination Al-Cu has been welded with success.

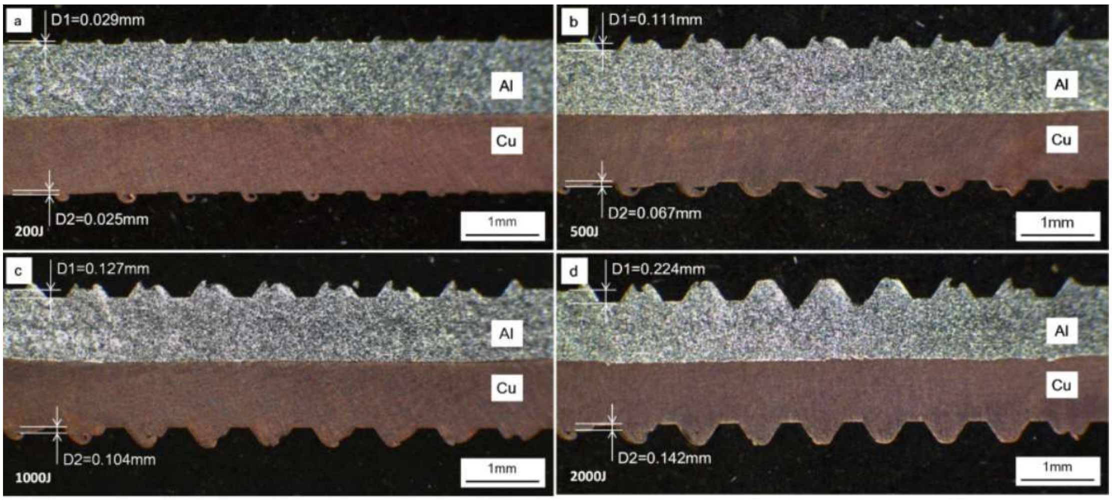
	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be Alloys		●	●			●										●		
Cu Alloys			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						●		●	●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo Alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		●	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

Figure 1.7: possible material combinations UW [2]

1.3.1. **Aluminium-Copper**

Joining dissimilar materials such as aluminium-copper is attaining increasing importance for some application. Because of that, new welding techniques are being tested to weld these combinations. UW is one of those processes. Results of previous researchers showed that welding aluminium to copper is possible to weld with good mechanical and electrical properties. Y.Y. Zhao et al. show in their paper 'Effect of welding energy on interface zone of Al-Cu ultrasonic welded joint' [18] that it's possible to weld aluminium to copper. Before some of their experiments will be explained, it's important to know that the welding energy, which they have used, from 200 to 2000 J corresponds to welding time from 0,1 to 1,0 s.

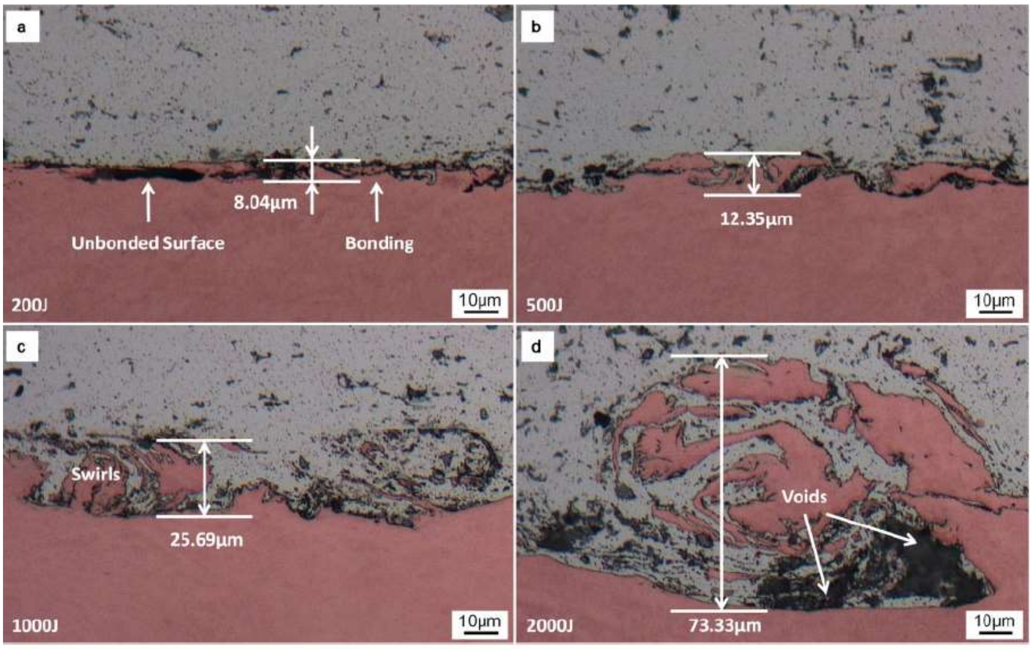
In Figure 1.8, cross-sections of Al-Cu weld produced under different welding energies are shown. In this image, the penetration of the sonotrode is visible and results in a serrated external features. It is obvious that welds with larger energy (2000 J) have a deeper weld indentation than the ones with smaller energy (200 J). Good indentation ensures better gripping can take place and therefore more friction will occur. But on the other hand, larger energies would lead to thinning of the sheets but also expulsion, which is not good for the strenght of the weld. Another thing that stands out in this figure, the join line remains flat macroscopically. A better look of this line is presented in Figure 1.9, the microscopic examination.



a 200 J; ***b*** 500 J; ***c*** 1000 J; ***d*** 2000 J

Figure 1.8: macroscopic images of the cross-sections of Al-Cu weld produced with different welding energies [18]

Figure 1.9 illustrates the plastic deformaton at the weld interface. Here, Y. Y. Zhao et al. observed a wavy-like pattern because of the friction and sliding. At 200 J welding energy (Figure 1.9a), they found that the plastic deformation is small (8,04 μm) and there are unbonded surfaces. So they experienced that the plastic deformation is not strong enough and the weld line is only partially bonded. At higher welding energy, they have observed a swirl-like structure and the intermetallic layer is much bigger. These swirls would lead to higher joint strength and quality. When the welding energy becomes higher and higher, the swirls become bigger but they will be accompanied with a lot of voids. Their presence will reduce the joint strenght and ductility.



a 200 J; *b* 500 J; *c* 1000 J; *d* 2000 J

Figure 1.9: microscopic images of the cross-sections of Al-Cu weld produced with different welding energies [18]

Figure 1.10 shows a SEM to detect the intermetallic compounds (IMC). At the yellow line, a linescanning EDS was taken. This EDS is displayed in Figure 1.10. A smooth and continuous line of atomic content from 0 to 100%. This means they haven't found a stable IMC. The cause of the continuous line can be attributed to the fast welding method and lower temperatures compared with other techniques. This explains the higher joint strength of ultrasonic welded sheets.

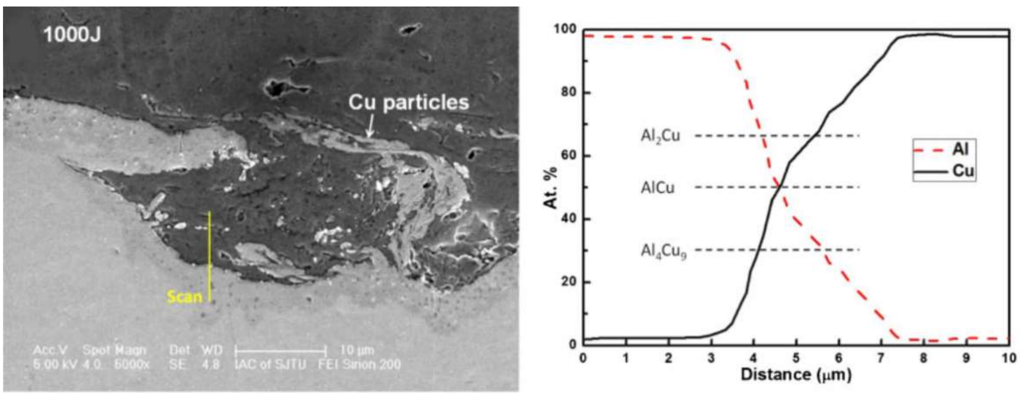


Figure 1.10: SEM and EDS [18]

Regarding the tensile shear strength, the welding energy/welding time have an important effect. As can be seen in Figure 1.12, the failure load increases until 1000 J and reached its maximum that is corresponding to a strength of about 3,3 kN. But after that, when the weld energy/time increase a rapid decline is observed.

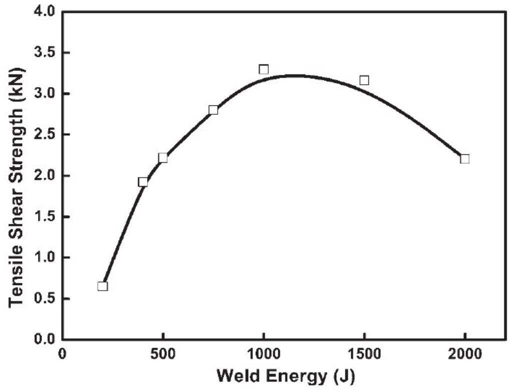


Figure 1.12: relation of tensile shear strength and weld energy [18]

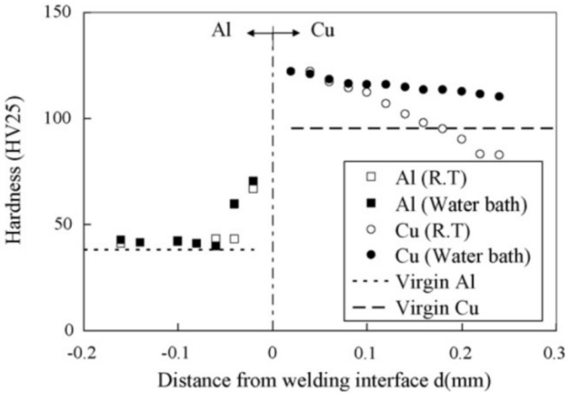


Figure 1.11: the hardness at the weld interface [6]

S. Matsuoka et al. also succeeded in combining Al with Cu [6]. Figure 1.11 shows the hardness of the welding interface. This figure clearly confirms that the hardness of both the materials Al/Cu is increased at the weld interface. The main cause of the strain hardening at the weld interface is owing to the crystals becoming fine after welding. Further away from the weld interface, the hardness is lowered because of the annealing effect. This effect is due to the temperature increases inside the welded material that ensures recrystallization.

In addition, R. Balasundaram et al. have researched the effect of a zinc interlayer between the Al and Cu [19]. Out of their experiments, they concluded Al-Cu joints with Zn interlayer had larger lap shear tensile strengths and fracture energy than those without Zn. This because the joints with Zn interlayer created an Al-Zn eutectic film and IMC's of $CuZn_5$.

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