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Improving the quality management of the thermosonic welding process of gold wires in automotive industry

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Abstract

This scientific paper conducts a study meant to improve the quality management of the thermosonic welding process of gold wires in the automotive industry. Within the large amount of electronic products manufactured worldwide, the gold wire bonding is the preferred technology for creating the needed interconnections in the microelectronic industry. In this paper, the quality management improving starts with an experimental research in the automotive industry, based on the gold wire thermosonic bonding, in terms of: conformal structuring, robustness and integrity of the electrical contacts. The experimental research is based on the processing parameters and on the independent variables and objective processing functions. In order to highlight the impact which one or more factors have on the quality of the thermosonic bonding, the dispersion analysis method was used. According to this, the importance of each factor, but also each factor's optimization, was underlined. The final goal was to reach a high reliability and quality of the finished goods.

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Keywords: quality management, optimization, thermosonic bonding, gold, wire, automotive, ball – wedge, reliability

1. Introduction

The competitive advantage gained through quality by Japanese companies becomes considerable, being further consolidated and amplified by its own dynamics. Revolutionizing production systems, by introducing microelectronics and informatics on a large scale, making flexible manufacturing systems, using high technologies,

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have made it possible to produce more and more complex products. In order to control the complex processes, a new approach is needed, quite different from simple processes. Integrated Computer Manufacturing (CIM) systems have been developed, in which an imported subsystem is the (CAQ) Computer Aided Quality (Ţîţu & Oprean, 2006).

Experimental research is a component of quality assurance and management. Juran (Juran & Gryna, 1973), defines the quality management functions in terms of a "quality trilogy". In his opinion, the quality management comprises three main management processes: quality planning, quality control and quality improvement. In his view, the planning is aimed primarily to develop the products and processes according to the customers' requirements. The quality control means to provide a minimum variation range reported to its relative prescribed level. In this purpose, the values of the measured quality characteristics with the standards specifications are compared, establishing in this way the necessary corrective measures on the entire production flow. In the Juran "trilogy" the quality improvement function is considered the most important. The appropriate processes that this function ensure, are, in Juran's view, the problems elimination that cause the "chronic" quality problems. On the other hand, by improving the quality, the aim is to achieve a higher performance levels required in standards. Therefore, the challenge to be considered, is to provide a higher quality level as against the planned level (Ţîţu, Oprean & Boroiu, 2011).

In this paper a study with a high relevance and a high interest is presented. This study wants to improve the quality management of the thermosonic welding process of gold wires in automotive industry.

The most common methods of classical statistical analysis of data measurement are dispersion analysis and regression analysis (Nicolescu, 2000).

The basic idea of dispersion analysis derives from a dispersion theorem. If it is estimated that a range of measurements will be dispersed over an objective function in two different ways, namely, taking into account the factor (s) influence and that influence removal, and then, comparing the two dispersions, information of the analyzed factor influence exerted on the objective function, can be obtained. The influence factors can be qualitative or quantitative in the field of research located on different levels (Ţîţu, Oprean & Boroiu, 2011)..

Effectively, the dispersion analysis (Prasad, 2004) will be used because in many problems two or more variables appear to be dependent one to each other, and some of the most important objectives of experimental research are to model and analyze the relationship between these variables.

Therefore, in the first part of the paper, a few aspects about the thermosonic gold wire bonding process will be presented and then the dispersion analysis will be applied to optimize this process. The automotive industry evolution is related to the different innovations: in the field of fuels, auto subassemblies and manufacturing methods (Oprean & Suciu, 2003), (Oprean & Țîțu, 2008). The microelectronics used in the auto applications helps the integration of more functions in smaller scale devices, meaning we will get a reduced weight, a more accurate handling, and an increased lifetime of the auto vehicles. Larger organizations have developed the necessary microelectronic technology for the interconnections. The gold became the preferred material for this manufacturing method. Nowadays, there are about 60 billion devices produced yearly, and more than 90% are interconnected by means of using gold wires, bonded between 2 points (chip and IC), in order to ensure the electrical connection. Thus, the unique benefits combination of Gold is including an astonishing resistance to corrosion, ductility, electrical and thermal conductivity. In our daily automotive microelectronics applications, the main focus is on the ability of Gold to withstand the harsh conditions of the environment. Numerous researches, with different approaches, have been conducted in the field of the thermosonic gold wire bonding: Gold behavior in the electronics, new manufacturing methods, comparisons between Gold and other metals, connection support materials, cost efficiency, each parameter influence on the lifetime. As stated before, we are driving an approach towards the thermosonic bonding for the automotive industry. Knowing that the reliability of an auto vehicle is closely linked to the electrical interconnections, it was concluded that by determining the influence of the most important factors and the optimum correlation of that influence we can get the optimum welding resistance and by this the highest product quality. The experimental research was put to practice by means of the dispersion analysis (Ţîţu & Oprean, 2006), (Harman, 1989). The goal is the quality management improvement of the thermosonic gold wire bonding process.

2. THERMOSONIC GOLD WIRE BONDING

Nowadays, the thermosonic welding of gold wire can be counted in the ranks of the dominate technologies for interconnecting due to its reputation for multilateralism, performance and reliability. The manufacturing technology dictates the environment and, this is the reason why the thermosonic gold wire bonding technology is being used in a clean room based on the 1000 or 100 class, in order to reach a high quality and consistency for the material properties. Nevertheless, the material has to fulfill a high purity (99.999% - pure metal 5N), due to the fact that even in a reduced quantity, the impurities will cause a change in the mechanical properties of the material. There is no doubt that the wire welding has brought a significant reduction in terms of device integration, becoming a choice for most of the electronic device manufacturing industries. The sizes of the connection supports (chip & IC) have diminished from 101.6 (4 mils) to 63.5 µm (2.5 mils). The thermosonic bonding process needs ultrasonic energy, high temperature, bonding time and bonding force. This is presented in Fig. 1.

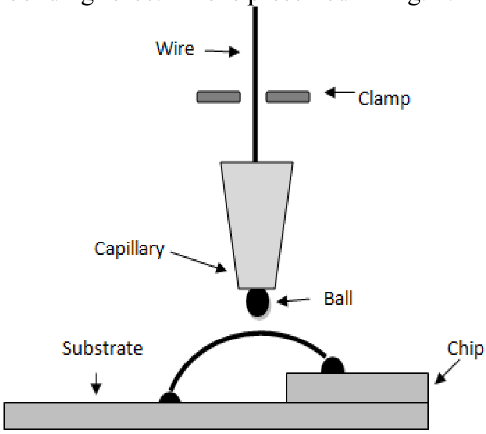

Fig. 1. Gold Wire Bonding. Overview.

2.1. Detailed description of the ball – wedge thermosonic bonding process:

Wire feeding: the process flow starts with the feeding of the wire into the capillary. The wire is being fed through the capillary, and a certain amount of the wire extends from the top of this capillary, determining the height of the ball which is formed in the air.

EFO (Electronic Flame Off) electrode: is acting with a high voltage, melting the wire and transforming it into a ball. The amount of electrical current and the distance between the wire and the electrode are defining the dimension and form of the ball. The negative EFO electrode is the most used for the welding equipment. The charges vary between 1500 and 6000 Volts, these are being controlled for a fixed amount by this ensuring the dimension of the ball. The benefits of the negative EFO electrode are: a better forming of the gold ball and a protection of the capillary against carbon releases.

Capillary ball positioning: The EFO electrode is retracting into its initial position. The clamps which are holding the wire are being opened. After this, the holding element of the tensioned wire is bringing a force for placing and centering the ball. This alignment is based on the capillary conical construction. This phenomenon happens after the execution of the welding, at each wire end.

First welding execution: the capillary is heading towards the first welding position, the surface of the substrate. Afterwards it is pressing the ball against the heated substrate. Also, there is an amount of ultrasonic energy applied for a certain period of time. During this procedure, a contact between the gold ball and the substrate is being formed. This connection is the so called “bump”.

Performing the second welding: the capillary is heading towards the component surface. The ball, formed during the approach is pressed on the surface, with the same combination of force, ultrasonic energy, temperature and time, thus, a contact between the gold ball and the component surface being realized.

Loop height execution: from the attached ball the wire loop execution is starting the capillary ascends at the loop height level. During this movement, the required wire length is precisely measured and it is kept for all the wires. At the moment when the wire is creating the requested loop, the clamps are closed in order to avoid the feeding of extra wire. The clamping mechanism is offering an accurate control and helps in the determination of the wire trajectory during the welding process. The gap between the wire and the clamps, and the force which is applied by the clamps on the wire, when these are being closed, are influencing the loop trajectory.

Forming the loop: during the movement of the wire, the precise parameter algorithms for wire ascension and its descent, until it is pressing in the bump, are being controlled. After the wire is being crushed in the bump the so called wedge is created. The loops have to be consistent in height and linearity in order to avoid interferences with the other neighbor wires. Also the wire loops need to be adapted to each device, thus eliminating the short circuit danger, before encapsulation.

The capillary is raised, and the cycle is restarted until the interconnection is realized.

The main advantages of this process are: reduced cycle times, high grade of automation possibility, high reliability due to the high temperature and maximum efficiency. Among its disadvantages we can count the sensitivity to contaminants and the large amount of parameters.

The human factor is playing an important role in the quality control of the wires/ bonding, due to this being still necessary (Țîțu, Oprean & Boroiu, 2011). The wire welding process is the most important in the semiconductor assembly flow. The efficiency of the process depends on the materials and the equipment but also on the operator's know-how level. The capability of the process is determined by its efficiency, the welding quality and the interconnection reliability. A high variable number plays an important role, influencing the welding process: welding parameters, component pad metallization layer, substrate metallization, wire material, bond tool and, the last but not least, the operator's know-how.

2.2. The parameters

The parameters are the settings, which an engineer develops on the equipment for each device, having in mind the devices, components and substrate dimensions. The most important parameters, which control the bonding process, are: the pressing force, the time, the ultrasonic energy and the temperature. These controlled factors lead to response factors in terms of bonding and wire resistance (Shear & Pull).

The ultrasonic energy - In order to get a real understanding of the impact of ultrasonic energy in the welding process, there must be an understanding regarding the troubles which this energy type brings. The ultrasonic energy is an electrical energy conversion result, by means of using a piezo – ceramic transducer. This transducer is manufactured from various elements and is designed to transfer the ultrasonic energy towards the welding surface with maximum efficiency. The transducer is one of the most critical subassembly from a bonding equipment.

The bonding force which is applied during the process is the intensity with which the ball is pressed on the metallic surface. It is ranging between 35 – 55 grams and has to be enough to hold the capillary – wire – surface contact, without slipping. Also, it has to be high enough to realize the ultrasonic coupling between the wire and the pad, but not excessive because it can cause severe deformations of the wire or the pad.

The temperature is applied to the substrate and can affect the forming of the interface between the gold ball and the metallic surface during the welding process. Temperatures lower than 250 degrees Celsius can be used, and a proper setup of the temperature can lead to obtaining a strong welding. Usually, it was observed that a higher temperature is generating a better reaction speed, and the necessary bonding time is lower (Țîțu, Oprean & Boroiu, 2011).

The boding time is the period in which the capillary is applying ultrasonic energy to the wire.

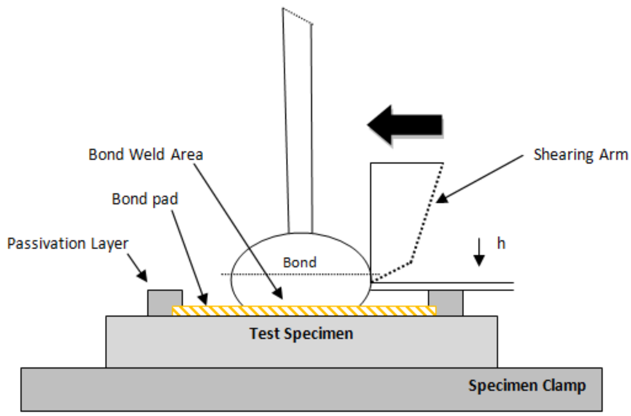

Fig. 2. Gold Wire Bonding. Overview.

In the gold wire thermosonic bonding, the interfacing reaction is diffusion controlled. The longer the time is, the higher the interfacing reaction. This means that when the ball is in contact with the metalized surface for a longer time, there will be a higher diffusion, and a uniform alloying will take place on the interfacing. Usually the required time for the thermosonic bonding is about 20 milliseconds. The disadvantage of the welding time is the productivity loss. The reliability of the integrated circuit, during its operation, is depending on the gold wire bonding quality. If the bonding is weak, the interconnection is inconsistent and the products are non-conformal. The bonding quality is determined by the strong link between the substrate and the gold ball and it is controlled by using certain methods like Pull Test and Shear Test.

2.3. Shear Test and Pool Test

The Shear Test is a procedure in which with a tool the gold ball is scraped from the metalized connection supports.

The necessary setups for performing the shear test are as follows:

- The choosing of a shear tool bigger by 1.5 – 2 times than the wire thickness;
- The positioning of the tool above the bonded surface, at about 30% from the bonding height;
- Positioning of the bonding tool at an angle of 45^{o} or 90^{o};
- Applying a constant movement speed, about 100 µm/s.

The force measured after the separation is recorded and mentioned as an adhesion force of the gold ball, on both the component and the substrate. After this, the force is correlated with the diameter and the height of the bond. The result obtained is a quality indicator for the welding resistance. During the shear test is necessary to consider the different situations which can occur, and so to be able to decide if the results are optimum or not. By the remaining gold quantity we can trace 4 possibilities, highlighted in Fig. 3. It is very important to highlight the fact that the shear test is performed after each capillary replacement (Harman, 2010).

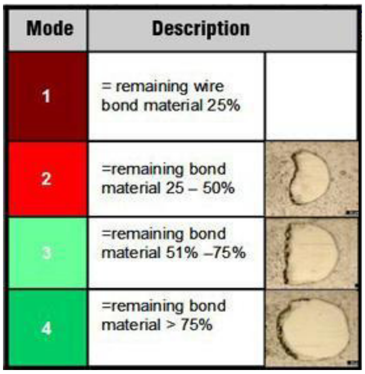

Fig. 3. Shear Test results.

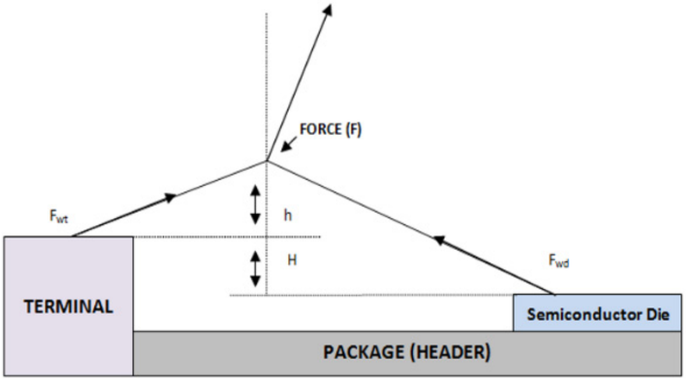

Fig. 4. Bond Pull test.

The Pull test is a procedure for testing the welding resistance and the wire resistance (Fig. 4). By using a hook shaped tool, the wire is grabbed in the middle and it is pulled to its breaking. Usually the hook is placed in the middle of the wire length. The force measured during the wire breaking represents the resistance of the welding (Cicală, 1999).

3. Thermosonic gold wire bonding process optimization by using the dispersion analysis method

For the next experiment we are considering one device, manufactured in an industrial organization, specialized in the automotive electronics field. The subassembly is vital for the automobile reliability. This product is interconnected with the help of the gold wires, bonded between the electronic devices and the substrate. The bonding process is the thermosonic ball- wedge welding, and the experiment is focused on the forming of the second bond, meaning on the wedge. The applicable and set parameters are the substrate temperature, the ultrasonic energy, the bond force and the bond time. The temperature is set to 160 ± 5^o C, the bond force is constant set to 50 grams and the bond time to 0.25 seconds. The ultrasonic energy has a high frequency and can vary between 115 – 135 kHz, and the ultrasound impedance is in a range of 20 – 40 Ohms. Besides the parameters we are considering the values of the bumps diameters and heights, due to the fact that these are counted among the factors which are influencing the welding resistance. For the conformity, the diameters have to be between 93.94 – 118.95 micrometers, and the heights between 27.5 and 37.5 micrometers. It is necessary to mention the fact that all these parameters, which play a major role in the welding process quality, have been set for a gold wire with a diameter of 32 micrometers, with a purity of 99.999 %. In addition, the substrates have the bonding pads realized from the same material with the same characteristics. In order to optimize the process, we are going to use the dispersion analysis method. We are tracing the influence of each factor and we are correlating them accordingly. The aim of this experiment is to improve the quality of the second bond (wedge). During the experimental approach we traced the bonding process of 32 wedges, coming from different substrates. Samples were obtained from each substrate and they were analyzed according to the dispersion method in order to improve the wedges. The following factors were used as influencing ones: the substrate heating temperature, ultrasonic frequency, bumps' heights and diameters. The representative functions were determined to be the qualitative measurements of Shear and Pull. So: x1– substrate heating temperature [^{o}C]; x2 – ultrasound frequency [Hz]; x3 – ultrasound impedance [Ohms]; x4 – bump heights [μm]; x5 – bump diameters [μm]; y1– Shear test [mN]; y2– Pull test [mN].

3.1. Histograms

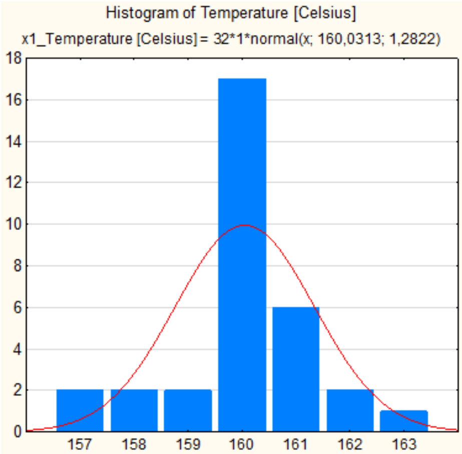

Fig. 5. Temperature histogram.

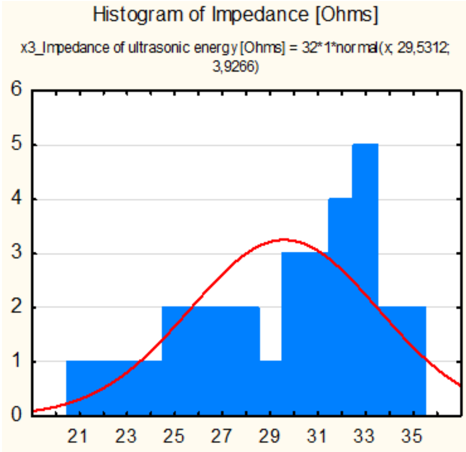

Fig. 6. Impedance histogram.

The two histograms illustrate the temperature and impedance values (Fig. 5 and Fig. 6). The temperature histogram has a normal distribution, presenting values between 157 – 163°C. We can observe that more than half of the values are equal to the average value, and the action of the others is uniform realized, in both directions, according to the average. The impedance histogram shows values ranging from 21 to 35 Ohms. As an average value, we can say that the impedance is 29.5312 Ohms, the value distribution having a negative asymmetry. Most measurements have had the impedance value ranging between 30 – 33 Ohms.

3.2. 2D Scatter Plot

The graph presented in Fig. 7 and Fig. 8 shows the shear test value based in the diameter measurements. We can observe a powerful positive link between the two value sets. By increasing the diameter, the shear test values are also raising.

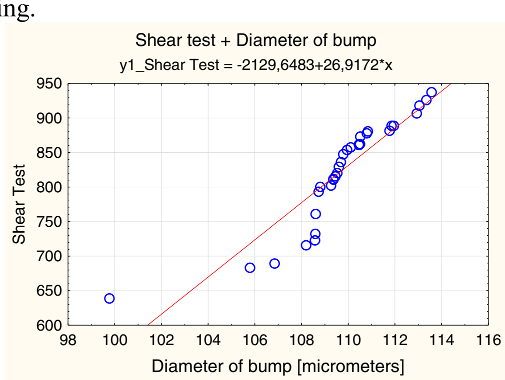

Fig. 7. Shear + Diameter.

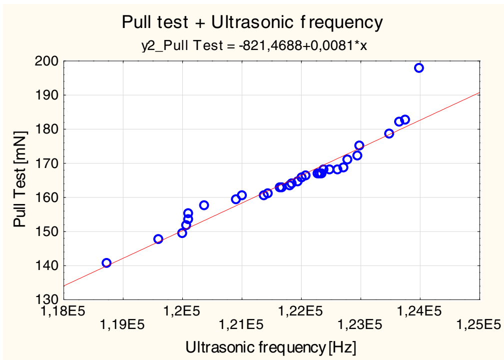

Fig. 8. Pull + Frequency.

As shown above the diameter measurements are between 108 – 110 micrometers, determining most of the values for the shear test, 800 – 900 mN. It can be concluded that keeping the diameter values constant we are ensuring the proper shear test values. Figure 8 represents the pull test values based on the ultrasonic frequencies. It can be stated that the frequency is directly and positively influencing the pull test values, both value sets being ascendant. More than half of the measurements had a frequency place between 122 – 123 kHz, delivering optimum values for the pull test, 160 – 170 mN.

3.3. 3D Surface Plot

Fig. 9 represents the shear test values as a function of the ultrasonic variation and impedance function. According to the graphic, we can observe that, as long as the frequency and the impedance are rising, the shear test values are also rising.

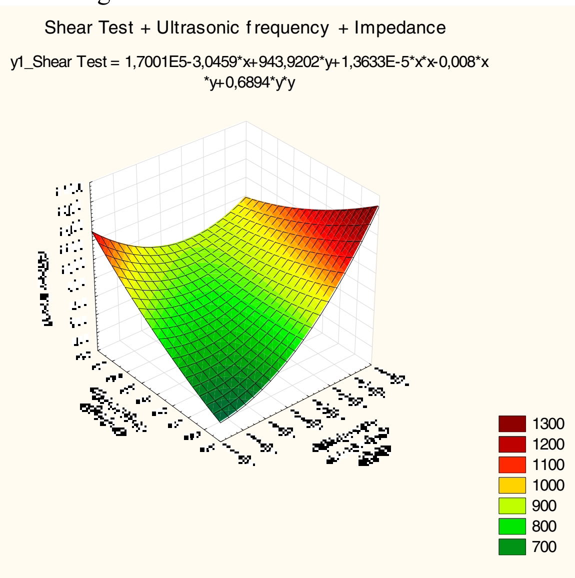

Fig. 9. Shear test+ Frequency+ Impedance.

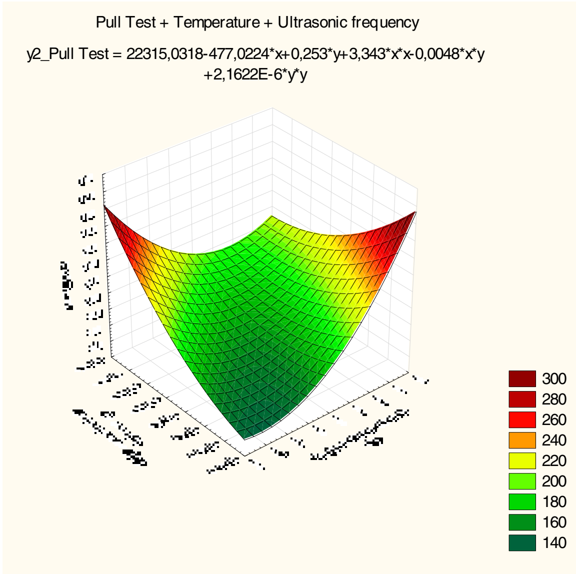

Fig. 10. Pull test+Temperature+Frequency.

The optimum combination of the two variables can be traced through a measurement where we look for the maximum efficiency. In the graph, we highlighted the fact that the ultrasound frequency placed between 122 – 123 kHz, combined with the values of impedance between 30 – 33 Ohms, is generating the most appropriate values for the shear test. Usually, the shear test values should fit in the 500 – 1500 mN range. A very important fact is represented by the same raise of the two variable values sets. In the case where this is not happening, the welding can have a deformed or an inconsistent look, which can lead to a nonconformity.

Fig. 10 is illustrating the values of the Pull as a variation of temperature and ultrasound frequency. The graph shows the fact that the pull test values are rising once the temperature and the ultrasound frequency have been increased. Most of the measurements have been placed between 160 – 170 mN, and the optimum combination is formed by 160 – 161 ^{o}C and ultrasonic frequencies between 122 – 123 kHz. Principally, the pull test values need to be placed in a range of 100 – 300 mN. This is also applicable for the shear test, the two value sets (temperature + frequency) need to bring a simultaneous raise, in order to avoid inconsistency, golf club or deformed wedge appearance.

4. Conclusions

This research was carried out to improve the quality management of the thermosonic welding process of gold wires in automotive industry.

According to our experiment we can state the following conclusions, based on the variables which are influencing at his peak the welding process of the second bond (wedge):

The temperature can vary between 155^{o}- 165 ^{o}C, but the most important values were placed between 160^{o} -161^{o}C.

The ultrasound frequency can be placed, generally speaking, between, 115 and 135 kHz, but the most favorable values are between 122 and 123 kHz. The ultrasound impedance can vary between 20 and 40 Ohm, but the most appropriate value ranges between 30 – 33 Ohms.

The bonding force was set constantly at 50 grams due to the fact that it is considered the most appropriate intensity with which the ball is pressed on the metallic surface. Even though this can vary between 35 – 55 grams, in order to perform a proper bonding of the wedge, a force close to 55 grams has to be chosen (especially if we want to avoid the situation where a smaller force can break our welding point). Also, it is considered that the force has to be the same for each wedge, in order to ensure the adhesion of each wire. The bond time is also constant set.

The requested time period for applying the ultrasonic energy is 0.25 seconds, in one second there are 4 wires done. Keeping a constant time will increase the production efficiency, and by this we will increase the productivity. Being dependent on the ultrasonic energy the time has to be reduced. The bump height can be between 27.5 and 37.5 micrometers, but to be in a safe area, we have to consider 29 – 33 micrometers.

The bump diameter requests a variation of 93.94 – 118.15 microns, but it was noticed that the most appropriate were 108 – 112 micrometers. The proper adjustment of the variables has as a consequence conformal wedge, which can be numerically highlighted through the qualitative test values. Initially, in order to obtain the proper results, the shear test values had to be between 500 – 1500 mN.

After our experiment, we found out that the best welds had the shear values between 800 -900 mN. In the case of the pull test, the initial values had to be placed in a range of 100 – 300 mN. But, it was demonstrated that the most resistant wires had the values between 160 and 170 mN.

After analyzing our graphs we can state: It was observed that there is a powerful positive link between the temperature values and the Shear & Pull test values, and by this we mean that the temperature rise is influencing the shear & pull test values rise. The ultrasound frequency is influencing directly and positively the values of shear & pull tests; this frequency is directly proportional. We saw that the increasing impedance variation, also determines the shear & pull test values to increase. The negative influence of the bump heights was also noticed. The higher the bumps are, the lower the shear & pull tests values.

During our study, we observed the fact that if we increase the bump diameter, we could also increase the shear & pull tests values. Individually or combined, all the influence factors values, which proved to have a more restricted link, have proved that they can generate more precise values for the shear & pull test values.

By this we can say that all the parameters need a more accurate consideration, due to the fact that each of them plays a major role in the product quality. Nonconforming products result when one of the parameter values is neglected.

As a perspective of this research, it is proposed a change in the bonding process which should be implemented the influence factors tolerances replacement. More precisely, the initial values limits should be limited to those obtained after the dispersion analysis. Thus, the process will not show a lot of alternatives regarding the parameters, and should non-conformities occur the cause/causes will be easier to detect. Moreover, the process will be centered, and the products will be characterized by reliability and, last but not least, quality.

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