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MAIN INCOMPATIBILITIES OF SOLDERING PROCESS IN AUTOMOTIVE INDUSTRY

Summary. Electronic systems are very important part of the automotive industry. Electronic products have high reliability due to the critical functions performed by some of the modern modules. Cyclic mechanical load and vibration are main of the conditions, that the electronic modules are subjected during the transport. In this paper, the main incompatibilities in the internal transport processes of soldering of selected elements for automotive company are presented. The main purpose of the article is to identify the causes of these nonconformities. The source of the cause of nonconformity was determined by means of quality tools and methods: 5 WHY analysis or modified p-FMEA analysis. The results obtained from the presented investigations enable the elaboration solutions for the transport process inside the analyzed company. The presented solutions are the result of eliminating or limiting the amount of non-conformities in the analyzed process. The important expectations of solutions are presented. The proposed solutions are the result of eliminating or limiting the amount of non-conformities in the analyzed process on the soldering line.

1. INTRODUCTION

The paper reviews important technology for automotive industry based on lead-free soldering. The technical aspects of these technologies, strategies for implementation, and future directions are reviewed in the paper. With the development in the field of electronics, the size of elements has been miniaturized, giving rise to problems with their precise connection. Soldering is a process in which two or more metal parts are joined together by filler metal (solder) by melting and putting alloy between the parts [1]. The filler metal always has a lower melting point than the adjoining metal parts. Unlike welding, soldering does not involve melting the workpieces. In a very similar process, brazing, the filler metal melts at a much higher temperature, but metal parts do not melt. Solders containing lead are very popular, but, because of environmental and health reasons, organizations have increasingly dictated the use of lead-free alloys for electronics and plumbing purposes [1-3]. For soldering, the solder, flux, and temperature must be selected properly. Soldering plays an important

role in the construction of vehicles especially the electronic components. The quality of the connected parts is strongly determined by well-chosen parameters of the soldering process [1, 4]:

- type of solder,
- type of flux, and
- the temperature of the joining process.

In soldering, all parameters must be selected properly. Precision and high qualifications of the operators are very important in the soldering-automated process. Apart from soldering technology, a well-planned production process is also important. For the few years, the most popular solder based on eutectic alloy Sn-Pb (the lowest possible melting point) was widely used, which now is strongly not recommended due to environmental reasons. Currently, there are over 70 solder alloys that do not contain lead. In the automotive industry, lead is occasionally used in Zn-Pb alloys (especially for joining aluminum parts). Zn-Al alloys are recommended when good strength and corrosion resistance is required. Good strength of soldered connection can be achieved using silver alloys: Pb-Ag and Cd-Ag. For good conductivity, tin alloys are recommended: Sn-Ag and Sn-Bi. Both of these solders help in joining parts for electronics for needs. In the automotive industry, an Sn-Ag-Cu solder (SAC) is used. It contains high amount of eutectic alloy (melting point or M.P. 217° C) for reflow, and Sn-Ag-Cu or Sn-Cu eutectic alloy (M.P. 227° C) with Ag content from 3.0% to 4.0%. In the soldering process, a proper selection of flux is very important. Flux is a material that facilitates the soldering process by:

- eliminating impurities from the joint (dirt, oil, and oxidation),
- acting as a wetting agent, and
- reducing surface tension.

When selecting a flux for point-to-point soldering, many factors must be considered. Flux could be in many forms: paste, liquid, in flux-cored solder wire, and in flux-cored or flux-coated preforms. All fluxes based on their composition are divided into one of four classes [1]:

- Rosin (RO),
- Resin (RE),
- Organic (OR),
- Inorganic (IN).

Each composition category is subdivided into flux activity levels according to the corrosive or conductive properties. Most popular fluxes include ammonium chloride and zinc chloride. Of which, very popular are rosins and borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10 \text{H}_2\text{O}$). The two-stage soldering process (SMD and wave soldering) gives very good results, where the most important are the Sn-Ag solder and solder paste with the presence of Sn and Ag micro-granules. The process of surface-mount devices or surface-mounted devices (SMD) is a type of soldering process used in the manufacture of printed circuit boards using soldering paste. Wave soldering is also a process used in the manufacture of printed circuit boards. The circuit board is passed over a pan of molten solder in which a pump produces an upwelling of solder similar to the wave. As the circuit board is in contact with this wave, the components become soldered precisely to the board. This technology is presented in the article.

The problem of inter-departmental transport between workstations in the soldering process and the problem that is the result of the assembly of the elements on the analyzed line are of great importance. It is believed that the reduction and even elimination of the incompatibilities will positively affect the quality of the manufactured components and reduce downtime in the production process [2-3]. It is expected that the introduction of the proposed changes will make a significant contribution to the reduction of the quality costs of the production [4-5]. Main defects in point-to-point soldering process are connected with wrong parameters of the process.

Main popular defects such as “cold joint”, “too much solder”, and “insufficient wetting” are presented in Fig. 1.

During the soldering process, the other defects can be detected, but the probability of their presence and identification is very low.

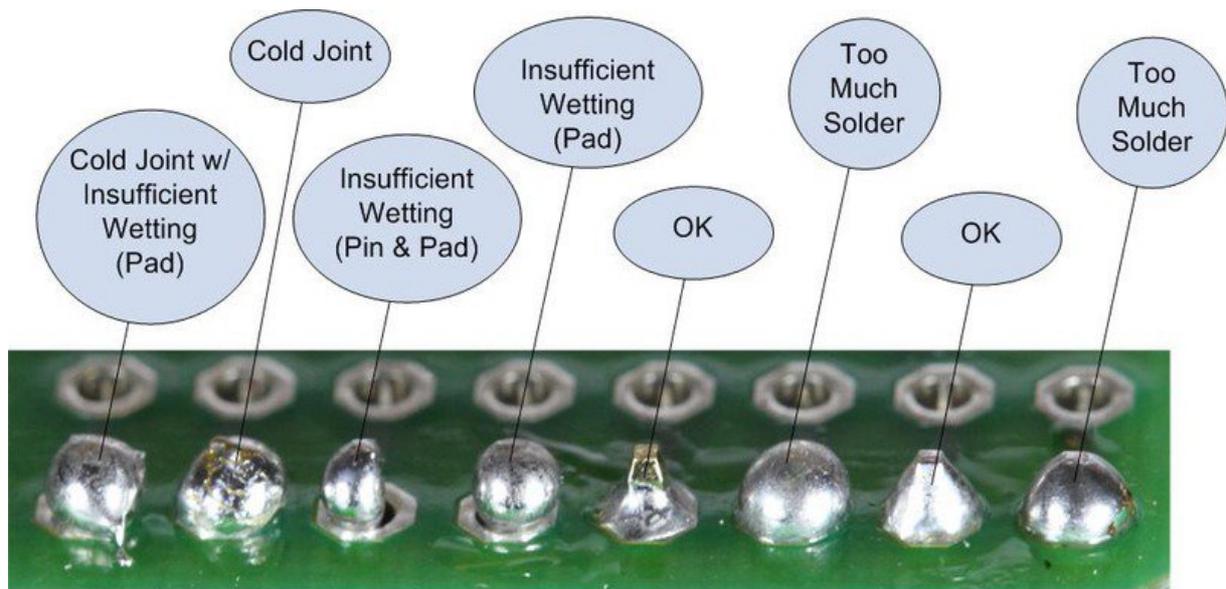


Fig. 1. Main defects of soldering process [3]

2. EXPERIMENTAL PROCEDURE

Incompatibilities in the production and transport processes on the soldering line were precisely analyzed. The solder (97%Sn-3%Ag by weight) and soldering paste (with Sn and Ag micro-granules) as a proper flux were chosen. Many physical properties of the Sn-Ag solder are similar to those of the eutectic Sn-Pb solder. The density of the Sn-Ag solder is much lower than that of the Sn-Pb solder. Also, the thermal conductivity of the Sn-Ag solder is very close to that of the eutectic Sn-Pb solder. The melting point of the eutectic Sn-Ag solder (221 °C) is higher than that of the eutectic Sn-Pb solder (183 °C). In connection with this, several-stage soldering technology was used, which consists of the SMD process and wave soldering [4-5].

In the first stage, SMD soldering was realized:

- dosing of a soldering paste (which fulfills the role of a flux and solder),
- assembly of elements using a robot,
- scanning the position of elements (verification of the arrangement of elements),
- initial thermal heating (wave soldering: different temperatures are set at different parts of the tunnel which dissolves the paste including tin and silver micro-granules. Only the flux dissolves in this stage, initial temperature is about 140° C).
- continuation of thermal heating, where metal granules dissolve to form a liquid phase (higher temperature, about 240° C),
- natural and slow cooling by moving the plate in the tunnel (the temperature at the end of the tunnel is about 100° C),
- before the internal transport of the plates, the whole tunnel is cooled naturally to the ambient temperature (cooling time about 20 minutes).

The second stage known as "tin wave" is the montage of conductors such as capacitors, resistors, plugs, and plug-in sockets. An important element of this assembly is soldering on a "tin wave". Liquid tin (with 3% Ag), as the solder is sprayed from the bottom of the plate in the soldering machine. This step is not implemented in the tunnel. It is carried over a built-in ladle with liquid tin. After finishing the two-stage soldering process, it is possible to apply larger elements such as capacitors or resistors. Silicone is dispensed in order to strengthen and protect elements from breaking them as a result of vibrations.

2.1. Subject to analysis

The soldering process of the printed plate with the motor was analyzed. The process consisted of 11 main operations. The name of the operation and the number are given in Table 1.

Table 1

The operations in the soldering process

The name of the operation	The number of the operation
Paste dispensing	O1_LED
Downloading and loading parts before soldering	O2_BAI
Verification and visual control	O3_FER
Heating of terminals before soldering	O4_AUS
Soldering of elements (Sn-Ag solder)	O5_MAR
Wave soldering	O6_MAR
Verification and visual control	O7_FER
Silicon and thermoactive paste dosing	O8_LED
Plate painting and heating	O9_PER
Tightening the cover	O10_CEM
Unloading of parts into a buffer trolley	O11_OOO

All operations take place in the EPA zone (electrostatic protected area) that efficiently prevents the electrostatic charges from components. Production stations are partly automated. Three operators work on the soldering line. Other production sites are fully automated. The transporting operation of components before the soldering process and then the transport with finished products is made by the buffer trolleys. In addition, manual transport occurs between the soldering line and the testing machine.

2.2. Research method

The soldering process of car elements was being observed for three months. During this time, each incompatibility that took place on each of the eleven operations was recorded. Identified incompatibilities had considerable influence over the quality of the final product and downtime of machinery and equipment during production. Identified incompatibilities were then divided into specific groups, and for each stage the so-called critical incompatibilities were established. Which of these incompatibilities were responsible for almost 80% of financial losses on the soldering line was determined.

In the first place, the corrective actions were taken for the critical incompatibilities, taking results of 5 WHY analysis into account. The 5 WHY method is a simple problem-solving tool that is easy to use in any organization. The effectiveness of this tool does not require any specialized preparation from employees. This method encourages employees to think analytically and identify the problem by themselves [6-7].

A proper group along with the people from the company management was involved in the 5 Why analysis. The group wrote down on paper sheets all the issues that were encountered and confirmed that every participant understood it. One of the most important issues in the process of analysis was to distinguish causes from symptoms. During the analysis, the group had to pay attention to the logical aspect of a cause-and-effect relationship and made sure that they established the correct root causes. All the statements must be based on facts and knowledge, and it is quite significant that the working group assess the process, not people. During the 5 WHY method, the question "Why?" is being asked until the root cause is determined [7]. The next step of our research was the modified FMEA analysis [8-9]. The analysis was connected to the results of the 5 WHY method. The methods of the root causes elimination (described in the 5 WHY analysis) were proposed. It was assumed that the elimination of the identified root causes will prevent the error from occurring again.

In the modified FMEA analysis of transport and production processes on the soldering line, the following factors were determined [10-14]:

- the means of detection (D) of the identified incompatibilities
- probability (P) of the failure occurrence
- severity (S) (of the event) - considers the worst potential consequence of a failure or lost time.

The risk priority number (RPN) is calculated according to formula 1 [15]:

$$\text{Severity (of the event)} \cdot \text{Probability (of the event occurring)} \cdot \text{Detection} \\ (\text{Probability that the event had not to be detected before the user was aware of it}) \quad (1)$$

3. RESULTS AND DISCUSSION

A lot of incompatibilities (on the level of about 1700) were found during 3 months observation, which corresponds to the production of 320,000 products. The principle of transport is similar as in the case of delivering of elements for production. The events recorded are a frequent fastening of the buffer trolleys, pulling trolleys to each other, moving items on the trolley and damaging elements which stand out beyond the frame of trolley frame.

As a result of observation during three months, 11 incompatibilities identified (tab.2) were related to both assembly and control operations and 221 incompatibilities were related to internal transport with buffer trolleys.

It is possible to deduce that the basic incompatibilities include a frequent fastening of the trolleys together and the problem of their disconnection by operators. An uncontrolled jerk in order to separate buffer trolleys provokes the movement of elements that are transported by the trolley. As a result, the elements that stand out beyond the frame of the buffer trolley are damaged. For operation O11_OOO, it was found that critical incompatibilities are related mainly to the internal transport in the department but not the assembly operations. First of all, there were registered 221 events resulted from incorrect storage of elements. These elements like, for example, plugs or pins of the plugs could then be damaged as a consequence of falling from a height. One group of incompatibilities was classified at the last stage of the process (operation O11_OOO). It resulted from damage to the manufactured elements during transportation by a buffer trolley.

In the group of 320 thousand soldered panels, approximately 1600 non-conformances were concealed, which is 0.005% of solder connections defective.

Various defects (434) occurred in the soldering process such as "cold joint", "too much solder", "insufficient wetting". It was decided to analyze a percentage of various defects in the tested soldering process (Tab. 3). The table data show that in soldered joints, all basic defects can occur with the same probability.

For the incompatibilities that were considered as critical, analyze the "5 WHY" method was used [according to the methodology presented in chapter 2]. The results are presented in (Tab. 4). Then, by the modified p-FMEA analysis, the corrections of respective operations in production and transport process were proposed.

Table 2

Registered incompatibilities on soldering line

The operation	The number of incompatibilities	Types of incompatible groups
O1_LED	20	too high paste density, lack of elements,
O2_BAI	117	damaged plug, element incorrectly set, insufficient amount of fluxing agent, excessive amount of flux, polluted plate, incorrect location of the fluxing agent, severe damage of plate, no flux
O3_FER	101	the wrong location of the elements
O4_AUS	44	instability of the soaking stage, inappropriate temperatures
O5_MAR	50	instability of the soaking stage, inappropriate temperatures
O6_MAR	271	instability of the soaking stage, inappropriate temperatures
O7_FER	434	defects such as “cold joint”, “too much solder”, “insufficient wetting”
O8_LED	10	inadequate silicone content
O9_PER	220	Too thick coat of varnish, for a thin coat of varnish
O10_CEM	118	damaged seal surface of the cover, improper model of cover, blurred gap filler, too high or too low screw tightening moment, too large or too small screw tightening angle, lack of signal from pin sensor or lost pins, too high or too low screw tightening moment, too large or too small screw tightening angle, damage to elements, damage to the plug, damage to the pins of the plug, incorrect storage of elements
O11_OOO	221	damage to elements during transportation by buffer trolley

Table 3

Main defects in the soldering process

Defects:	Percentage of defects, %
cold joint	30
too much solder	35
insufficient wetting	35

3.1. Results of 5 why analysis

Table 4

Registered incompatibilities on soldering line

Designation of the operation	Critical incompatibility	5 WHY analyze
O1_LED	too high paste density	Because there was used expired product.
O2_BAI	element incorrectly set, damaged joints, plugs,	Because there are no exact measuring instruments of distance. Because the trolleys have holes and easy fasten together.
O3_FER	the wrong location of the elements	Because the elements in operation O2_BAI were incorrectly set.
O4_AUS	inappropriate temperatures	Because the elements in operation O2_BAI were incorrectly set.
O5_MAR	incorrect location of fluxing agent	Because the elements in operation O1 were incorrectly set. Because they were set by the machine like that. Because there are no exact measuring instruments of distance.
O6_MAR	improper temperature	Because it was an improper set. Because the pyrometer was not calibrated. Because it was even not in the instruction.
O7_FER	solder in the wrong place	Because it was made on a faulty machine. Because of defect and elevation of cover. Because the machine was not inspected. There were no instructions or tasks.

O8_LED	solder in the wrong place	Because the elements were incorrectly set in the previous operation Because they were set by a machine like that? Because there are no exact measuring instruments of distance
O9_PER	acceptance of an improper element	Because the settings of the vision system were not checked. Because there are no exact measuring instruments of distance. Because there was no instruction to do it.
O10_CEM	damaged elements, damaged plugs, damage to the pins of the plug, incorrect storage of elements	Because elements are falling Because elements are incorrectly put away Because there is not enough space in the post-load station Because it is impossible to put the widest table between the machines
O11_OOO	damage to elements during transportation by buffer trolley	Because the elements stand out beyond the frame of trolley during transport. Because the trolley is pulled and jerked by the operators. Because the trolley has holes and easy fasten together.

The results of the p-FMEA analysis research are the base of the implementation of a change to the company regarding the operation O11_OOO of the process. The reconstruction and retrofitting of buffer trolleys are implemented in the company. Therefore, a temporary solution was introduced to the organization regarding the installation on all trolleys of separators. It is important that the separators are placed at the appropriate level, both on the sides and the front of a buffer trolley. The first prams have already been modernized; however, this stage will take several months. The proposed corrective action regarding the reconstruction of the table has also been accepted and implemented. Incorrect placement of parts on the table was the main cause of damage or fall from a height, as a result of which these parts had to be scrapped. The dimensions of the storage table are determined by the free space between the machines. Due to the fact that it is not possible to set a larger or another table, it was proposed to add a second level of the countertop to the current table. Currently, instead of 4 pieces, 8 pieces of the product were put on a two-shelve table. The solution ensures the continuity of the process and prevents parts from falling down. The parts are put on top of the table and not on top of each other.

It should be emphasized that the majority of causes of non-conformity arise from errors that arise during the design of the transport process.

Internal transport was considered separately as a process without integration with the production process. It can be assumed that after the company has implemented all corrective measures, expenses related to the scrapping or dismantling of parts will be reduced to a significant extent. Therefore, it is stated that the implementation of tasks resulting from the introduction of modifications in the in-house transport process will enable the organization to improve the soldering process and reduce downtime and eliminate the main causes of incompatibilities.

4. CONCLUSIONS

Sn-Ag soldering technology for automotive electronics manufacturing has been reviewed in this paper. It has been demonstrated that Sn-Ag soldering technology can reduce production cost and improve process capability. Developing the soldering process and exercising quality control is the key to the success of no clean soldering technology. On the contrary, Ag-Sn solders are currently under development that may provide the potential to enhance solder interconnect reliability. The development of quality control procedures and partnership with suppliers in implementing these procedures must be considered as an integral part of soldering technology development and implementation. In addition, every effort should be made to minimize contamination during the soldering operation and production packaging process.

The presented investigations show that for 11 stages of the manufacturing process on the soldering line, during the observations, 221 incompatibilities were identified in internal transport processes. The result confirms that the transport process must be corrected, because the result is unacceptable for the analyzed company. Other incompatibilities were connected with the production process, directly with the O2_BAI operation, because the elements in the operation were incorrectly set. During the brainstorming and 5 WHY analysis, the main causes of non-compliance were identified. In the transport process, the most important causes are as follows:

1) Construction of the buffer truck because:

First - the trolleys have holes and hooks at different levels and that's why it's easy to connect them accidentally.

Secondly - the transported items protrude beyond the frame of the trolley during transport.

Thirdly - the trolley is pulled by the operator, which leads to the movement of the elements on the trolley.

2) Construction of the table in the post-load station

The elements are falling, because there is not enough space in the post-load station on the table.

The correcting of the internal transport process was determined using the modified p-FMEA analysis. A measurable effect of the conducted research is the implementation of a change to the company regarding the O11_OOO operation of the process - that is, the reconstruction and retrofitting of buffer trolleys. The first trolleys have already been modernized, but this stage will take several months due to the number of buffer trolleys and the lack of production stoppages.

Revise action concerning the reconstruction of the one-shelve storage into a two-shelve table was also proposed and implemented.

The company also accepted other solutions regarding the introduction of cameras and sensors on the production line in the O2_BAI operation. The company also adjusted the instructions for the station and activities in terms of the changes.

The all presented solutions are successively implemented on the soldering line in the automotive company, and the results presented below are only expectations:

1. It can be assumed that after the introduction of all corrective actions by the company, expenses related to the scrapping or dismantling of parts will be reduced to a significant extent.
2. It is, therefore, concluded that the implementation of tasks resulting from the introduction of modifications in the in-house transport process will enable the organization to improve the soldering process and reduce the quality costs related to downtime. The proposal of implementation is the company's expectations to improve the functioning of the production.
3. The next step in improving the process may be the elimination of the remaining incompatibilities.

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