Suitability of Quality Management Methods for Adhesive Bonding Processes

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Abstract

Due to its ability to join different materials, adhesive bonding has established as one of the most important joining techniques especially for lightweight applications. In addition, it offers further advantages as a planar load transfer. However, there are also some challenges that limit the application of adhesive bonding and one of these challenges is the quality assurance. Adhesive bonding is a special process as the quality of an adhesive bond cannot be determined by non-destructive testing. Although numerous testing methods have been applied in recent years, none has proven to be able to verify the conformity of adhesive bonds reliable. Therefore, it is essential to implement a quality management systems.

Therefore, within this study, quality management methods are evaluated regarding their suitability to be used to implement a quality management system for adhesive bonding processes. Based on the evaluation, instructions for the implementation of a quality management systems are derived and a procedure for the introduction of a quality management systems for adhesive bonding processes is given.

Keywords: Adhesive bonding, quality assurance, quality management

1. Introduction

Adhesive bonding is a joining method that is widely used in industrial applications. This joining method uses an adhesive to join the adherends and offers some advantages compared to other joining methods like riveting or welding as it is not limited to certain materials and prevents tension peaks due to the planar load transfer. However, the application of adhesive bonding is complicated as it is a special process. That means, that the outcome of the process is influenced by many parameters on one hand and a non-destructive evaluation is not possible on the other hand.

In recent years, several non-destructive testing methods have been applied without satisfactory results. Thermographic testing methods [1], shearography [2] as well as ultrasonic testing methods [3, 4] have been applied and some relevant bonding defects like voids or a lack of adhesive can be detected. Other defects like kissing bonds and weak bonds cannot be detected with sufficient reliability. Therefore, quality management methods like Total Quality Management are applied [5].

As a result, the only way to achieve reliable adhesive bonds, quality management systems (QMS) have to be applied. In recent years, the introduction of QMS was specified in German standards concerning adhesive bonding. Within the standard DIN 2304-1 it is stated, that the requirements of the standard have to be integrate into a QMS for the bonding process. However, there are no guidelines how a QMS for adhesive bonding process should look like.

Therefore, within this study, a process for the planning of an adhesive bonding process as a key element of a QMS based on well-established methods for quality management is proposed and the suitability of the considered methods is evaluated. The presented experiences on the suitability of the methods are derived from two process chains that have been considered within an ongoing research project called “EcoQuality” that focus on the development of a model to implement QMS for adhesive bonding processes.

2. Planning of Adhesive Bonding Processes

Once it has been decided to use adhesive bonding as a joining method, numerous influences have to be considered. This includes communication chains, education of employees as well as storage conditions and supply chains. Beside these factors, the bonding process itself requires particular attention. If the adhesive bonding process is well-planed and understood, many defects can be avoided. In general, the planning of all adhesive bonding process with respect to quality can be divided in six stages. The process chain to implement an adhesive bonding process is given in Figure 1.

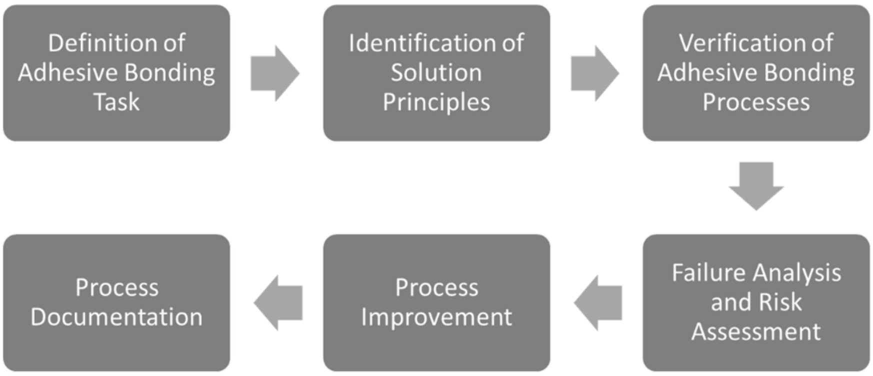


Figure 1: Process for the implementation of an adhesive bonding process

First, a precise definition of the bonding task is required. This include on one hand the bonding task itself (what should be bonded) as well as constructive limitations and all requirements that arise from the production process (cycle times, batch size) and the final application (loading conditions, safety requirements) on the other hand. Based on these boundary conditions, possible bonding process can be defined. This includes the choice of suitable adhesives, surface pre-treatments as well as the application of the adhesive. Then the bonding process has to be verified. Within DIN 2304-1, several ways to verify the bonding process are proposed. If these steps are conducted, the requirements are well-described and the bonding process fulfilling these requirements is defined. However, before the bonding process can be applied, a further critical analysis with respect to the manufacturing conditions has to be conducted. The influences of production parameters have to be investigated and an evaluation of the effect of parameter variations have to be performed. Potential defects have to be identified and a risk assessment has to be performed. This weak point analysis is the basis for the following step, the process improvement, where measures are taken to reduce the risk of unexpected failure. Following this improvements, a process documentation can be provided and the bonding process can be implemented.

3. Quality Management Methods for Adhesive Bonding Processes

Also the approach described above seems quite logical and simple, the practical application is challenging. As adhesive bonding processes are influenced by many parameters, it requires a strategic approach to identify all boundary conditions and parameters so that a well-planned adhesive bonding can be implemented. Some methods of quality management have shown potential to be applied with this process and are described below.

3.1 Step 1: Definition of Adhesive Bonding Task

In order to get a proper definition of the adhesive bonding task, it has shown to be appropriate to use a checklist based on “Five Ws and How” (5W1H). The application of this method is basic in information gathering and enables a detailed description of the bonding task. However, a detailed description has to cover several fields. First of all, the people involved have to be identified and the responsibilities have to be clarified. Then it is also important to give the motivation, why adhesive bonding should be applied and the expectations on this joining method should be specified. Furthermore, it is necessary to describe the basic bonding task as detailed as possible. This includes a description of the materials and the surfaces to be joined as well as a description of planned construction. In addition, the production process should be described. This includes information of cycle times, batch sizes as well as the expected costs as all these factors are essential for the process planning. Additional facts to be considered may be the functions the adhesive bond should have. This may be sealing or insulation functions as well as load bearing functions. However, the main question to be answered may be summarized as follows:

- Who is involved in the process planning?
- Who is responsible for the adhesive bond?
- What materials/parts should be adhesively bonded?
- Why should the materials be bonded adhesively?
- How does the production process look like?
- What production requirements have to be considered?

In a second step, the functions have to be gathered more detailed. The loads that apply in all stages after the actual bonding process (manufacturing process, transport, assembly and operation) have to be considered as well as chemical and physical loads. In addition, requirements concerning stiffness and deformation have to be considered. This information can be gathered by 5WH1 as well and by properly answering the associated questions, it is possible to get a good description of the bonding process, the expectations and the requirements and to derive the requirements on the adhesive, the surface pre-treatment, the application of the adhesive and the curing process as major steps within the adhesive bonding manufacturing chain.

3.2 Step 2: Identification of Solution Principles

Once the process is described, principles solutions can be developed. Within the project, two approaches have shown to be suitable to identify principle solutions for given adhesive bonding tasks.

One suitable tool to identify solution principles is the application of a morphological box as it offers the possibility to generate numerous possible solutions and is easy to implement. Within this method, suitable adhesives and surface pre-treatments can be identified in a first step and, in a second step, associated techniques for the application of the adhesive and the curing can be added. However, as many solution may be possible, a selection of the most significant approaches is difficult.

An alternative approach is 6-3-5 Brainwriting where six participants develop three initial ideas each that fulfil the requirements in a first step. This ideas are continuously detailed by the other participants. This method offers the opportunity to develop and specify solution for the adhesive bonding task. The ideas of all participants are respected and the detailed description of the solution allows a sound selection of suitable solution principle and ease the documentation of the selection. A main disadvantage is, that it is possible, that the proposed solutions overlap and therefore, only a limited number of solutions may appear. Furthermore, it requires basic knowledge of adhesive bonding processes from all participants.

In both cases, the evaluation of the defined processes starts from the selection of possible adhesive fulfilling the requirements. Based on that, suitable surface pre-treatments, application methods as well as curing procedures can be selected.

3.3 Step 4: Verification of Adhesive Bonding Processes

The suitability of the selected bonding processes has to be demonstrated in the next step. According to DIN 2304-1, this may be done by experimental tests, component tests or based on experiences made with adhesive bonding processes that are already approved or a combination of the before-mentioned methods. As the outcome of the bonding process highly depends on the process parameters, in a first step all controllable process parameters have to be identified and the specimens for the experimental evaluation have to be manufactured under realistic conditions. Ishikawa diagrams were identified as a suitable method for parameter identification for each step of the bonding process. The considered parameters can be divided into two categories. On one hand, there are parameters that are well to handle. This includes machines, materials the working environment, the materials as well as the measurements where possible parameters and parameter windows can be defined. On the other hand, the influence of human resources can hardly be captured. Therefore it is essential to determine to derive minimum requirements that have to be fulfilled and to give detailed instructions on how to bond.

If all parameters are identified, design of experiments was found to be a suitable method to reduce the testing effort to verify the adhesive bonding process. It has to be shown, that the chosen process is suitable to fulfil all requirements. If it fails, the failure cause has to be identified and it has to be checked, if parameter variations are suitable to prevent failure. In case parameter variations do not give satisfying solutions, the adhesive bonding process has to be changed to meet the requirements.

3.4 Step 4: Failure Analysis and Risk Assessment

When the adhesive bonding process has been chosen, it is suitable to perform a Failure Mode and Effects Analysis (FMEA). Based on the results of the verification of the process and the determined parameters, an evaluation of the likelihood of appearance a specific fault has to be conducted. This can be done by simulations, experiments or based on experiences from former processes. The probability P is then rated within a group starting from 1 (extremely unlikely) to 5 (frequent). Furthermore, the severity S of the fault has to be rated. This can be done by a rating form 1 (no effect) to 5 (complete failure). The third parameter is the probability to detect the fault. It has to be determined whether a fault will certainly will be detected (1) or whether a fault cannot be detected (5). The numbers can be changed to meet the requirements of the bonding process and as a result, it offers the possibility to prioritize the risk of a certain fault by a risk priority number (RPN) computed as a product of P, S and D. However, it has to be considered, that these RPN numbers may not depict the most critical faults. Therefore, a critical evaluation of the result is essential.

Other techniques for failure analysis like Ishikawa diagrams as well as failure tree analysis have also be considered. These methods can help to identify the fault and their causes, however an evaluation is not really possible and therefore, FMEA was preferred. Based on these results

3.5 Step 5 & Step 6: Process Improvement and Process Documentation

The process parameters that have been identified as critical have to be considered to improve the process. In general, there are three possibilities to improve the process: The probability for a certain fault can be reduced, the severity of the fault can be lowered or the possibility to detect the fault can be improved. When the actions to improve the process are defined, a detailed documentation has to be prepared. Then the process can be implemented.

As a QMS is designed to improve the process continuously, all actions the whole process have to be evaluated regularly.

3. Example - Surface pre-treatment for a test case

As mentioned, the recommendations concerning the suitability of the methods base on the experiences gathered during the project “EcoQuality”. Within this project, two adhesive bonding task with industrial background were considered to develop a basic QMS for adhesive bonding processes. One of the bonding tasks was the adhesive bonding of a pane of toughened safety glass to powder-coated aluminium profiles. Within the project, two different epoxy-based powder-coatings (black and white) were considered.

According to the proposed procedure, in a first step the bonding task was precisely defined based on a questionnaire developed within the project. In a second step, solution principles were identified using a morphological box. Two processes using different adhesive were chosen. On one hand, a pressure sensitive adhesive was applied, on the other hand, a two part silicon-based adhesive was used. In this case, the surface pre-treatment consisted of a cleaning of the surfaces and the application of an activator to improve the adhesion. The adhesive bonding process is shown in Figure 2.

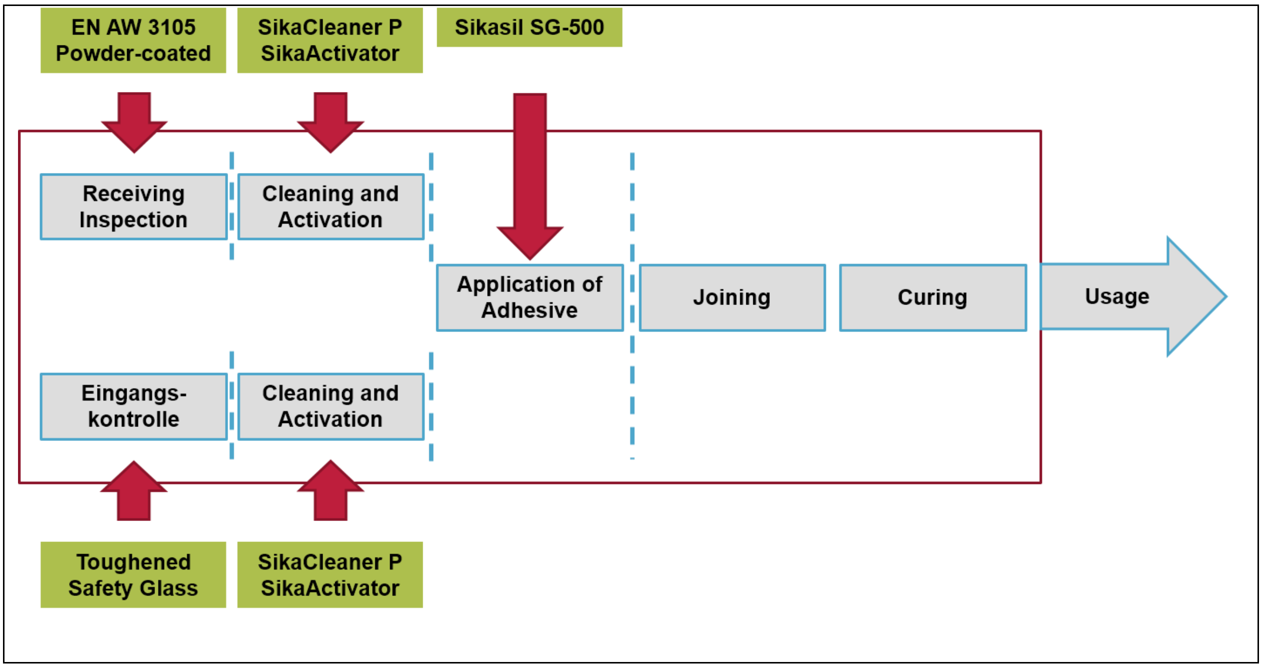
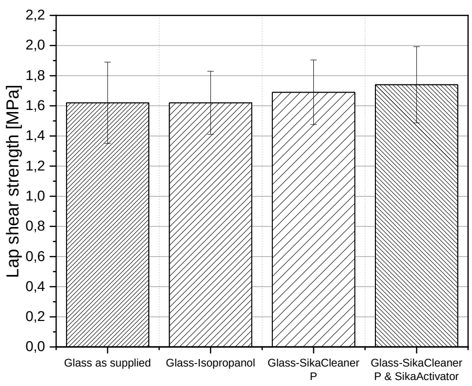


Figure 2: Scetch of the adhesive bonding process

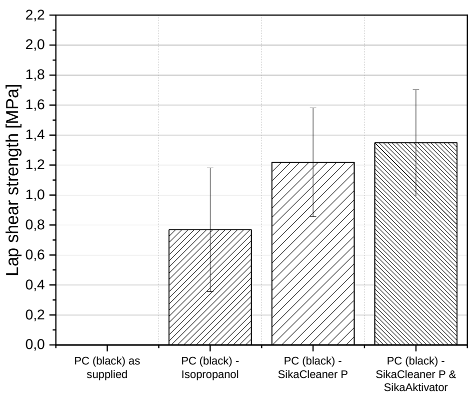
After the process was defined, the parameters influencing each process step were determined using Ishikawa diagrams. As it is a manual manufacturing process, machines have no influence on the outcome of the surface pre-treatment. In contrast, the employee has a large impact as is fully responsible for the process. This is closely connected to the method as the number of cleaning steps or the way how to apply the activator have to be described. Additionally, the materials have a major influence on the surface pre-treatment as well. The level of contamination of the adherends as well as the chemical composition of the surface influence the result of the surface pre-treatment. The cleaner and the activator have an influence, too. On one hand, they can be contaminated or they might be expired. Furthermore, the environmental conditions have to be considered. For example, it has to be investigated, whether contaminations could occur.

Based on the defined influence parameters a worst case scenario was defined. That would mean, the adherends were bonded without any surface pre-treatment. Further investigations considered the lack of activator and the use of another cleaning agent (Isopropanol). Specimen were manufactured with the described fault and compared to the verified process. The test results for all three considered surfaces are shown in Figure 3.

a.)



b.)



c.)

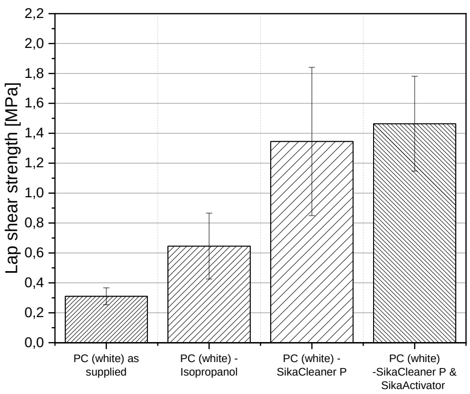


Figure 3: Lap shear test strength of specimen with different surface properties – a.) Adherends made of toughened safety glass; b.) Adherends made of EN AW 3105 with a black epoxy based powder coating and c.) Adherends made of EN AW 3105 with a white epoxy based powder

As the results show, the lap shear strength highly depend on the surface condition of the adherends. The lap shear strength for the adherends made of toughened safety glass are independent from the surface pre-treatment (a.). The adhesive shows cohesive failure in all cases. In contrast, the powder-coated specimens are highly sensitive to the surface conditions. If the specimens are bonded as delivered, they either fail on a low level (c.) in case of the white coating or they cannot be bonded at all in case of black coating (b.). A cleaning step with isopropanol increases the bonding strength in both cases significantly, however the failure mode is still partly adhesive. The recommend SikaCleaner P shows better results and the lap shear strength increase even more. This is caused by a bonding agent added to the cleaner. The failure is mainly cohesive. The application of the activator finally gives cohesive failure.
Based on these results, an FMEA was performed. The three cases considered were "Lack of surface pre-treatment", "Use of wrong cleaner and No activator" and "No activator". The results of the FMEA is given in Table 1. It is possible to detect the absence of the activator as the surface shows streaks on the surface.

Table 1: FMEA for surface pre-treatments

Adherends	Fault	P	S	D	RPN
Glass	No surface pre-treatment	2	1	5	5
Glass	Use of wrong cleaner and no activator	2	1	5	5
Glass	No activator	2	1	1	2
PC (white)	No surface pre-treatment	2	5	5	25
PC (white)	Use of wrong cleaner and no activator	2	4	5	20
PC (white)	No activator	2	2	1	4
PC (black)	No surface pre-treatment	2	5	5	25
PC (black)	Use of wrong cleaner and no activator	2	4	5	20
PC (black)	No activator	2	2	1	4

The results show, that the most critical case is the absence of any surface pre-treatment for the powder-coated aluminium. This would cause a drop in the lap-shear strength and it cannot be detected properly. Wetting measurements were performed, however the results do not give an indication of the missing cleaning step. Although the probability of an occurrence is low, as there are no suitable methods to detect the fault and the effect on the bonding strength is significant, the RPN is high. Therefore, actions has to be taken to improve the process and to prevent the fault. In order to avoid the critical case action can be taken. For example, it is suitable to remove all liquids that might be interchanged with the SikaCleaner P from the work space. Furthermore, it is necessary that the worker confirm the orderly implementation of the surface pre-treatment. This would not affect the severity or the detectability, however the probability of occurrence is reduced and therefore, the process is improved.

4. Conclusions

Within this study, the suitability of established methods for quality assurance for adhesive bonding processes was investigated. A process for the implementation based on the selected methods was proposed and the suitability was demonstrated for a surface pre-treatment. The developed process based on established methods for quality assurance seems to be suitable to identify the critical parameters and allow a clear presentation of the effects and a good basis to establish a QMS. A critical evaluation of the adhesive bonding is essential and the methods proposed can help to identify deficiencies and their causes. However, it is the responsibility of the user to implement the process and to improve the adhesive bonding process continuously.

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