Implementation of a quality framework on the launch phase of an automated assembly line for top class automotive chassis

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Abstract. Today the assembly lines of cars chassis are highly automated by robotic operations. Even in the top class automotive sector, the production of aluminium chassis involves numerous automated operations, such as TIG and MIG welding, riveting and gluing. This practice allows, on the one hand, to reduce time and costs, improve process repeatability and quality standards. On the other hand, it requires the quality improvement of the whole process (from supplied parts approval to welding reworks minimization). The industrialization phase of a new car chassis and the launch of its automated assembly line are particularly critical, even more if the line has already been designed and only minimally modifiable. Therefore, this paper proposes the implementation of a quality framework to manage the launch of an automated assembly line of a new aluminium chassis of top class cars, selected as a case study. The framework was implemented, aiming at improving the entire process quality, and finally validated by critically comparing the results obtained with those relating to models currently in production. Due to their importance to the final quality, we focused on the welding operations, which require actions both on process parameters and supplied parts approval (e.g. tolerances on parts end cuts). The new line shows a clear improvement compared to the past, with highly significant reduction of welding non-conformances, high quality level and lack of many critical issues of the previous lines thanks to corrective actions taken in the early process stages, during the pilot phase.

Keywords. Quality management, Assembly process, Process FMEA, Car chassis, Geometric and tolerance specification, Robotic welding.

1. Introduction

A car chassis is commonly produced by assembling extrusions, castings, sheet metal parts through manual and robotic operations, such as TIG and MIG welding, riveting and gluing. Over the past few decades, the use of robotic operations has increased and, nowadays, even top class automotive chassis are manufactured in automated assembly lines, using lightweight alloy materials [1],[2],[3], such as aluminium. The required high quality standards are achieved thanks to the use of robots, able to guarantee an excellent repeatability of the process [4], with a consequent reduction of time and costs. On the contrary, automated operations are less flexible than manual ones, so the quality of the entire process must be evaluated and systematically managed, in order to limit errors, welding reworks, manual adjustments of parts. In particular, the final quality of the chassis is influenced by two main critical issues: firstly, the geometry and tolerances of the parts to be joined [5],[6], which cause gap variations between the parts, and secondly, the distortions due to the welding process [7]. The automotive fields, as well the other industrial ones, may benefit from the use of Computer-Aided technologies [8],[9],[10] that may improve the product/process quality and, apart from the design phase, can also be employed for dedicated prediction and analysis purposes [11],[12],[13]. However, the real process may differ from simulation due to simplification and uncontrollable variables. Therefore, the industrialization phase of a new car chassis and the launch of its automated assembly line are still particularly critical, so a quality management process is required and implemented through specific tools, such as the Advance Process Quality Planning (APQP) [14], endorsed by the Automotive Industry Action Group (AIAG). This is even more important if the line has already been designed and only minimally modifiable: this is the case of small batches assembled in previously existing lines (or partially redesigned) or, again, of outsourced lines, i.e. lines designed by the automotive company but commissioned to third-party suppliers, who are responsible for achieving the final quality of the chassis. Therefore, even in those cases, is it possible to apply specific tools and recover in quality?

This paper aims to address this question, by implementing a quality framework on the launch of an automated assembly line of aluminium chassis for top class cars. Using this approach, we can identified and promoted corrective actions in advance, in order to reduce time and variable costs related to the chassis production, to limit reworks, to minimize waste. Additionally, we reduced the plant surface necessary for the production line (i.e. the on-line safety buffer), which is a very critical variable in the analysed context.

The paper presents the quality framework based on APQP and systematic tools in Section 2. Then, Section 3 describes its application on the case study in and some final comments close the paper in Section 4.

2. Method

Focusing on the production launch phase of an already designed process in the automotive field, we propose a quality framework based on a “chunk” of the APQP, which is extracted and applied to the launch phase, highlighting the contributions of detection and correction tools in accordance with Fig. 1. The APQP is a framework for producing a product quality plan that will support the development of a product [15]. It formalizes a correct and efficient planning of the production (time plan), based on the results of product and process verifications, in order to guarantee a serial product that meets predetermined quality goals, by reducing times and costs.

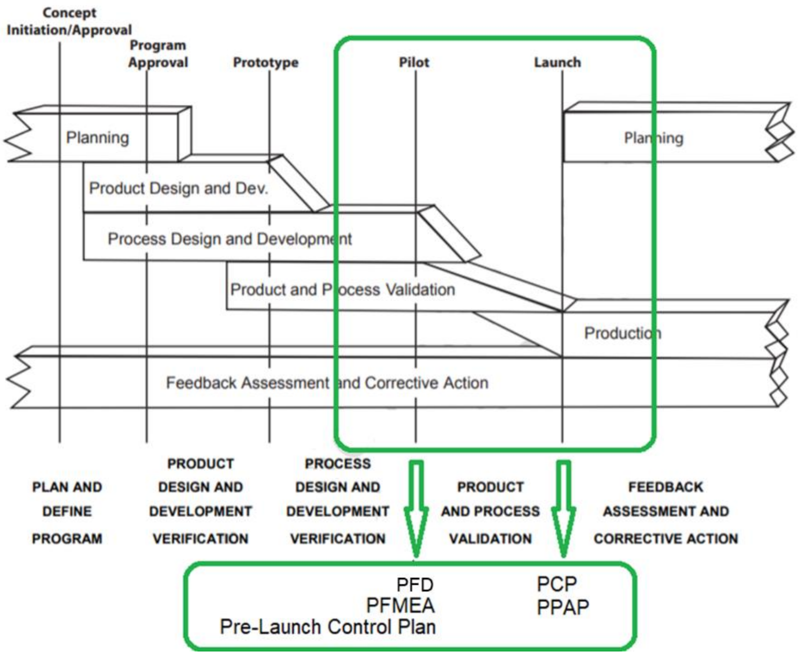

Figure 1. The implemented quality framework is highlighted in green, based on the "Process Design and Development" and the "Process Validation" phases of the APQP.

The Process Failure Mode and Effect Analysis (P-FMEA) is a technique for analysing the potential failure modes generated in the serial production process, by identifying the potential causes and effects

in order to establish corrective actions. The P-FMEA is implemented by a multidisciplinary product development team, capable of identifying potential process problems in advance, thanks to experience and know-how. The causes of failure modes are mainly due to the product/process development phase, thus much earlier than the Start Of Production (SOP). Therefore, their early identification leads to simpler and less expensive corrective actions. More generally, the FMEA is a structured method to analyse the entire internal production process. However the identification of failure modes has to be performed on each operation that constitutes the entire production process. This purpose is fulfilled by the Process Flow Diagram (PFD), a document that explains in detail the various phases defined by the line/process designer. In this way, each failure mode is analysed, defining the related causes, effects and risks, and associating an occurrence ranking, a severity ranking and a detection ranking, which allow to calculate a Risk Priority Number. This priority rule defines where to spent efforts (and investments) for facing failure modes with greater risk. In this way, detection and corrective actions can be planned, which may consist of a process change if the PFMEA is made in the initial phase of industrialization (prototype), or in an additional controls or scheduled maintenance activities. The FMEA is therefore the document that provides inputs for the activity of continuous improvement, involving different company departments, such as quality, maintenance, process technologies, production, technical department, or human resources, depending on the activity to be implemented. Moreover, the P-FMEA highlights the preliminary critical elements emerged before serial phases (the so-called *lessons learned*), which allow to define an effective control plan for serial production, with fine-tuning actions or additional controls.
The Production Part Approval Process (PPAP) is a formal and standardized method [16], which serves to test and approve a priori the production process of the supplier and of the related parts. The practice requires the supplier to submit the Part Submission Warrant (PSW) form during the pilot phase in order to obtain the approval, as well as a very specific report to document the parts conformity.
The Process Control Plan (PCP) is a serial production control tool capable to concentrate resources on the controls of the most critical features. The assessment of the characteristics to be checked and the relative control frequency are defined on the basis of: experience; results coming from the pilot phase; statistical trend of production indicators as Cp and Cpk indicators; severity of possible damage to the customer; key features defined by the customer.

3. Application to the case study

An automated assembly line for automotive chassis had already been designed, but not yet tested, as this activity had to be carried out throughout the pilot phase.
Scenario: The layout of the assembly line presents a main flow with different stations that generate many sub-assemblies of the chassis, then joined together into two main modules, called front extended frame and rear extended frame. These modules are welded together with other parts, such as the sills and sheet metal parts. The upper frame is generated and then completed by assembling the engine sub-frame and the rear sub-frame to the main body. Conversely, the previous assembly lines consisted of a much higher number of single parts directly welded together in two macro sub-assemblies, with consequent thermal distortions that must be compensated by appropriately locating the single parts in the welding jigs. Again, the new assembly line has a high percentage of automated operations (67% automated, 33% manual), necessary to cope with the high expected production volumes of the cars here produced. The previous lines are dependent on a marked manual contribution (e.g. in line A: 46% automated, 54% manual).
Critical elements: Analysing the statistics of the previous A, B, C lines, the Welding Non-Conformances (WNC) represent 23% of the total defects found at End of Line. WNC are not the most frequent defects, but the importance of the welding quality inside a chassis is high, as well as the cost necessary to welding reworks. In particular, two WNC have primary importance:
1) WNC due to end cuts of the parts to be welded, classified as weld burn-through (excessive penetration) and uncompleted welding, in the extrusion-casting joints: the main cause is the use of raw profiles for castings. The geometric tolerance of profile of a surface on the end cuts of castings is very large (around 2.5 mm), while on the end cuts of extrusions they are around 0.5-1 mm. Considering the precision of the torch of the welding robot around 0.01 mm, and the wire diameter around 1.2 mm, the geometric variability related to the prescription of raw profiles for castings is not compatible with the requirements

of precision of the welding robot. Conversely, in the extrusion-extrusion joints, the precision is higher since the tolerances are narrower, therefore the frequency of WNC caused by the variability of the end cuts is smaller.
2) WNC due to post-cooling deformations, caused by a high number of joints welded simultaneously in the same station. Therefore, the chassis distortion is not very predictable and, despite the adopted precautions, it affects the final tolerances on the chassis assembly. A greater modularity in the assembly process would make post-cooling deformations less incident. The analyses of the previous lines together with the company’s experience have the task of highlight the critical elements before the launch phase.
Implementation: Various tools are concurrently implemented within the quality framework. In accordance with the "Process Design and Development" phase of the APQP, firstly the PFC and PFMEA tools are performed, whose results act as inputs for the subsequent tools. Then, in accordance with the APQP "Process Validation" phase, the PCP and PPAP tools are applied to monitor the production quality. The APQP provides for the preparation of a table showing the project time-plan shared with the customer during the planning phases. It allows to manage unexpected events, respecting the milestones.
P-FMEA: In accordance with ISO/TS 16949, the identification of fault modes must be performed on each operation of the entire production process, thanks to the Process Flow Diagram (PFD), a document that explains in detail the various phases defined by the line designer. It is necessary to draw up a detailed and accurate PFD (Fig. 2), with all the information needed to identify the failure modes (i.e. about the production process, the product, statistics related to similar models, etc.), their priorities and risks.

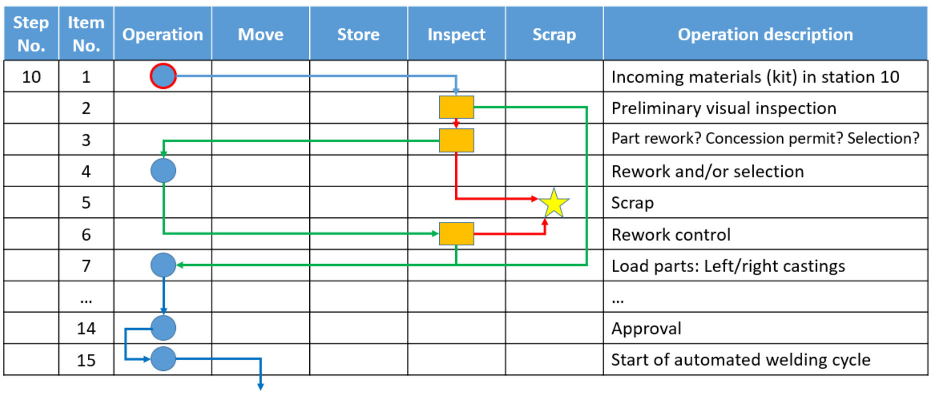

Figure 2. An extract from the PFD related to the automated welding station No.10.

In this paper, we focus on the effects of Non-Conformances (NC) of parts and process characteristics on welding operations:
a) Approval of parts from suppliers: In the previous lines, the parts were checked by the line operator, without a real inspection before the storing. This “free pass” approval has contributed significantly to produce chassis containing NC on the supplied parts, which often required subsequent reworking. Therefore, the P-FMEA is applied to identify recommended actions in parts approval (Fig. 3)
Based on the sequence formalized in the PFD, we analyse one operation after the other trying to understand for each identified failure mode, the cause, the generated effect and the current methods of prevention and detectability. A risk value is then assigned on the basis of the results of each analysis, which makes it possible to establish a priority in the possible assignment of a corrective measure.
Regarding casting parts, we redesign the joints with tighter tolerances, which have been rethought with single component processes in order to increase the level of precision of the parts to be welded, thus reducing the negative contribution that the geometric variability had on the quality of the weld. Therefore, we implement a control cycle in materials approval, thus guaranteeing the 100% of compliant parts in the line, at least in the pilot and serial launch production. Regarding extrusions, we have instead implemented a simple check of the packaging board, or rather of the quantity and arrangement of the parts as well as the conformity of the packaging, during the storage phase.

PROCESS PHASE	POTENTIAL FAILURE MODE	POTENTIAL EFFECT(S) OF FAILURE	POTENTIAL CAUSE(S) OF FAILURE	ACTUAL STATUS: CURRENT PROCESS CONTROL PREVENTION	CURRENT PROCESS CONTROL DETECTION	#OCC	# SEV	# DET	#RPN	RECOMMENDED ACTION(S)	RESPONSIBILITY & TARGET COMPLETION DATE	ACTION TAKEN	#OCC	# SEV	# DET	#RPN
Incoming materials Approval: extrusions, castings, sheet metals	Dirty part	Welding non conformities	Lack of storage space	For castings: packaging datasheet not provided	Visual control by the operator	10	5	7	350	Provide containers with closed packaging or storage in a covered area	Technical office, Quality		1	5	7	35
	Wrong identification	Assembly of wrong version of parts	Wrong identification of container	No prevention	Warehouse audit	7	5	7	245	Automatic error proofing on each part	Technical office, Quality	Datamatrix on each part	7	5	2	70
	Wrong quantity	Supply problems	Packaging datasheet not complying by supplier	No prevention	Warehouse audit And stock control	10	2	9	180	Create a materials approval phase. Define packaging datasheet	Logistics, quality assurance	Incoming materials control	4	2	7	56

Figure 3. Extract from the P-FMEA report of the new process, related to the materials approval phase: it shows only the failure modes with high Risk Priority Number.

b) Automated welding: The first step of the automated welding process is the manual or automated loading of parts and sub-assemblies to be joined. Based on statistics relating to the history of WNC, the assembly of an incorrect version of a part represents a rather risky mode of failure. Moreover, its possible rework entails a high cost also in terms of time. For this reason, we implement a datamatrix reading in the operator data sheet (Fig. 4). This reading is connected with the automated welding line software, so that it does not allow the operation if the operator has mistakenly loaded the wrong version of a part. The operator, in accordance with the instructions of each station represented in the operator data sheet, is then required to inspect the jigs locating the components and subgroup to look for any WNC.

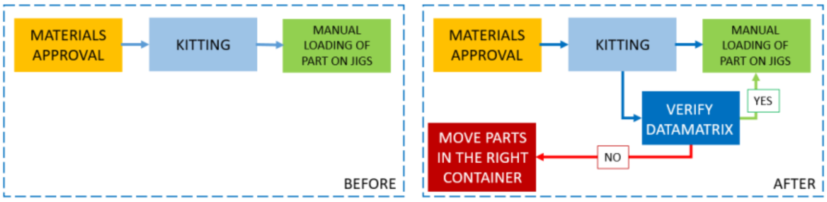

Figure 4. Flow chart before and after the datamatrix reading.

The next step was to consider the potential execution of an incomplete welding and of burn-through (excessively penetrated) welding. The case of burn-through welding is considered in Fig. 5.

PROCESS PHASE	POTENTIAL FAILURE MODE	POTENTIAL EFFECT(S) OF FAILURE	POTENTIAL CAUSE(S) OF FAILURE	ACTUAL STATUS: CURRENT PROCESS CONTROL PREVENTION	CURRENT PROCESS CONTROL DETECTION	#OCC	# SEV	# DET	#RPN	RECOMMENDED ACTION(S)	RESPONSIBILITY & TARGET COMPLETION DATE	ACTION TAKEN	#OCC	# SEV	# DET	#RPN
	Burn-through welding	Welding NC: joint structural failure	Welding torch out of geometry	No prevention	WDM and visual control 100%	4	7	7	196	Tool check procedure and WDM mapping			2	7	3	42
	Burn-through welding	Welding NC: joint structural failure	parts out of tolerance	Dimensional control (incoming materials)	WDM and visual control 100%	4	7	7	196	Complete WDM mapping			4	7	3	84

Figure 5. Extract from the P-FMEA report of the new process, related to operations with burn-through: it shows only the failure modes with high Risk Priority Number.

The characteristics influencing the temperature increase are: proximity of the torch, excessive gap of the joint to be welded that leads to a higher temperature peak in the extremal area of the two end-cuts, incorrect or unsuitable welding parameters. Through these actions, we reduce the on-line safety buffers, minimizing the plant surface necessary for the production line, which is considered a critical variable in the analysed context. The P-FMEA provides useful inputs to process the PCP.

PCP: Based on the collected data, improvement activities are implemented to ensure greater efficiency for future production. Other NC not yet found during the line fine tuning, emerge during the production process, from materials approval to the customer's approval. The elaboration of the PCP requires a multifunctional team that provides information from each company department to make effective the control action applied to the production process.

Fig. 6 shows part of the PCP for the new line. In particular, it lists the controls carried out during the preparation of the feeding parts for the assembly line (kitting) and for a robotic welding stations. The final document of the PCP does not specify in detail the characteristics to control, because the detailed control actions will be fully specified in other operational documents, e.g. check-lists.

Step No.	Process Name	Characteristics to control	Sample frequency	Control method	Reference doc.	References	Data registration	Reaction plan
05	Kitting	Identification	100%	Visual	BOM	Drawings		Stop/selection
90	Robotic welding	Datamatrix identification	100%	Datamatrix reader	Operation SOP	Operation datasheet	software	Isolate NC parts
		Preliminary inspection	100%	Visual				Out of line rework
		Parts loading	100%	Visual				
		SET-UP Approval		Visual		SET-UP procedure	SET-UP registration module	

Figure 6. PCP of the material preparation (kitting) and welding stations.

PPAP: The new line layout requires a supply approval process. The PPAP asks the supplier to report that all the specifications requested by the customer have been implemented into the final parts, e.g. the geometric conformity of parts, so as to minimize the problems related to parts supplied in the serial production. For this reason, the geometric report attached to the Part Submission Warrant (PSW) is examined, verifying the real accuracy of the parts in specific control points. The PSW examines the geometry of parts to evaluate the quality of the production process of this component. So, the Cp and Cpk indices are useful to express the productive capacity of a process in the form of a number (e.g. a Cp> 1.33 is required which indicates a deviation of about 96 ppm and a minimum value of Cpk = 1.33).

4. Discussion and conclusion

The new assembly line is mainly characterized by automated operations, so the reduced flexibility of the process cannot manage the same amount of WNC present in the previous lines. A quality framework based on the pilot and launch phases of the APQP was thus implemented, integrating quality tools and techniques (PPAP, PFMEA, PCP). Based on the experience gained during the pilot production, we acted from a technical point of view (chassis sub-modules, machined castings, etc.) and with appropriate methodologies applied in the launch phase. So, the following results are achieved:

- Management of the scheduled activities by means of the APQP, which allowed the Start of Production to obtain a production process cleaned of many critical issues.
- Preventive analysis of failure modes via P-FMEA, aimed at identifying as soon as possible the potential critical elements of the production process of a new chassis, before the launch phase. The P-FMEA allowed the company to analyse the production process step by step, evaluating and highlighting potential failure modes. These inputs led to important corrective actions: firstly, the creation of inspections in materials approval, which have contributed significantly to filtering NC in the supply, as well as new preventive maintenance procedures such as the periodic replacement of the wire guide. The impact of PFMEA is very important, especially with a view to continuous improvement, where it is also essential for cost containment to detect defects to be corrected in advance. From the *lessons learned*, the following corrective actions have been taken: a) increase the level of precision of the castings, which

have been redesigned and machined in the joint area to obtain joints with tighter tolerances, b) the adoption of a modular assembly sequence to reduce the thermal distortions caused by welding.
- The result in terms of quality of the final chassis is closely related to the quality of the supplied parts, whose compliance with the specifications of serial production was guaranteed by PPAP.
- Creation of a PCP plan before the start of serial production, aimed at maximizing the identification of WNC. We created 15 new control cycles related to the supplied parts.
Figure 7 shows the outcome of a quality assessment before and after the implementation of the quality framework during the pilot phase. Fig 7-a shows the quality performance of welded joints in a chassis assembled in one of the first runs of the pilot production. Fig. 7-b shows the welding quality performance obtained in a chassis at the end of the pilot production, thanks to the implemented quality framework. The comparison shows a reduction of WNC from 34% to a 1% relative to the last qualification performed, confirming the satisfactory result.

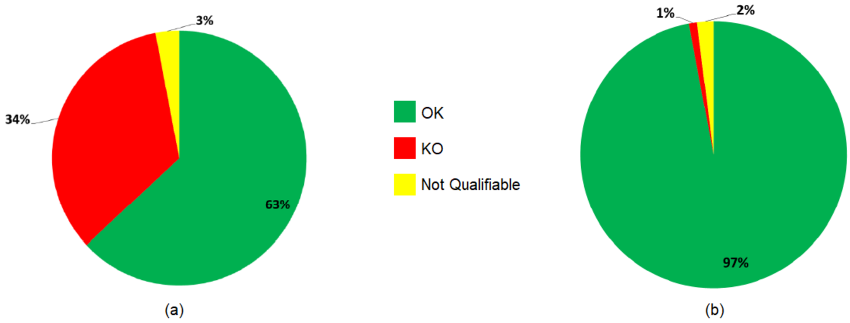

Figure 7. Quality of welded joints in (a) one of the first runs and (b) at the end of the pilot production.

Again, the quality of welded joints in the line A shows an average of 26% of WNC, calculated on the data throughout 2017. The new line shows an improvement even compared to the actual production.
In conclusion, the new line presents quality indicators that show a clear improvement compared to the past, thanks to a different global approach of quality management from pilot to launch phases. Future developments of this work will focus on the entire production, starting from the process line design.

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