IMPROVED MOLD TOOL DESIGN ROBUSTNESS THROUGH THE DMAIC PROCESS

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ABSTRACT

Mold tools represent a recurring capital expense in semiconductor packaging. The mold tools of Nexperia Philippines were approaching the end of life and thus require an investment of $3.48M to ensure the quality of products. The defined life of a mold tool is 300,000 strokes or equivalent to 3 years of operation. The typical approach in executing this program is to procure known working tools or repeat the order of the existing design. The Central Engineering team of Nexperia saw the tool replacement as an opportunity to address yield losses. These include Mold Plastic at the Back (MFB) with an average of 19.287 defect index, Copper on Plastic (CuP) Lot Rejection Rate (LRR) of 5.35 defect index, and OCAP (Out of Control Action Plan) 1.35 defect index in the year 2021.

A cross-functional team was created to plan and execute the replacement of old tools with design improvement to solve the MFB and CuP issues. The DMAIC (Define, Measure, Analyze, Improve, Control) process was utilized, and a project charter was created to guide the team in planning, executing, and closing the project. The Product Assembly Drawings (PAD) and Stack Tolerances were carefully analyzed. It was found that the MFB was a result of stack height variance between the incoming material from DACA (Die Attach Clip Attach) and the depth of the mold tool cavity. The tolerance at PAD which is +/-0.025mm was seen as a good opportunity to optimize the cavity depth without violating any product specifications. While the CuP was observed because of pinching when a lead frame is not properly aligned with the tools thus being hit by the edge of the upper tools during clamping. The MFB was resolved by reducing the depth of the cavity tool to eliminate the gap between the bottom lead frame and tool which prevented the plastic penetrating underneath. While the CuP was resolved by adding a 20° chamfer to serve as a self-aligner for the lead frame during clamping thus preventing pinching.

After the full implementation, a significant reduction of MFB from 19.287 to 3.918 defect index which is equivalent to an 80% reduction compared to the 60% target was achieved. The CuP LRR was reduced from 5.35 to 1.32 defect index and CuP OCAP from 1.35 to 0.53 defect index which both surpassed the target improvement. The overall financial gain was equivalent to $2.1M per year and gave 2.2 years of return on investment (ROI). Reliability tests showed no failure at 1,000 temperature cycles and 96 hours UHAST. It is highly recommended that this robust mold design for clip-bonded products be implemented across sites of Nexperia.

1. 0 INTRODUCTION

Nexperia is a leading expert in the high-volume production of essential semiconductors such as MOSFET (metal–oxide semiconductor field-effect transistor) which are widely used for automotive and power applications. Figure 1 shows examples of Clip Bonded MOSFET such as SOT669, SOT1205, SOT1023, and SOT1210.

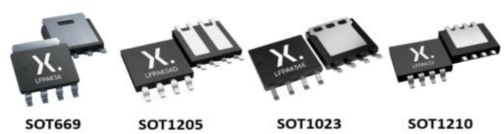

Figure 1: Examples of Nexperia Clip Bonded MOSFETs.

These products are being produced through several processes as illustrated in Figure 2. These include Sawing, Die Attach / Clip Attach, Molding, Plating, TFS (Trim, Form, Singulation), and Test.

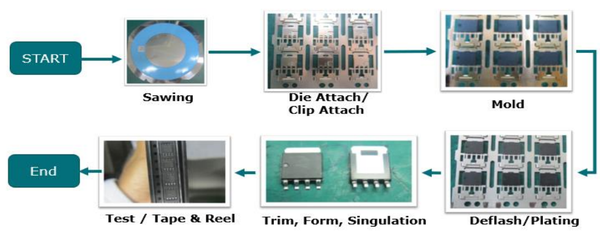

Figure 2: Production Process for Clip Bonded MOSFET.

The molding process is being done to encapsulate the components and protect them from environmental risks such as corrosion. As shown in Figure 3, it starts with the loading of the pre-assembled clip frame, bottom lead frame, and dies into a mold tool. The mold tool clamps and the liquified Epoxy Molding Compound (EMC) are transferred into the cavity. The EMC undergoes partial curing before the final unloading from the tool.

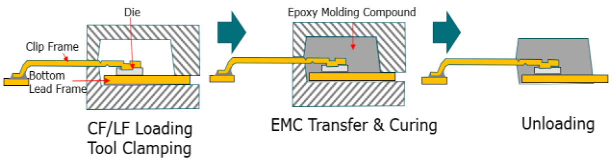

Figure 3: Molding Process Flow of Clip bonded products.

1.1 The Mold Tooling

The condition of the mold tool is important to ensure the quality of the products. Any defect in mold tool such as dents, wear, or damage would appear on the final molded product which could affect the form, fit, and function of the device when it reached customers. Figure 4 shows an assembly of a mold tool for clip-bonded products.

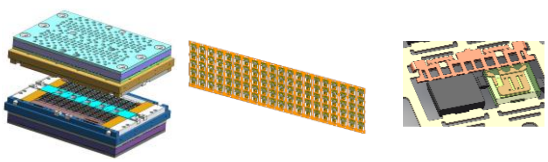

Figure 4: Mold tool for Clip Bonded Products.

There are quality defects that could occur if the end-of-life tools are not replaced. Examples are Mold Flashes, Leak, Pinching, and Pits as shown in Figure 5.

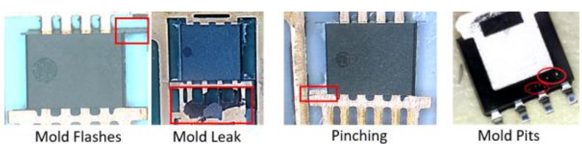

Figure 5: Examples of mold-related defects due to end-of-life tools.

The tooling for the molding process is considered the most expensive in terms of recurring capital expenses due to its short life of 300,000 strokes which is equivalent to 3 years of operations. In Nexperia, 43 out of 54 tools were approaching this limit and thus required a capital investment of $3.48M. This was an inevitable investment for the company to maintain the quality of products and prevent potential risks to the customers. Aside from the requirement to replace the tool due to the end of life, the company was experiencing yield loss due to MFB (Mold Flash at the Back) and reprocessing due to CuP (Copper on Plastic) defects.

1.2 Scope and Limitation

This paper discusses the risks of having end-of-life tools and the limitations of the current design to address the CuP and MFB. This paper discusses the issues and improvement opportunities related to mold tools only. It excludes other contributing factors to MFB and CuP problems such as the lead frame, molding compound, and other processes. It focuses on Clip bonded products only.

2. 0 REVIEW OF RELATED WORK

According to Mennig (2013), the surface quality and the shape of the mold cavity are transferred to the surface of the molded part. As per Pecas (2009), mold life cycle management can be considered a holistic approach to mold development considering all aspects from its preliminary design to its retirement, involving the multi-disciplinary competencies. These previous studies confirmed that replacing the end-of-life tools with the same capability is a wasted improvement opportunity. These encouraged the authors to introduce a more robust tool design for the new tool acquisitions.

3.0 METHODOLOGY

A cross-functional team was created to provide different expertise which is important to resolve the identified problems. The team was composed of a Six Sigma Greenbelt Certified Tooling Expert, a Six Sigma Black Belt Certified Process Expert, Tooling Engineers, and Procurement Specialist. The team utilized the DMAIC tool of Six Sigma for this project. This is a data-driven methodology for problem-solving, improving, optimizing, and stabilizing business processes and designs.

3.1 DEFINE

A project charter was created which served as a guide for the team throughout the project study and implementation. It is a brief document used to describe the problem statement, strategic objectives, stakeholders, and schedules. Below are the important information and an overview of the project charter.

3.1.1 Problem Statement

1) The 43 tools were approaching the end of life that have quality risks if not replaced.
2) High MFB yield loss at 19.287 defect index from Q3 to Q4 of 2021.
3) High CuP-related LRR Index at 5.35 and OCAP Index at 1.35 from July to December of 2021.

3.1.2 Strategic Objectives

The team aimed to resolve all challenges which are listed in the problem statement and to gain significant improvement. The following are the strategic objectives of this project:

1) Complete the replacement of the end-of-life tool by December 2022

2) To reduce the yield loss on MFB of Clip Bonded products from 19.287 to 9.643 defect index by the end of December 2022.
3) To reduce the CuP LRR by 50% from 5.35 to 2.675 defect index and OCAP of 1.35 to 0.675 defect index by the end of December 2022

3.2 MEASURE

The team has identified three problems that will be the focus of this study. These are end-of-life tools, high MFB yield loss, and high CuP OCAP and LRR.

3.2.1 End of Life Mold Tools

The 43 out of 54 mold tools of Nexperia Philippines were already at the critical level of its 300,000 strokes defined life, therefore replacement is necessary to maintain the quality of the products. If not, there will be quality risks to the customers, or the molding capacity will be reduced by 80%. Figure 6 shows the tool life status and age of mold tooling for the Clip Bonded line.

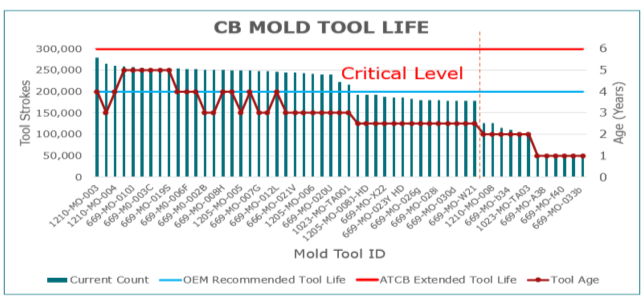

Figure 6: Mold Tool Life Status.

3.2.2 High Yield Loss due to MFB

Yield is one of the Key Performance Indices of Nexperia. Any yield loss means financial loss, which is why this is the top priority. Figure 7 shows the historical yield loss from Q3 to Q4 2021. The MFB was on top with an average of 19.287 defect index.

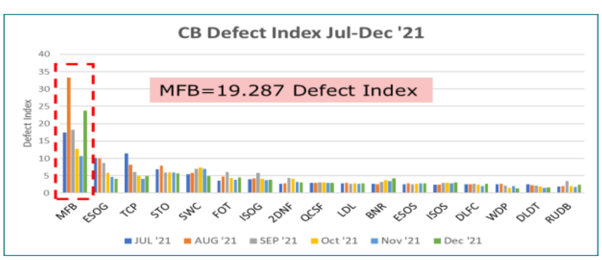

Figure 7: Top defect yield loss from June to December 2021.

Figure 8 shows that the MFB yield losses are evident across the four package types of Clipbonded products. It means there's a fundamental issue causing this defect.

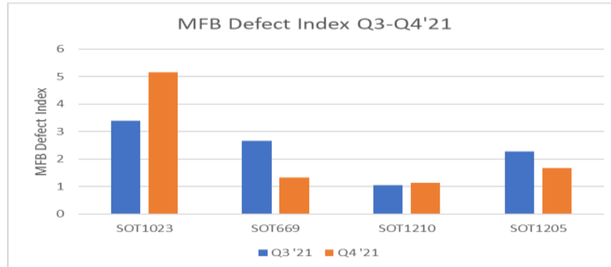

Figure 8: MFB defect index from Q3 to Q4 2021.

3.2.3 High LRR and OCAP due to CuP

The LRR and OCAP are also part of the KPIs of Nexperia to ensure that the organization is capturing the defects and thereby protecting the external customers.

3.2.4 High CuP Lot Rejection Rate (LRR) Index

The LRR is computed as the number of rejected lots over the total of lots produced. Figure 9 shows the LRR defect Index from July to December (Q3 to Q4) of 2021 with an average 5.35.

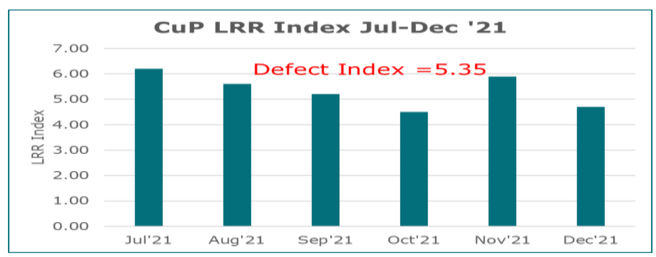

Figure 9: CuP LRR defect Index from July to December 2021.

3.2.5 High CuP Out of Control Plan (OCAP)Index

The OCAP is triggered when a certain lot was found with CuP during the inline monitoring by quality personnel or by the operator at Mold, TF, or test. It is a critical defect because it requires an X-ray to see the embedded copper inside the package which is a risk for potential electrical shorting. Figure 10 shows the OCAP defect index from July to December 2021 with an average of 1.35.

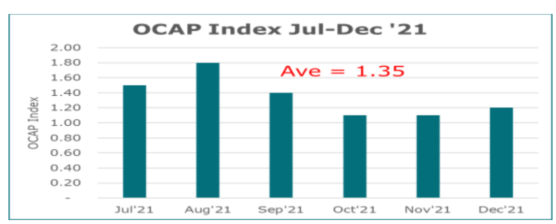

Figure 10: OCAP Index for CuP from July to December 2021.

3.3 ANALYZE

The defined tool life of 300,000 strokes was reviewed and the risk levels were assessed. This is to validate if the defined tool life was already optimized. The team utilized the Ishikawa diagram to fully understand and identify the root cause of MFB and CuP. All potential root causes were listed through brainstorming then each item was verified.

3.3.1 End of Life Mold Tools

The Original Equipment Manufacturer (OEM) of the tools recommended a 200,000 strokes tool life limit to guarantee the quality. The Nexperia team was able to extend the tool life to 300,000 strokes in the year 2020 through the enhancement of tool maintenance such as more frequent PM (preventive maintenance) and part-level tool life monitoring. Therefore, the 300,000-stroke life discussed in section 3.2.1 is considered as the optimized life already. Extending this further could result in quality issues or customer complaints.

3.3.2 The Yield loss due to MFB

The MFB is the plastic extended on the metal heatsink area. It is critical because it reduces metal contact with the board. The unit will be rejected if MFB goes beyond 10% of the heatsink surface as shown in Figure 11.

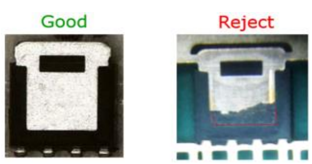

Figure 11: Comparison of good unit and MFB rejected unit.

Separate workshops were conducted with the OEM and the alternative supplier to get their input. Figure 12 shows the Ishikawa diagram for MFB. All potential root causes were listed by the team through brainstorming.

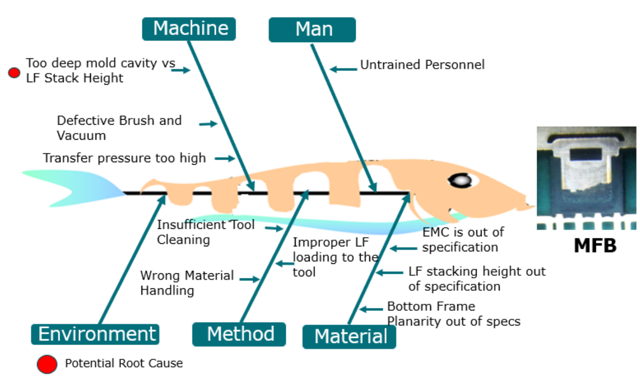

Figure 12: Ishikawa diagram for Mold Plastic at the Back (MFB).

Table 1 shows the validation plan and results for each hypothesis. Among the 10 potential root causes, the "too deep mold cavity compared to the stack height of lead frame assembly" was identified as a root cause.

Table 1: Root cause validation table for MFB.

Potential Root Cause	Validation Plan	Results	Remarks
Untrained Personnel	Review the training records of operators and technicians	All were certified	Not a Root Cause
Epoxy Mold Compound is out of Specifications	Review of MSDS and Inspection report	Within specifications	Not a Root Cause
Lead Frame stack height is out of specifications	Review of post DACA LF stacking height	Within specifications	Not a Root Cause
Bottom frame planarity out of specifications	Review of IQC report for BF planarity	Within specifications	Not a Root Cause
Improper LF loading to the tool	Check misload detection functionality and error logs	Sensors are working. No misload error logged	Not a Root Cause
Too Deep Mold Cavity vs LF Stack Height	Dimensional Simulations on Cavity Depth vs Stack Height	Dimensional Gap between LF Stack height and cavity depth.	Root Cause
Defective Brush and Vacuum	Check the functionality	Working	Not a Root Cause
Insufficient tool cleaning	Check the cleaning records	Within control limit	Not a Root Cause
Transfer Pressure too High	Check the parameters	Within control limit	Not a Root Cause
Wrong material handling	Check MPFM records and ECOI. Conduct audits	No deviation found	Not a Root Cause

3.3.2.1 Investigation Details for a Root Cause.

The identified root cause was thoroughly investigated. It was found that the gap between the cavity depth and the lead frame stacking height caused the MFB. As shown in Figure 13, the average actual stacking height was 0.53mm which was well within the limit. While the average depth for the mold cavity was 0.54mm which is the nominal also of the package parting line. Leaving a total gap of 0.01mm between the bottom frame and mold tool cavity surface. This is where the EMC penetrates. Any stack heights lower than the cavity depth are a risk to MFB.

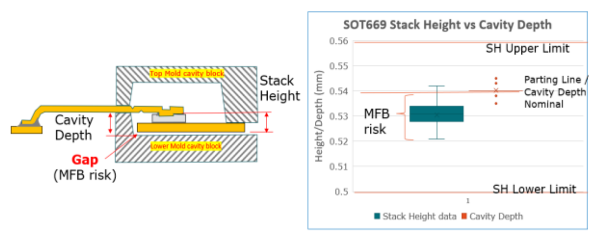

Figure 13: Gap between LF stack height and Mold Cavity Depth.

On the other hand, if the mold tool cavity is too shallow and the lead frame stack height is too high, it could result in solder crack due to high stress during mold clamping. Therefore, it is necessary to balance the actual lead frame stacking height and the depth of the mold cavity.

3.3.3 The High LRR and OCAP due to CuP

The CuP is any small copper particle embedded in the body of molded plastic as shown in figure 14.

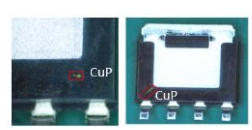

Figure 14: Photo of SOT669 unit with CuP.

The defect mechanism of CuP was carefully analyzed during the workshop with OEM and an alternative supplier. Both suppliers agreed that this was a result of pinching when a portion of the clip/lead frame is hit by the upper mold tool during clamping. Then the pinched copper mixed with the EMC on the succeeding mold shot resulted in CuP. Figure 15 shows the defect mechanism for CuP.

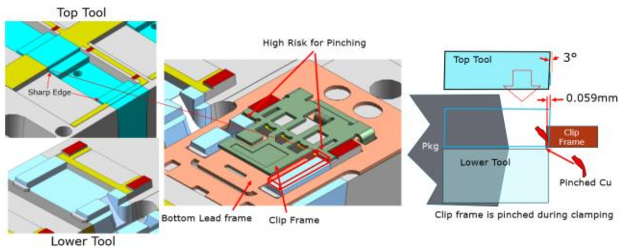

Figure 15: Defect mechanism of Copper on Plastic (CuP).

The CuP can be detected by x-ray, while those exposed to external surfaces can be screened by manual visual inspection. It hits the LRR when the lots are found with CuP at the central gate. The OCAP is done when CuP was found during the line inspection of the quality inspector or by the operator. This requires following the specific OCAP procedures for inspection, scoping, and machine interventions. Whether CuP is captured at inline processes or the central gate, both are causing additional costs for Nexperia. The Ishikawa diagram was utilized to understand the root cause of the CuP. Figure 16 shows the Ishikawa diagram for CuP where all potential root causes were listed by the team through brainstorming. Two items were identified as root causes.

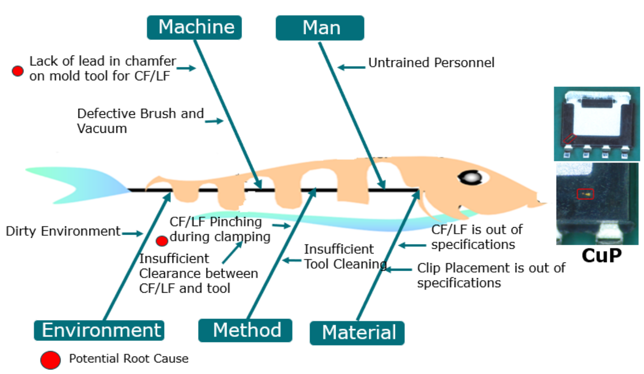

Figure 16: Ishikawa Diagram for Copper on Plastic.

Table 2 shows the validation plan and results for each hypothesis. Among the eight potential root causes, the lack of lead-in chamfer on the mold tool for the clip/lead frame and the insufficient clearance between the clip/lead frame and tool were confirmed as root causes.

Table 2: Root cause validation table for CuP

Potential Root Cause	Validation Plan	Results	Remarks
Untrained Personnel	Review the training records of operators and technicians	All were certified	Not a Root Cause
Clip Frame & Lead Frame are out of Specifications	Review the IQC data	All were with in specifications	Not a Root Cause
Clip Placement is out of specifications	Check escapee at Parmi AOI post DACA	No Escapee for swayed clip and tilted clips	Not a Root Cause
Lack of Lead-in Chamfer on mold tool for CF/BF	Review of part drawing	3-degrees draft angle with sharp edges	Root Cause
Defective Brush and Vacuum	Check the functionality	Working	Not a Root Cause
Insufficient clearance between CF/BF and Tool	Review of part drawing	Mold tool can't accommodate the max allowed swayed clip from DACA	Root Cause
Insufficient tool cleaning	Check the cleaning records	Within control limit	Not a Root Cause
Dirty Environment	Check the dust particle monitoring	With in control limit	Not a Root Cause

3.4 IMPROVE

3.4.1 End of Life Mold Tools

The capital investment for the replacement of 43 tools with robust design was approved. The production release was spread out within the year 2022 before the tool life limit is reached.

3.4.2 The Design Improvement for MFB Reduction

The team has recommended reducing the mold tool cavity depth but must be within the maximum limit of PAD to close the gap and address the MFB without violating the form, fit, and function of the product. The +/- 0.025mm tolerance of PAD was seen as the opportunity to close the dimensional gap between stack height and the mold cavity tool depth. As explained in Section 3.3.2.1, there's a gap of 0.01mm between the cavity depth and the stacking height causing the EMC to penetrate resulting in MFB. Therefore, adjusting the cavity depth by 0.02mm would resolve the issue. Figure 17 shows the comparison of the original and the more robust design.

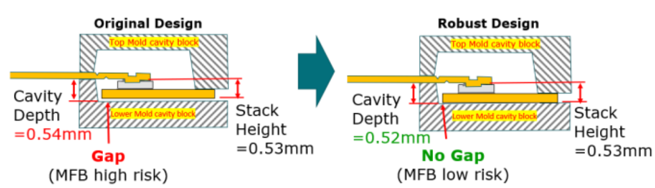

Figure 17: Dimensional comparison of original design and the robust design.

3.4.3 The Design Improvement for CuP Reduction

The variability in clip placement is inherited from the clip attach process. The root cause analysis confirmed that the maximum acceptable clip rotations could result in pinching and CuP when it reached the molding process. This was another focus of the team in enhancing the design of the mold tool. As shown in Figure 18, the original design has a 3° draft angle only with sharp corners which caused pinching during clamping. It was also found that the needed effective surface is just 0.20mm to prevent plastic leaks. With this realization, it was brought to an idea to enhance the outer portion of the top tool by adding a 20° lead-in chamfer for self-alignment of the clip/lead frame during clamping without pinching.

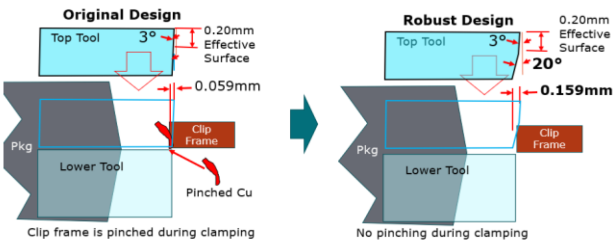

Figure 18: Comparison of original and the new robust design for CuP.

3.5 CONTROL

The pilot tool has undergone full qualification through QCM (Quality Change Management) with passing results on 1,000 Temperature cycles and 96 Hours UHAST. All relevant documents were updated to ensure that the newly deployed mold tools will be properly maintained, and the risks will be minimized. These include the Tooling Drawing, MRAT (Manufacturing Risk Assessment Tool), part 12NC number, and spare parts database.

4.0 RESULTS AND DISCUSSION

The deployment of the new tools was done across 2022 with high concentrations in Q2 and Q3. The impact of every tool deployment was carefully monitored and analyzed. This was compared to the listed objectives in Section 3.1.2.

4.1 Completion of replacement of end-of-life tools.

Figure 19 shows the progressive deployment of tools based on QCM production release dates. The prioritization was based on the remaining tool life of the tools, MFB ppm level, and the volume of the package. The replacement of end-of-life tools was completed in Q3 2022. The three other tools which were deployed in Q4 2022 were all spare tools or for SMED (Single Minute Exchange of Die) only. The project was completed ahead of schedule.

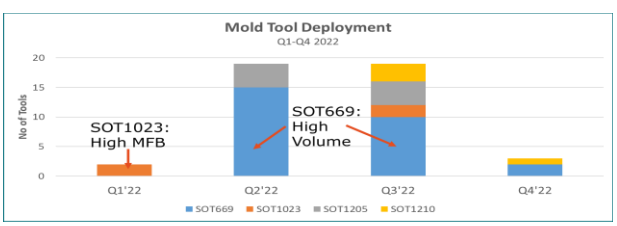

Figure 19: Completion of mold tool deployment Q1-Q4 2022.

4.2 Yield Improvement for MFB

Figure 20 shows that the MFB defect was reduced from a 19.287 defect index baseline in Q3 and Q4 of 2021 to a 3.918 defect index in Q3 of 2022 after the completion of tool replacement. This was equivalent to an 80% reduction, which is above the set target of this project.

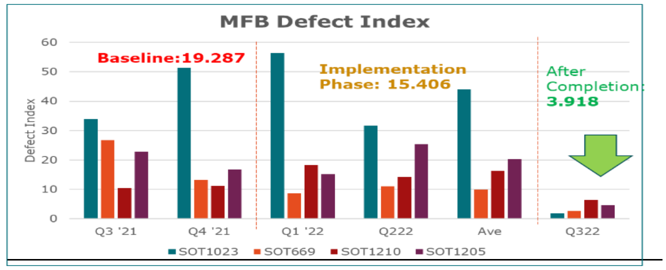

Figure 20: MFB defect index comparison before and after project implementation from Q3 of 2021 to Q3 of 2022.

Through the help of the finance team, the gained yield in MFB was translated into financial value in Table 3. The 80% (15.369 defect index) MFB reduction gave Nexperia a savings of $ 2,066,000 per year for combined die-free product cost (DFPC) and cost of the die.

Table 3: Equivalent Savings from MFB PPM improvement.

MFB COST SAVINGS	ANNUAL AMOUNT	
Cost of Die	$	1,420,000
Die Free Product Cost	$	646,000
	$	**2,066,000**

4.3 Reduction of Lot Rejection Rate for CuP

Figure 21 shows that the LRR defect index was reduced from 5.35 of the baseline periods (Jul – Dec '21) to 1.32 in Q3 (Jul-Sep) of 2022. This was a 75% reduction which was higher than the set target for this project.

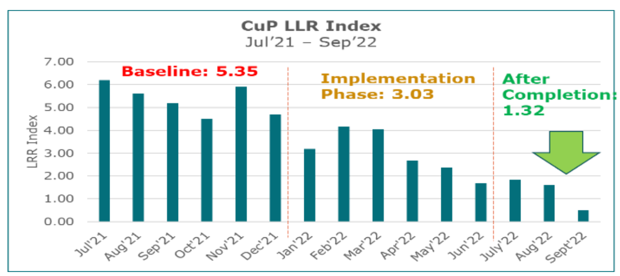

Figure 21: LRR Index Reduction for CuP from Jul '21 to Sep '22.

The reprocess due to CuP requires 100% X-ray, 100% VI, and Sorting. The LRR index reduction of 4.03 has equivalent number of lots of 409.9 per year. This is equivalent to cost savings of $18,466 per year as shown in Table 4.

Table 4: Cost Savings from CuP LRR Reduction.

Reprocessed Lot	Before	After	Reduction	Equivalent Lot / Yr	Reprocess Cost / Lot	Annual Savings
CuP LRR Index	5.35	1.32	4.03	409.9	$ 45.00	$ 18,446

4.4 Reduction of OCAP for CuP

Figure 22 shows the reduction of OCAP or line-detected CuP defect. The OCAP was reduced from 1.35 defect index baseline from July to December 2021 using the old tools down to 0.53 defect index in using new tools from July to September 2022. This was a 60% reduction, which is above the set target.

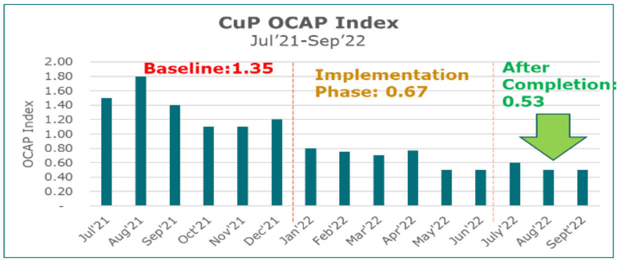

Figure 22: OCAP Index Reduction for CuP from Jul '21 to Sep '22.

The reprocess for this OCAP trigger is like LRR detection which requires 100% Xray, 100% VI, and Sorting. This improvement was equivalent to $3,988 in cost savings per year as shown in table 5.

Table 5: Cost savings from CuP OCAP reduction.

Reprocessed Lot	Before	After	Reduction	Equivalent Lot / Yr	Reprocess Cost / Lot	Annual Savings
CuP OCAP Inde	1.35	0.53	0.82	88.6	$ 45.00	$ 3,988

4.5 *Manpower Head Count Reduction*

The significant reduction in MFB has opened another cost savings opportunity for Nexperia Philippines. The number of visual inspectors was reduced from 45 to 7 headcounts, which gave the company $17,100 annual savings as shown in Table 6.

Table 6: Cost savings from head count reduction

	Before	After	Savings	Cost per Head	Annual Savings
MFB Visual Inspector	45	7	38	$ 450.00	$ 17,100.00

4.6 *Overall Cost Benefits and Return of Investment (ROI)*

The overall cost savings of this project were $2.1M as shown in table 7. This design robustness gave the $3.48M unavoidable investment for tool replacement a short ROI of 2.2 years.

Table 7: Cost savings from head count reduction

Overall Cost Savings	Annual Savings
MFB PPM Reduction (DFPC & Cost of Die)	$ 2,066,000
CuP LRR Reprocess Cost Savings	$ 18,446
CuP OCAP Reprocess Cost Savings	$ 3,988
MFB Visual Inspection Direct Labor Savings	$ 17,100
	$ 2,105,535

5.0 CONCLUSION

The more robust design of new mold tools was found to be effective in reducing the MFB and CuP. This improvement gave a significant return for the recurring capital expenses in replacing the end-of-life tools. The project has generated a total of $2,105,535 in cost savings and reduced the risk of Lot Rejection Rate by 75%, and OCAP reduction by 60%. These improvements gave a better-quality firewall for the customers.

6.0 RECOMMENDATIONS

The authors highly recommend the implementation of a more robust design in every tool replacement to maximize the return on investment. The low cavity and the chamfer designs are recommended for immediate fan-out to all Nexperia back-end sites and its external manufacturers. It is also recommended that the mold tool be refurbished after the first 300K strokes, then replaced after the second tool life.

7.0 ACKNOWLEDGMENT

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