ALIGNED FOR SUCCESS: THE JOURNEY TO REDUCING PACKAGE MISALIGNMENT THROUGH ROBUST DESIGN OPTIMIZATION AND LEADFRAME DESIGN INNOVATION

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ABSTRACT

Texas Instruments Clark introduced Wide Lead Frame (WLF) as roadmap package into the assembly line. However, along with the introduction of the WLF, new challenges arrived in Saw Singulation Process with yield killer mainly contributed by Saw Mechanical Defects Package Mis-alignment (PKMA) due to the inherent WLF properties of curved leads and warpage.

In this paper, specific systemic & technical solutions were tailored from lead frame design & DMAIC methodology was used to reduce the PKMA defects by curve leads and warpage. These approaches have led to significant improvements in yield, efficiency, and productivity, resulting outstanding outcomes with the resources already at disposal and engineering ingenuity.

1. 0 INTRODUCTION

Clark WLF is an extended version of the normal production lead frame size. It removed supporting panels in between the lead frame and reduce the fiducial area around the lead frame edge. This maximized the units per strip in similar print from up to 94% gain from baseline Fig. 1.0 shows the comparison between Standard Lead Frame (SLF) vs WLF. However, with the lessen supporting structure, it has a weaker lead frame support.

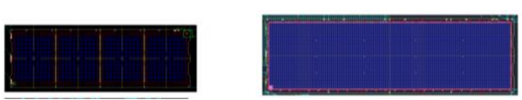


Fig. 1.0. Comparison between standard lead frame (left) and wide lead frame (right)

1.1 Molding Process and Lead Frame Deformation of Small Outline no-Lead Package (SON)

Molding Process in quad flat no-leads assembly process is also known as encapsulation process. It utilizes the panel molding technology to encapsulate the lead frame with Epoxy Mold Compound (EMC) protecting the critical and fragile component of an Integrated Circuit. (Fig. 1.1).

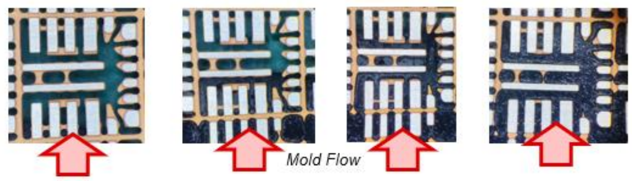


Fig. 1.1. Encapsulation Process

The connecting bar that form the interconnection between the units within a WLF panel is known as Tie Bar, and together with the designated lead area, it forms an exclusion zone known as saw street, which to be removed after Package Saw Process. Fig. 1.2 demonstrate the small outline no-lead package (SON) interconnecting tie bar.

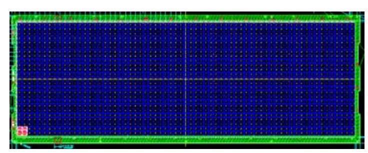


Fig. 1.2. Interconnecting Tie Bar links up all the units within a WLF Panel

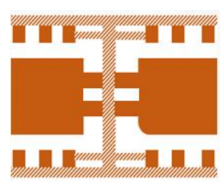


Fig. 1.3. Detailed illustration on Interconnecting Tie Bar between units.

During the transfer process of the EMC, it induces stress and create drag force as the EMC flow through the lead frame. This created a curvature across the lead frame within the highest drift at the center area. Fig 1.4 demonstrate the comparison between an original saw street.

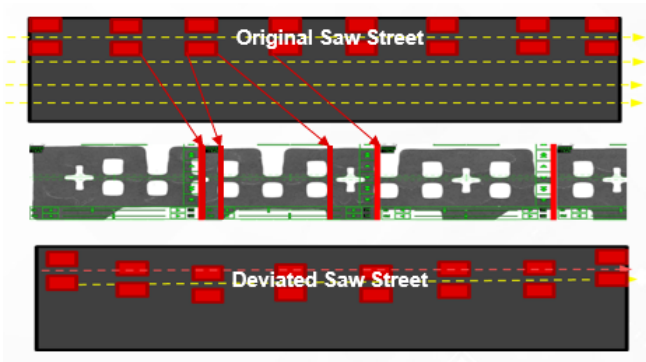


Fig. 1.4. Saw street deviation due to tie bar shifting

1.2 Package Singulation Process and Package Misalignment

Package singulation process is a process where the units are isolated from the strip form as individual functional units. It is usually the last processing step of a QFN Assembly Process. The package singulation process works by getting a number of fiducial target and form a desired or virtual cutting line through the alignment process. Once the alignment process is completed, the machine will then perform an actual cutting line based on the virtual cutting line. Fig. 1.5 shows a typical virtual cutting line without minimal deviation on saw street, the post-cut line is aligned properly with the virtual cutting line, and the singulated units are symmetrical.

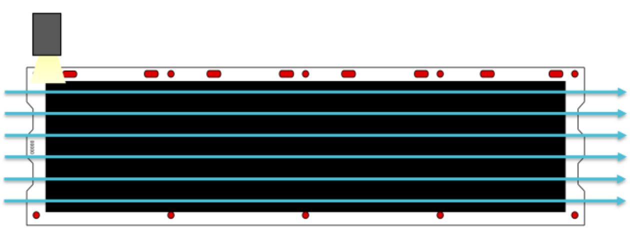


Fig. 1.5. Singulation with minimal fiducial deflection.

However, when there is a deviation on the saw street, the actual cut line will not be able to singulate all units along the cutting line symmetrically (Fig. 1.6 demonstrates the deviation of saw street and actual cutting line), causing an offset cutting for some of the units, package mis-alignment (PKMA) is then created. PKMA as shown in Fig. 1.7 happened when there is offset within a unit, and it is subject for rejection if the offset amount exceeds 50um.

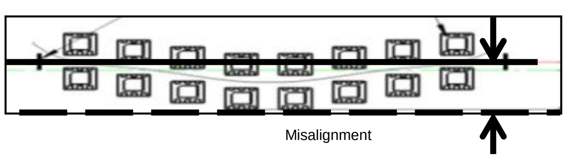


Fig. 1.6. Singulation with High fiducial deflection

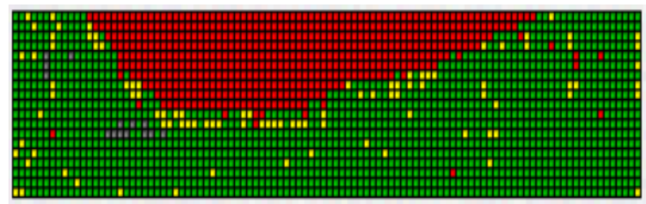


Fig. 1.7. Actual location of PKMA in the strip

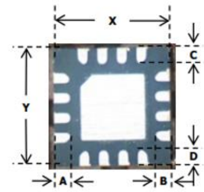


Fig. 1.8. PKMA signature and rejection criteria (A-B)/2

1.3 Tape Saw and Jig Saw Process Limitation

Tape saw process is a branch of saw singulation process which utilize the tape to hold the subject WLF for cutting, the tape is one-time use, and disposed after the singulated units are removed from the tape. On the other hand, Jig Saw process utilized fixed rubber to hold the material, and can be re-used until it reaches its lifespan.

Typically, tape saw process has a higher tolerance to saw street deviation as halved-cut process can be applied to partially compensate part of the deviation. Fig. 1.9 shows tape saw halve cut process

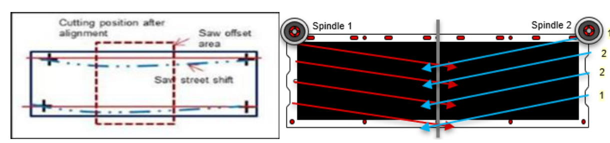


Figure 1.9. Tape Saw Halve-Cut Process.

Jig Saw Process, however, is more sensitive to saw street deviation as halve-cut process will damage the rubber underneath (Fig. 1.10), and thus, can only perform full cut.

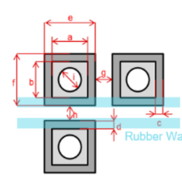


Fig. 1.10. Jig Saw Chuck rubber damage due to shifted cutline.

2. 0 REVIEW OF RELATED WORK

Not applicable.

3.0 METHODOLOGY

The methodological structure adopted in this study follows the Lean Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) approach. The goal is to identify potential root causes of yield loss and validate real causes through quantitative analysis and simulations.

3.1 Define Phase

Initial yield analysis revealed that the top contributor of yield loss in WLF is package misalignment, accounting for 22% of the total rejects.

3.2 Measure Phase

Using a fishbone (ishikawa) diagram, the team systematically identified all of the possible factors of package misalignment. These were categorized under the 4M framework: Man, Machine, Method, and Material. A total of 17 factors were identified which are shown below (Fig.3.1).

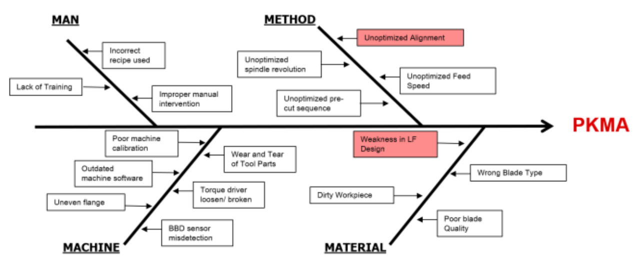


Fig. 3.1. Fishbone Diagram of Package Misalignment

In addition, measurement on lead curvature and tie bars were conducted and examined to confirm structural strength. The metal at the saw street of the longer side of the strip tends to bow and deform after molding process leading to incoming street offset at package saw and causing package misalignment (offset cut) as shown in Fig. 3.1. The displacement was measured at >0.52um which is beyond the allowable movement by saw machine.

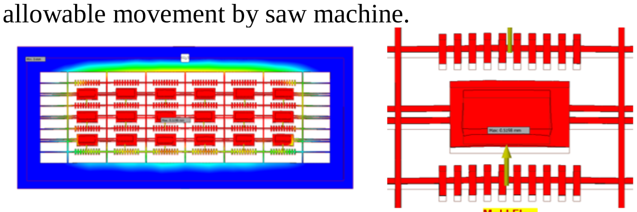


Fig. 3.2. Standard design shows high deviation during mold flow simulation at 150kN assumed force

3.3 Analyze Phase

During the mold simulation, the mold process is inducing mechanical stress on the lead frame. This stress is more pronounced in small outline no-lead (SON) devices due to their lack of structural support compared to quad flat no-lead (QFN) devices. During saw singulation, the cutting blade operated in a single direction and processing these high lead curvature strips with this method will lead to PKMA as shown in Fig. 1.6.

Elimination method was used to systematically narrow down the 17 potential root causes identified for package misalignment (PKMA) as shown in Fig.3.3.

4M+E	Factor	Verification	Findings	Conclusion
Man	Incorrect recipe used	Training and Certification	PS is trained and certified	Not a Cause
	Lack of Training	Training and Certification	PS is trained and certified	Not a Cause
	Improper manual intervention	Check if Specs are updated	Specs are updated and PS are trained	Not a Cause
Method	Unoptimized spindle revolution	Recipe Check and Simulation	Defined and standard parameters	Not a Cause
	Unoptimized Alignment	Recipe Check and Simulation	Using two-points alignment	Cause
	Unoptimized Feed Speed	Recipe Check and Simulation	Defined and standard parameters	Not a Cause
Machine	Poor machine calibration	Health Check and Audit Quarterly PM	Quarterly check of tool calibration is being done	Not a Cause
	Outdated machine software	Software verification	Tape saw tools are updated	Not a Cause
	Uneven flange	Health Check and Audit Quarterly PM	Flange is okay and quarterly PM is being done	Not a Cause
	Wear and Tear of Tool Parts	Health Check and Audit Quarterly PM	Machine parts are in good condition	Not a Cause
	Torque driver loosen/ broken	Health Check and Audit Quarterly PM	Quarterly PM is being done	Not a Cause
	BBD sensor misdetection	Tool Health Check	BBD sensor is okay and control is in place	Not a Cause
Material	Weakness in LF Design	Simulation and DOE	High lead curvature >60 um, High risk of Warpage >4mm	Cause
	Wrong Blade Type	Tool logs Check	Actual blade used and KParm is correct	Not a cause
	Poor Blade Quality	Actual blade check	Blade is qualified	Not a Cause
	Dirty Workpiece table	Actual Tool Check	Cleaning of chuck table is included in the SOP, specs updated	Not a Cause

Fig. 3.3. Verification Table

To further analyze, the team conducted curvature profiling by measuring 10 reference points across the strip, mapping the curvature behavior of the saw street. The profiling revealed two distinct types of curvature patterns: Symmetrical curvature and Asymmetrical curvature, as illustrated in Fig. 3.4.

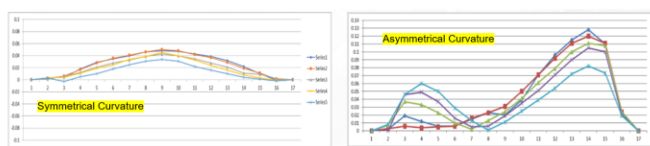


Fig. 3.4. Symmetrical and Asymmetrical Curvature

Furthermore, the team conducted simulations before prototyping. By introducing additional metal support to the leads structures and simulating the mold flow process, the team was able to redistribute the stress across the lead frame. This design modification significantly improved structural stability, achieving a displacement deviation of only 8um, effectively eliminating the high-stress areas identified in the original design as shown in Fig. 3.5.

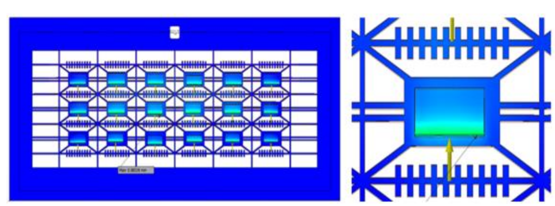


Fig. 3.5. Improved design shows minimal deviation during mold flow simulation.

Based on these analyses, the team was able to determine one confirmed root cause and two contributing factors:

a. Root Cause: Lead frame design weakness
b. Contributing Factors: Unoptimized strip alignment and saw cutting sequence

3.4 Improve Phase

This phase outlines the corrective actions implemented to address the identified root causes. Detailed performance outcomes are further presented in Section 4.0 – Results and Discussion.

3.4.1 Robust Process Optimization

The primary challenge addressed was the variability introduced by the two distinct curvature types as shown in Fig.3.4. To manage this, the team applied the least square method to determine the optimal alignment and cutting sequence for each curvature type.

The least square method is the mathematical capability of the tool to find the best-fit line or function that minimizes the sum of the squared differences between observed and predicted values. Essentially, it aims to reduce the overall error between the data and the fitted function. This approach allowed the team to:

a. Minimize alignment error across varying strip curvature profile
b. Establish regression models to describe curvature behavior
c. Tailor cutting strategies based on localized linear trends

X (strip distance)	Y (offset)
0	0
36.81	0.056
73.62	0.078
110.43	0.074
147.24	0.088
184.05	0.078
220.86	0.054
257.67	0.025
289.87	0

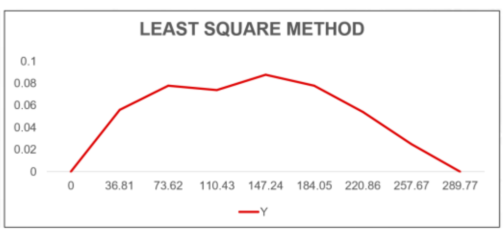


Fig. 3.6 Sample linear regression graph of the strip showing symmetrical curvature

Recognizing the importance of data points for accurate best fit-line or actual blade cutline determination, the team will be able to standardized and determine what alignment points should be consider when generating the recipe.

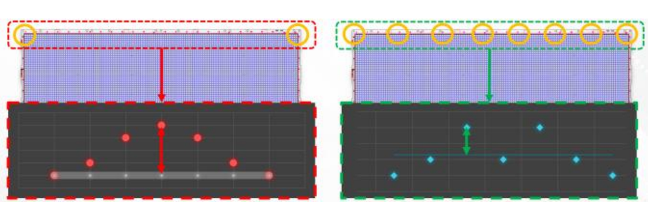


Fig. 3.7 Sample alignment points difference between 2-point and 8-point alignment

3.4.2 Lead frame Design Innovation

The prototyped additional support to the leads is 3-tie bar design and cross junction specifically for SON devices which was patented and publicized. The detailed design is described in publication number 20240178106 by Mateo, D.H (2024).

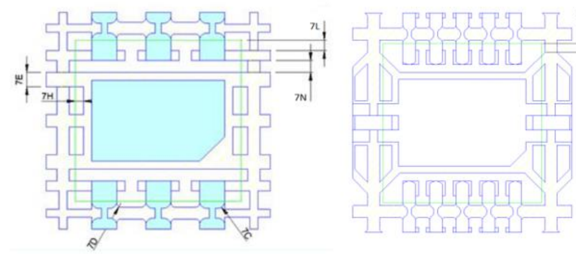


Fig. 3.8. The 3-tie bar design (left) and cross junction design (right)

3.5 Control Phase

To monitor the long-term and short-term effectiveness of the implemented action, the team executed 3+20 qualification lots using the new lead frame design. Continuous PKMA DPPM monitoring was also performed after recipe optimization. Moreover, all process and material changes including alignment strategy, regression-based cutting sequence, and mechanical design improvements, were fully documented in updated specifications and are now patented as part of the company's intellectual property.

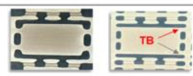
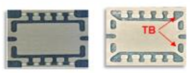
4.0 RESULTS AND DISCUSSION

4.1 Recipe Process Optimization and Lead frame Design Innovation

Following the identification of the optimal best-fit line method to calculate the best-fit line for strip alignment and actual cutting, the team conducted a detailed regression analysis for each package. This analysis determined the ideal cutting sequence, number of alignment points, and alignment points locations across the strip. The optimized saw recipe was gradually fanned out.

For the long-term solution, the new lead frame design was developed and qualified for 3X3 and below WLF packages. Post-implementation data shows significant reduction on leads curvature. Curve lead reduction was measured at around 22% depending on the package size. Table shows the measurement results on curvature.

Table 1. Lead Curvature Reduction using new LF design

Lead Frame	Design (From-To)	Lead Curvature Improvement
Lead frame A		21% reduction
Lead frame B		22% reduction
Lead frame C		21% reduction

Qual and 20 lots data has been released to monitor the optimized recipe as well as the lead frame design effectiveness. Lead frame A design demonstrated a 5.73% improvement in yield compared to the baseline. Lead frame B improved the device yield to 6%, while Lead frame C has a significant increase of 15.6% yield from the device baseline. In parallel, the implementation of optimized process recipe to legacy lead frames resulted in around ~50% yield improvement prior to the phase out of the old design.

4.2 Project Impact

The implementation of the improvement project yielded significant benefits in yield, cost, and productivity. A notable overall WLF yield increase of 1.2% was observed, corresponding to an 85.7% reduction in PKMA defective parts per million. This improvement translated to estimated cost avoidance of around $2.9 million from scrapped units attributed to PKMA-related defects.

In addition, a 76.9% reduction in pad smear DPPM was achieved, primarily due to the decreased of the occurrence of marginal PKMA. This contributed around $900K in cost avoidance from scrap reduction associated with pad smear defects.

Furthermore, the initiative positively impacted equipment utilization. Overall equipment utilization improved, resulting in around $100K cost avoidance from mitigated capacity loss due to tool downtime related to critical defects.

These results demonstrate the effectiveness of the implemented actions enhancing yield, reducing scrap-related losses, and improving manufacturing efficiency.

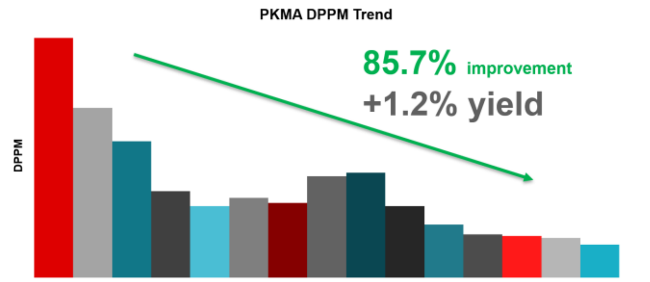


Fig. 4.4 Package misalignment parts per million trends upon implementation of defined actions.

5.0 CONCLUSION

This study successfully addressed the high package misalignment (PKMA) DPPM in the wide lead frame (WLF) through a structured application of the Lean Six Sigma DMAIC methodology. Root cause analysis identified lead frame design weakness, unoptimized alignment, and cutting sequence as the primary contributors to PKMA.

Targeted improvements were implemented, including curvature profiling, regression-based recipe optimization, and a redesigned lead frame with enhanced structural support. The first two actions were able to compensate the high curvature in the existing lead frames for process, while the last action resulted a significant decrease in lead curvature—up to 22% in some WLF package types.

The robustness and effectiveness of the solution were validated through 3+20 qualification lots and proceeding with continuous DPPM monitoring. All innovations were formally documented and patented to support long-term implementation.

Overall, the initiative not only reduced defect rates and scrapped material costs but also contributed to improved equipment utilization and long-term process stability.

6.0 RECOMMENDATIONS

Building on the success of regression-based alignment and cutting optimization, future work may focus on integrating artificial intelligence and machine learning techniques to further enhance accuracy, adaptability, and automation of the process.

Specifically, the use of supervised learning models such as regression algorithms can help predict optimal alignment and cutline paths based on historical curvature data and tool parameters.

These models can learn complex, nonlinear relationships that go beyond what traditional least squares methods can offer. Furthermore, implementation of real-time image recognition and feedback systems combined with Al can enable dynamic adjustment of alignment points and cutting paths based on actual strip deformation detected in-line-thus moving toward a smart, self-correcting process.

Over time, such a system could:

a. Reduce reliance on fixed recipe configurations Automatically detect and classify curvature types (symmetrical vs. asymmetrical)
b. Recommend or execute the best-fit cutting strategy per strip
c. Continuously improve through data accumulation

The integration of Al will not only further reduce PKMA occurrence but also elevate the manufacturing line's responsiveness, efficiency, and scalability across multiple package types and configurations.

7.0 ACKNOWLEDGMENT

The team extends their sincere thanks to the TICL EOL team for their valuable input and dedicated efforts in this study. The team also appreciate the management team for their invaluable guidance, constructive criticism, and continuous support in implementing the solutions and innovations shared in this paper. Special thanks to the manufacturing team for their support in conducting this study.

8.0 REFERENCES

1. Mateo, D.H.," Leadframe Apparatus, Semiconductordevice and Method of Making Semiconductor Device, Publication Number: 20240178106 (2024)
2. Design Rule POR 6512539

9.0 ABOUT THE AUTHORS

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