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Modification and Implementation of a Dual-Variant Compatible Sheet Metal Welding Fixture for Flexible Manufacturing in a Live Production Line

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***Abstract* - The shift towards multi-variant production in the automotive industry has created a strong need for flexible manufacturing systems. This paper presents the modification of a welding fixture system to enable dual-variant production in an automotive Body-in-White (BIW) assembly line without changeover time. The existing fixture was redesigned using the 3-2-1 locating principle, incorporating reconfigurable elements and pneumatic clamping to ensure accurate positioning, stability, and repeatability during welding. The implementation was carried out in a live production environment without interrupting operations. Performance was evaluated through cycle time analysis across nine stations. The results show a reduction in cycle time variation and elimination of bottlenecks, leading to an improvement in line efficiency from 96.9% to 98.15%. The modified system successfully supports two different component variants on a single production line while maintaining dimensional accuracy and consistent weld quality. This approach demonstrates a cost-effective method to enhance manufacturing flexibility, improve resource utilization, and achieve stable production in high-volume automotive manufacturing and production environments.**

Keywords: Flexible manufacturing, welding fixture, dual-variant system, BIW assembly, reconfigurable fixtures, 3-2-1 principle.

I. INTRODUCTION

The automotive industry is increasingly adopting flexible manufacturing systems to accommodate multi-variant production within a single assembly line. In Body-in-White (BIW) assembly, welding fixtures are critical for ensuring accurate positioning, dimensional stability, and repeatability of sheet metal components during welding operations [3], [5]. Conventional fixtures are typically designed for single variants, resulting in increased downtime, higher costs, and reduced production flexibility during changeovers.

To overcome these limitations, reconfigurable and flexible fixture systems have been developed, enabling adaptation to multiple product variants with minimal modification [1], [2]. The 3-2-1 locating principle is widely used to constrain all degrees of freedom of the workpiece, ensuring precise positioning, while pneumatic clamping systems provide consistent clamping force and rapid actuation for improved process reliability [4], [7].

However, limited work exists on modifying existing fixtures in live production environments without interrupting operations. This study addresses this gap by developing a dual-variant compatible welding fixture system through modification of existing fixtures. The proposed approach integrates reconfigurable elements and pneumatic clamping to enable zero changeover production. Performance is evaluated using cycle time analysis and line efficiency, demonstrating improved line balancing and production efficiency.

1.1 Production Line Overview

The BIW production line consists of nine sequential stations performing loading, locating, clamping, spot welding, and unloading operations. Each station uses welding fixtures based on the 3-2-1 locating principle to ensure accurate positioning and repeatability. Pneumatic clamping systems provide consistent clamping force and rapid actuation during welding.

The line operates on a fixed takt time with synchronized station activities for continuous production. Initially designed for single-variant production, the system required modification to support dual-variant manufacturing without affecting line balance or production continuity.

II. LITERATURE REVIEW

Welding fixtures are critical in BIW assembly for accurate positioning and weld quality, with the 3-2-1 locating principle widely used to ensure proper constraint and repeatability [3].

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Conventional fixtures are designed for single variants, limiting flexibility in modern multi-variant production systems. Flexible and reconfigurable fixtures enable adaptation to different component geometries with minimal modification, improving productivity and reducing downtime [1], [2]. Pneumatic clamping systems are commonly used for consistent force application and rapid actuation in high-volume production [5].

However, most studies focus on new fixture designs, with limited work on modifying existing fixtures in live production. This gap is addressed by developing a dual-variant compatible fixture system without interrupting production.

2.1 Fundamentals of Welding Fixtures

Welding fixtures are specialized devices used to hold and position components during welding. Their primary function is to ensure that each part is consistently located in the correct position, thereby maintaining dimensional accuracy across production batches [3]. A well-designed fixture improves productivity, reduces human error, and enhances weld quality.

2.2 Locating Principle

The locating principle is a fundamental concept in fixture design used to restrict all six degrees of freedom of a workpiece. By placing three locators on a primary plane, two on a secondary plane, and one on a tertiary plane, the workpiece is fully constrained without being over-restricted [4]. This method ensures stability and repeatability, making it widely applicable in automotive manufacturing.

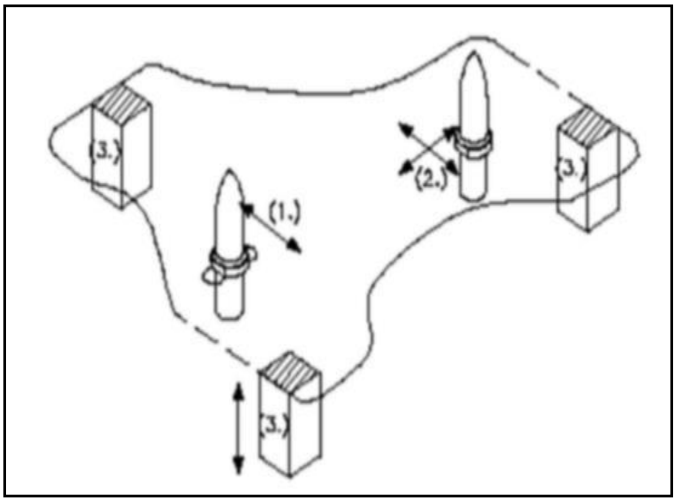

Figure 1: Locating Principle for Sheet Metal

2.3 Point in Specific Tolerance (PIST) Concept

PIST is used to ensure that critical points of a component remain within specified tolerance zones during assembly. It is particularly important in automotive welding fixtures where dimensional variation directly affects assembly quality. By integrating PIST with fixture design: Dimensional accuracy improves, Assembly variation reduces and Rework is minimized

2.4 Pneumatic Clamping System

Pneumatic clamping systems are widely used in welding fixtures to provide consistent clamping force, rapid actuation, and reliable operation in high-volume production environments. Compared to manual clamping, they reduce human variation and improve process stability during welding [5], [7]. The use of pneumatic cylinders ensures uniform holding of components, minimizes displacement during welding, and contributes to improved dimensional accuracy and repeatability in BIW assembly [3], [5].

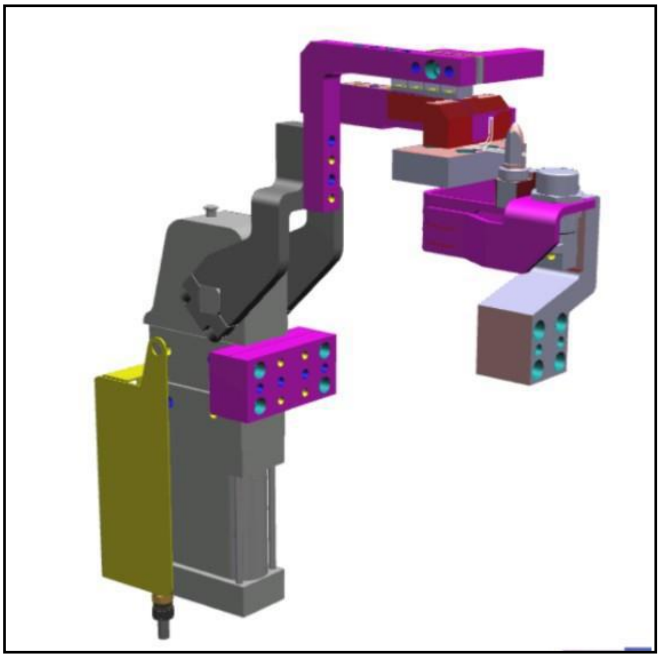

Figure 2: Pneumatic Clamping Used in the Fixture

2.5 Flexible and Reconfigurable Fixtures

Flexible and reconfigurable fixtures are designed to support multiple product variants using adjustable locators, modular elements, and pneumatic clamping. Unlike dedicated fixtures, they can accommodate geometric variations without complete redesign, thereby reducing changeover time and improving production flexibility [1], [2]. Such systems are widely applied in automotive BIW assembly to maintain dimensional accuracy and consistent weld quality while supporting multi-variant manufacturing [3], [5].

III. METHODOLOGY

A structured approach was followed to modify the welding fixtures:

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3.1 Analysis of Existing Setup

The existing welding fixture system was systematically analyzed to understand its configuration, functionality, and limitations with respect to multi-variant production. The study focused on evaluating locator positions, clamping arrangements, and support structures used in the current setup. This analysis provided a clear understanding of the constraints present in the existing production system.

3.2 Identification of Modification Requirements

Based on the analysis of the existing setup, the requirements for modification were identified. Key aspects considered included adjustment of locator positions, modification of clamping reach, and improvement in accessibility for welding operations. The objective was to adapt the existing fixture system to accommodate variations in component geometry while maintaining dimensional accuracy.

3.3 Fixture Modification Approach

Instead of developing a completely new fixture, modifications were carried out on the existing system to improve flexibility. In addition, the concept of Point in Specific Tolerance (PIST) was considered to ensure that critical points of the component remained within acceptable tolerance limits after modification.

3.4 Implementation in Production Line

The modified fixture system was implemented during planned maintenance intervals to avoid interruption of ongoing production. Trial runs were conducted to verify proper fitment, welding accessibility, and operational performance. Minor adjustments were made based on observations during the trials.

3.5 Data Collection and Line Efficiency Evaluation

Production data was collected from an automotive manufacturing company under confidentiality. Cycle time data for each station was collected from an automotive production line for both conventional and dual-variant systems under normal operating conditions. The data was used to identify bottlenecks and evaluate line performance.

Line efficiency was calculated using:

$$\text{Line Efficiency} = \frac{\sum t_i}{N \times CT} \times 100$$

Where t_i is station cycle time, N is the number of stations, and CT is the maximum cycle time.

3.6 Validation and Performance Assessment

The performance of the modified fixture was validated through dimensional inspection, weld quality evaluation, and operator feedback. The inspection ensured that all critical dimensions were within tolerance limits, while weld quality checks confirmed process stability. The successful validation demonstrated that the modified fixture system could support dual-variant production without compromising quality or efficiency.

IV. FUNDAMENTALS OF BIW AND WELDING FIXTURES

Body-in-White (BIW) refers to the stage in automotive manufacturing where all sheet metal panels are assembled and welded together before painting and final finishing operations. At this stage, structural components such as the floor, side-walls, roof, and reinforcement members are joined to form the vehicle body structure.

Welding fixtures play a critical role in BIW assembly by ensuring accurate positioning and alignment of individual components during welding operations. These fixtures are designed to maintain dimensional consistency across all produced units, which is essential for maintaining product quality and assembly compatibility.

A typical welding fixture consists of:

- Locators for positioning the component
- Clamps for holding the component securely
- Supports to prevent deformation
- Base structures for stability

Proper integration of these elements ensures that the work- piece remains stable during welding, thereby reducing distortion and improving weld quality.

V. VEHICLE LINE COORDINATE SYSTEM AND REFERENCE FRAME

In automotive manufacturing, particularly in Body-in-White (BIW) assembly, a standardized line coordinate system is used as a reference framework for defining the position and orientation of components. This coordinate system ensures consistency in design, manufacturing, and inspection processes across the production line.

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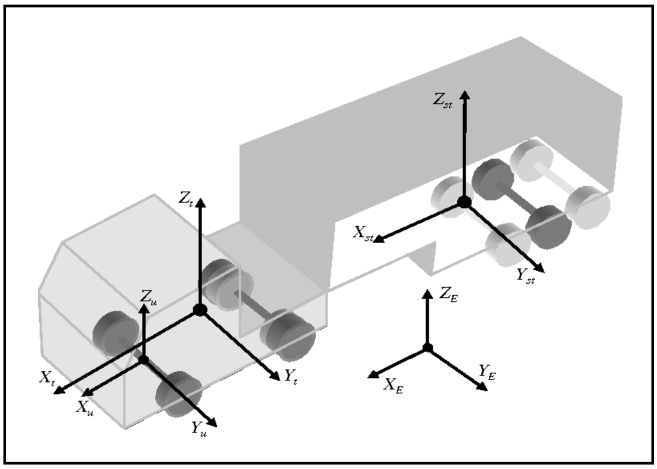

Figure 3: Vehicle Line Coordinate System

The vehicle line coordinate system is defined by using three mutually perpendicular axes, namely the X-axis, Y-axis, and Z-axis. The X-axis represents the longitudinal direction of the vehicle and is typically referenced from the front axle center. The Y-axis represents the lateral direction and corresponds to the centerline of the vehicle body. The Z-axis represents the vertical direction and is generally defined from the top surface of the floor or reference plane. The origin of the coordinate system is defined at the intersection of these three axes. In standard industrial practice, the X-axis origin is taken at the front axle center, the Y-axis origin lies along the centerline of the vehicle, and the Z- axis origin is referenced from the floor level.

VI. RESULTS AND DISCUSSIONS

6.1 Cycle Time Analysis and Line Balancing

The cycle time at each station for both the conventional line and the dual-variant compatible line was analyzed and shown in Table 1.

Table 1: Cycle Time Comparison Table

Station No.	Conventional Line (min:sec)	Dual-Variant Compatible Line (min:sec)
10	4 min 30 sec	4 min 30 sec
20	4 min 36 sec	4 min 27 sec
30	4 min 28 sec	4 min 26 sec
40	4 min 27 sec	4 min 25 sec
50	4 min 27 sec	4 min 25 sec
60	4 min 24 sec	4 min 24 sec
70	4 min 35 sec	4 min 26 sec
80	4 min 23 sec	4 min 22 sec
90	4 min 20 sec	4 min 20 sec

The collected cycle time data was used to evaluate line performance and calculate line efficiency.

The graphical comparison is shown in Fig. 4.

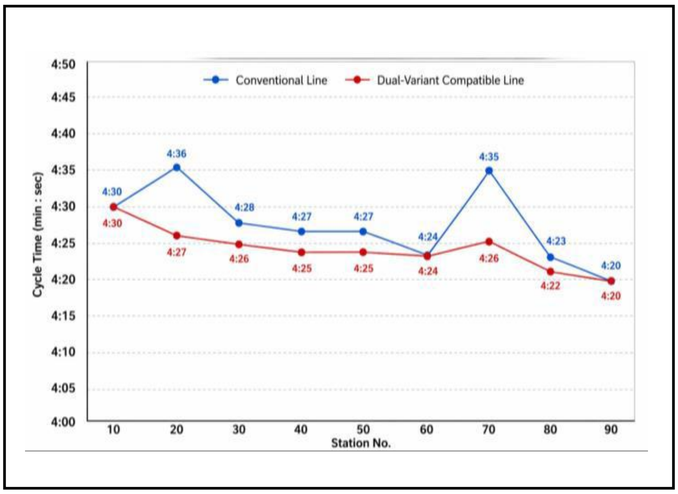

Figure 4: Cycle Time Comparison Between Conventional Line and Dual-Variant Compatible Line

From the plotted graph:

- The conventional line shows significant peaks at Station 20 and Station 70, indicating poor load distribution and presence of bottlenecks.
- The dual-variant compatible line shows a smoother trend, indicating uniform workload distribution across stations.

This confirms improved line balancing in the proposed system.

6.2 Line Efficiency Calculation

The line efficiency is calculated using:

$$\text{Line Efficiency} = \frac{\sum t_i}{N \times CT} \times 100$$

<u>1. Conventional Line</u>

Total Time = 2410 sec
Cycle Time (max) = 276 sec
Number of Stations = 9

$$\text{Line Efficiency} = \frac{2410}{9 \times 276} \times 100$$

Line Efficiency=96.9 %

<u>2. Dual-Variant Compatible Line</u>

Total Time = 2385 sec
Cycle Time (max) = 270 sec
Number of Stations = 9

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$$\text{Line Efficiency} = \frac{2385}{9 \times 270} \times 100$$

Line Efficiency=98.15 %

Line efficiency was evaluated using total cycle time, number of stations, and maximum cycle time. This represents an improvement of approximately 1.25%, which is significant in high-volume automotive production. The increase in efficiency is attributed to reduced bottlenecks, better workload distribution, and consistent clamping provided by the pneumatic system.

The results clearly demonstrate that the dual-variant compatible fixture system significantly improves line balancing performance. The reduction in cycle time variation, idle time, and bottlenecks leads to improved efficiency and smoother production flow. The proposed system supports flexible manufacturing while maintaining production stability.

6.3 Dual-Variant Compatibility

The redesigned fixtures successfully accommodated variations in component geometry, demonstrating the effectiveness of reconfigurable fixture design [1].

6.4 Flexible Manufacturing Capability

The modified fixture system enabled the production of multiple variants on the same line without requiring changeover time. This significantly improved manufacturing flexibility.

VII. CONCLUSION

This study demonstrates the successful modification of a welding fixture to enable dual-variant production in an automotive BIW assembly line without interrupting production. By applying the 3-2-1 locating principle, incorporating reconfigurable elements, and integrating pneumatic clamping, the system achieved accurate positioning and consistent weld quality. Cycle time analysis across nine stations showed improved line balancing, with maximum cycle time reduced from 276 s to 270 s and line efficiency increased from 96.9% to 98.15%. The modified fixture enabled zero changeover between two variants while minimizing capital investment, providing a practical and cost-effective solution for enhancing manufacturing flexibility, efficiency, and resource utilization in high-volume production environments.

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