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Investigating Distortion in Automotive Rear Arms: A Finite Element Analysis and Experimental Approach

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ABSTRACT – This project investigates the distortion of automotive parts subjected to a continuous virtual simulation process, from stamping to welding. The objective is to determine the optimal parameters for both the stamping and welding stages. In this sequential process, the properties derived from the stamping simulation are utilized in the welding simulation. The analysis was conducted using finite element software, Simufact.Forming 13.0 and Simufact.Welding 5.0, which are highly effective tools for simulating stamping and welding, offering fast and reliable results. To validate the simulation outcomes, an experimental study using an automated welding process was also performed. The automotive rear arm was selected as a case study, using materials SPH440 and STKM13A, which belong to the general steel category. This paper examines the distortion error percentage between the simulation and the actual welding process of the rear arm. The findings demonstrate that Virtual Manufacturing with Simufact.Welding 5.0 provides a solid understanding, as confirmed by experimental verification.

KEYWORDS: Chained Process; Distortion; Simulation; Stamping; Welding.

1.0 INTRODUCTION

In the manufacturing industry, particularly in the automotive sector, stamping and welding are critical processes that offer economical and efficient methods for forming and permanently joining metals. During the stamping process, materials are subjected to springback and residual stress, while welding introduces complex thermal cycles that lead to transient thermal stresses and non-uniform distribution of elastic strains in the weld and surrounding regions. These factors contribute to distortion, which can adversely impact the performance and dimensional accuracy of welded structures, making its control essential.

Manufacturing involves a series of processes where raw materials are transformed into finished products. The design and manufacturing stages are closely intertwined, as the manufacturability of a component often dictates the success of its design [1]. Among various manufacturing processes, stamping, forging, and punching are widely used and have a long history in metal processing. Welding, as a metal joining process, is highly favoured for producing homogeneous and permanent joints. It involves melting and fusing parts, with or without the addition of filler material.

Process simulation has become an indispensable tool in the design and development phases within the manufacturing industry. It involves creating and analyzing a computerized mathematical model of a physical system [2]. Utilizing process simulation before conducting the actual process can reduce costs and time [3]. Simulation is an integral part of Virtual Manufacturing, with the Finite Element Method (FEM) being a widely adopted technique for analyzing and simulating the physical behaviour of mechanical parts, including forming, welding, and cutting processes [4].

2.0 CHAINING PROCESSES

The concept of chaining processes refers to the sequential analysis of selected metal forming and welding processes, where the output of one process becomes the input for the next. This approach is not only limited to manufacturing but is also applied in various fields, including business processes and factory layout planning [5]. According to Buijk et al. [6], the chaining process integrates forming and welding, where the data and products from the forming stage are utilized in the welding stage. One of the primary challenges in welding is the distortion caused by the expansion and contraction of weld and base metals during heating and cooling [7]. This distortion can lead to dimensional inaccuracies, which are particularly problematic in high-tolerance applications [8]. Furthermore, distortion can compromise the aesthetic and structural integrity of the product. In this paper, the chaining process is analysed to evaluate the distortion in an automotive rear arm after forming and welding processes. The Finite Element Method is employed as the optimal approach to effectively analyse and manage these complex processes. The study compares welding distortion in both chained and unchained processes, acknowledging that while many efforts have been made to minimize distortion, it cannot be entirely eliminated.

3.0 METHODOLOGY

The distortion of the rear arm is analysed through simulation to compare the outcomes between the chaining and unchaining processes. This comparison is then validated against the actual distortion observed in the industry. The study's objective is accomplished by applying this project methodology to finalize and compare the results of the two simulation processes. The rear arm model is created using Catia V5. This software is also employed to design a simplified die set for the forming process, using the existing rear arm model parameters rather than those of a newer model available on the market. Before initiating the simulation, it is essential to define all the necessary parameters. Both chained and unchained processes require initial physical data. This data is then modified to align with industrial parameters using Simufact.Forming 14.0 software, which also handles the meshing required for the pre-processing stage, enabling the simulation to proceed in the subsequent stages. In the welding process, conducted with Simufact.Welding 5.0, the welding parameters closely match those provided by industry standards. However, not all parameters are identical; the approximation of the heat source used in the simulation contributes to discrepancies between the actual and simulated results. Data from the forming process, modified in Simufact.Forming 14.0, is exported to Simufact.Welding 5.0 using a .spr file. The distortion results from both processes are then obtained during the post-processing stage of the simulation. The rear arm assembly consists of a body, collar, and attachment. In the chaining process, the rear arm first undergoes the forming process, and the resulting data is then used in the welding process. The die and workpiece drawings for the rear arm are exported from CATIA to Simufact.Forming 14.0 in. stl format. For the unchaining process, the rear arm design created in CATIA is transferred to MSC Patran for meshing, using the .igs file format. Subsequently, the meshed model is exported to Simufact.Welding 5.0 as a .bdf file. Figure 1 below presents the CAD drawing of the rear arm (left) alongside the actual rear arm (right).

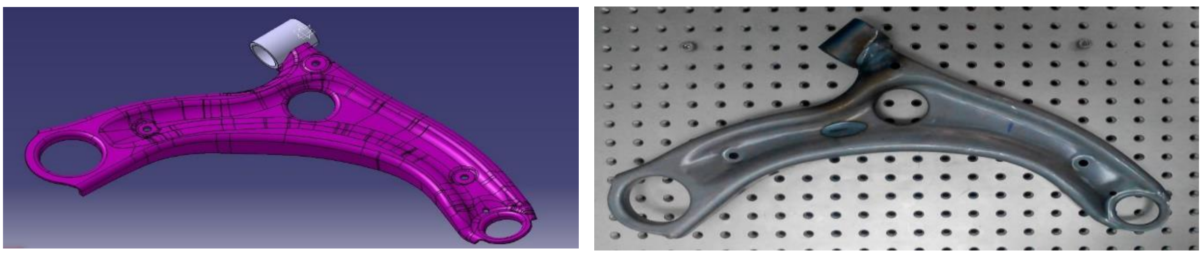

Figure 1: The CAD drawing of the rear arm (left) alongside the actual rear arm (right).

The parameters for the stamping process were sourced from industry standards. These parameters are essential for initializing the software and running the simulation. Table 1 outlines all the parameters utilized in the simulation conducted with Simufact.Forming 14.0.

Table 1: Parameters for stamping simulation

Parameter	***Value***
Forming process	Sheet forming
Process type	Cold stamping
Ambient Temperature	20°C
Material	SPH440
Press	Hydraulic press
Die Friction	Medium
Temperature	Die - 20°C / Sheet metal - 20°C
Mesh	5mm Hexahedral
Stroke	50mm

The initial stage of this simulation requires physical parameters to execute the process effectively. The heat source is determined by calculating the thermal input along the welding path. Data chaining between processes is facilitated by transferring information from Simufact.Forming 14.0 via a .spr file. For unchaining, after meshing in MSC Patran software, the .igs file is exported into this software to initiate the simulation. The parameters utilized in Simufact.Welding 5.0 are detailed in Table 2, with the welding simulation setup illustrated in Figure 2 below.

Table 2: Parameter for welding simulation

Parameter	***Value***
Process type	Arc Welding
Number of bearing	2
Number of clamping	4
Clamping deactivation	3s after welding process
Clamping force	4200 N
Number of robotic welding	2
Number of weld path	6

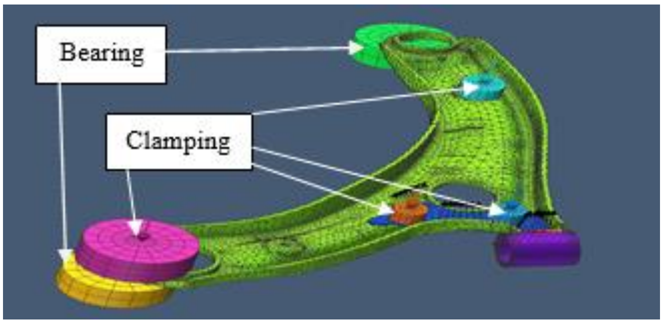

Figure 2: Setup for welding simulation

The selection of materials for this simulation is critical due to the unique properties of each material. Consequently, materials were chosen from the software library provided in Simu fact, as they closely resemble those used in the industry. Two different materials were utilized in the simulation process: one for the body and attachment, and another for the collar. The materials used in this simulation are listed in Table 3 below.

Table 3: Material used in simulation

Part	***Body and Attachment***	***Collar***
Material	SPH440	STKM13A
Type of Steel	General Steel	General Steel
Young’s Modulus	210 MPa	210 MPa
Poisson’s Ratio	0.3	0.3
Density	7852.17 kg/m3	7852.17 kg/m3
Manganese Composition	1.1	0.9

To ensure accuracy and validity in addressing real-world welding challenges, proper calibration of the heat source in simulations is crucial [9]. Inaccurately calibrated heat sources can lead to discrepancies between simulation results and experimental outcomes, undermining the reliability of the simulation. Therefore, it is essential to calibrate the heat source in Simufact.Welding 5.0 to achieve an appropriate heat distribution along the welding path. For arc welding processes, the widely recognized Goldak's double ellipsoid model is employed in this simulation. Accurately defining the numerical parameters of the heat source is critical for ensuring the correct material structure, actual strains, and residual stresses. According to M. Hashemzadeh et al. [10], both semi-ellipsoidal and double-ellipsoidal models accurately represent experimental and real-world conditions across various welding processes, such as Gas Metal Arc Welding (GMAW) and laser welding. The distortion, residual stresses, and grain structure issues in a weld joint are directly related to the thermal cycle induced by the localized intense heat of fusion welding. The primary goal in selecting the welding process and developing a welding plan is to minimize the heat input to the workpiece [11]. This study utilized Goldak’s ellipsoidal moving heat source, which is the most widely accepted model for the Finite Element Method, as illustrated in Figure 3 below.

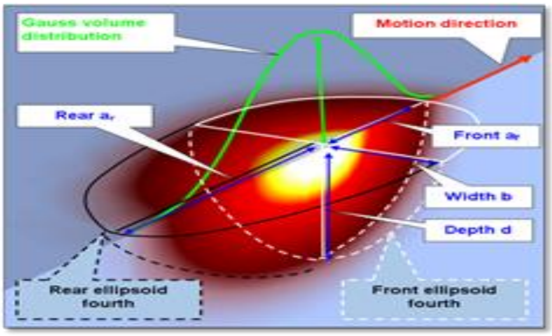

Figure 3: Goldak's double ellipsoid heat source model

The simulation process required calibration of heat source parameters following standard procedures. Micrograph analysis of weld path 1 was used for parameter optimization. As shown in Figure 4, the simulated and experimental fillet welds exhibited excellent agreement.

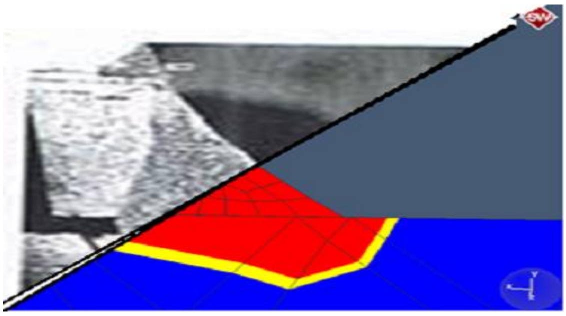

Figure 4: Calibration procedure

Both the chaining and unchaining processes incorporated stamping and welding operations in this simulation. The stamping phase was conducted using Simufact.Forming 14.0 software. Subsequently, a welding process was applied to the rear arm assembly, including the attachment and collar components. The welding sequence implemented in the simulation mirrored the actual production sequence for the rear arm. The spatial arrangement of welding points for both chaining and unchaining operations is illustrated in Figure 5.

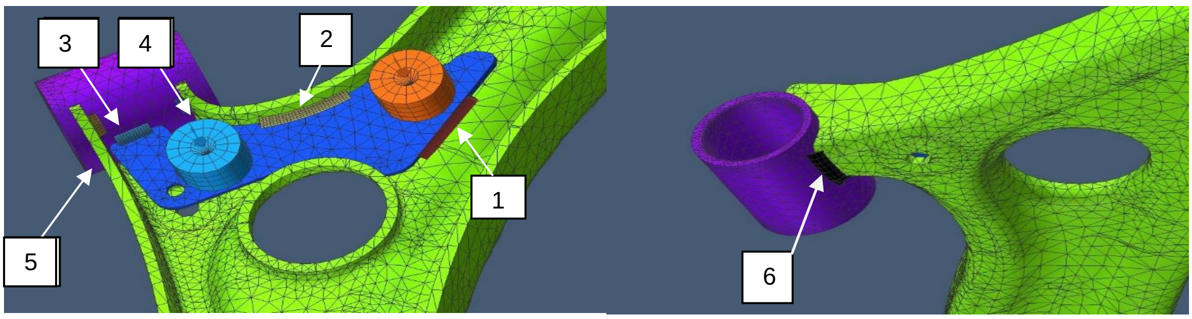

Figure 5: Welding Sequence of chaining and unchining process simulation

A sequential welding approach, designated as sequence 123456, was employed for this process. Comparative analysis indicated that this sequence outperformed alternative welding sequences. To quantify distortion, three strategic points were identified for measurement. These points were meticulously chosen based on their anticipated sensitivity to distortion, prioritizing areas where minimal displacement was desirable. Figure 6 visually represents the selected tracking points for both chaining and unchaining simulations.

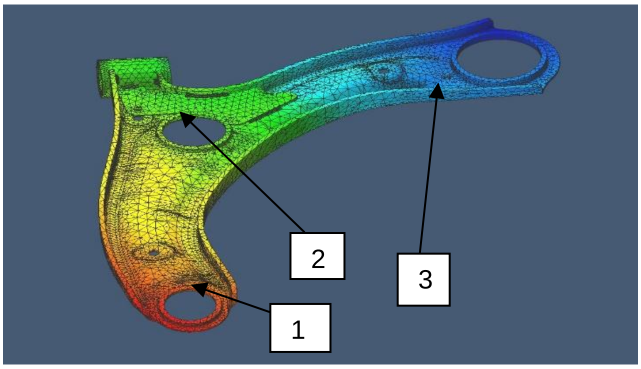

Figure 6: Selected tracking points of chaining and unchaining process simulation

Each welding sequence comprises multiple welding paths, each characterized by distinct parameters. Consequently, variations in path length, velocity, current, voltage, and welding angle result in differing distortion levels for each sequence. The specific welding path and corresponding parameters for each sequence are detailed in Table 4.

Table 4: Parameter of welding path

Number of path	Velocity [m/s]	Current [A]	Voltage [V]	Welding Angle
1	0.01	220	26	y-axis / -74.1°
2	0.01	220	22	y-axis / 69.6°
3	0.0083	230	26	y-axis / -72.9°
4	0.0075	260	23	x-axis / 118.4°
5	0.0075	260	23	x-axis / 57.5°
6	0.0083	230	24	y-axis / -50.5°

4.0 RESULTS AND CONCLUSION

Process simulation was conducted to analyse the manufacturing process. Post-simulation analysis yielded data on distortion, temperature, equivalent stress, and yield stress. This study primarily focuses on total distortion of the arm during the chaining and unchaining processes. Distortion levels at specific tracking points were examined. Lower distortion values are preferable as they minimize impacts on the rear arm's aesthetic appeal and material integrity. Table 5 presents distortion data for the chaining process, while Table 6 compares the simulated chaining results to actual measurements, expressed as a percentage difference.

Table 5: Data of distortion of chaining process simulation

Tracking Point	Distortion / End time [mm / s]
1	0.133 / 20.00
2	0.066 / 20.00
3	0.189 / 20.00

Table 6: Comparison data between the chaining process and the actual

Tracking Point	Chaining Process	Actual Distortion	Percentage of difference
1	0.133	0.123	7.5 %
2	0.066	0.058	12.1 %
3	0.189	0.162	14.3 %

Four sequence configurations were simulated independently in this study. The industrial sequence demonstrated superior performance, exhibiting the lowest cumulative distortion. This characteristic is advantageous for assembly tolerances. Additionally, this sequence required the shortest average time to reach minimal distortion, which is beneficial for inter-process production efficiency. Tables 7, 8, 9, and 10 present the simulated cumulative distortion values for each sequence.

Table 7: Distortion value for 123456 welding sequence

Tracking Point	Distortion / End time [mm / s]
1	1.6732 / 20.00
2	1.0051 / 20.00
3	2.6235 / 20.00

Table 8: Distortion value for 654321 welding sequence

Tracking Point	Distortion / End time [mm / s]
1	3.3695 / 20.00
2	6.457 / 20.00
3	6.0163 / 20.00

Table 9: Distortion value for 214536 welding sequence

Tracking Point	Distortion / End time [mm / s]
1	1.474 / 20.00
2	1.1558 / 20.00
3	0.5334 / 20.00

Table 10: Distortion value for 124536 welding sequence

Tracking Point	Distortion / End time [mm / s]
1	0.2502 / 20.00
2	0.5905 / 20.00
3	0.2602 / 20.00

Among the evaluated welding sequences, the 124536 sequence demonstrated the highest efficiency. Consequently, it was selected as the benchmark for comparison against the actual welding results. As shown in Table 11, the percentage difference between the unchained simulation and the experimental part was calculated based on the distortion values. A lower distortion typically correlates with a smaller percentage of error. The overall distortion for the simulated welding process is visually represented in Figure 7.

Table 11: Comparison data between 124536 welding sequence and actual

Tracking Point	124536 Welding Sequence	Actual Distortion	Percentage of difference
1	0.2502	0.123	50.8 %
2	0.5905	0.058	90.2 %
3	0.2602	0.162	37.7 %

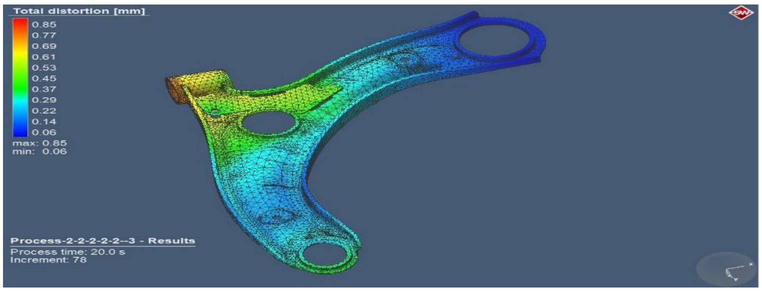

Figure 7: Total distortion for 124536 welding sequence

4.1 Comparison Data

Data generated from both chaining and unchaining simulations were compared to the actual distortion of the rear arm. The comparative results are presented in Tables 12 and 13.

Table 12: Comparison of all data with actual

Tracking Point	Chaining Process	Unchained Process	Actual Distortion
1	0.133	0.2502	0.123
2	0.066	0.5905	0.058
3	0.189	0.2602	0.162

Table 13 : Comparison data between chaining and unchaining

Tracking Point	Chaining Process	Unchained Process	Percentage of difference
1	0.133	0.2502	46.8%
2	0.066	0.5905	88.8%
3	0.189	0.2602	37.7%

This study contrasts two processes and reveals a significant disparity in their outcomes. The data indicates that the chaining process exerts a considerably greater impact on final distortion compared to the unchaining process. Consequently, simulation-based analysis of the chaining process is crucial for effective design optimization in industrial applications.

This research successfully employed process simulation to model both chaining and unchaining processes. Finite element analysis (FEA) utilizing the Simufact.Welding method accurately predicted distortion in the lower arm, revealing a substantial disparity in distortion between the two processes. These findings align with previous research highlighting the significant impact of stamping processes on distortion.

Simulation enhanced the understanding of the chaining process, providing insights into product mechanical properties and behaviour. This enabled clear differentiation between the two processes. By employing FEA, potential distortion-related failures were mitigated, emphasizing the importance of simulation in preventing product damage. The potential for rear arm design improvement through optimization within the simulated chaining environment was identified.

1. Distortion error analysis for tracking points 1, 2, and 3 indicated respective differences of 7.5%, 12.1%, and 14.3% between the simulated chaining process and the actual rear arm.
2. Comparing the unchaining process to the actual rear arm, distortion errors for tracking points 1, 2, and 3 were determined to be 50.8%, 90.2%, and 37.7%, respectively.
3. Results consistently demonstrated that the chaining process exhibited lower distortion values, indicating superior performance in this aspect.

The integration of complete chain manufacturing processes through Simufact software has spurred increased interest in simulation within the metal forming industry.

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