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MÜHENDESLİK FAKÜLTESİ

FEASIBILITY STUDY OF THE ROBOT-ROLLER HEMMING PROCESS

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(Danışman)

YÜKSEK LİSANS TEZİ

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SHADI SAFA tarafından hazırlanan "**FEASIBILITY STUDY OF THE ROBOT-ROLLER HEMMING PROCESS**" adlı tez çalışması aşağıdaki jüri tarafından oy birliği ile Bursa Uludağ Üniversitesi Mühendislik Fakültesi Konstrüksiyon ve İmalat Anabilim Dalı'nda **YÜKSEK LİSANS TEZİ** olarak kabul edilmiştir.
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ÖZET

Yüksek Lisans Tezi

ROBOT-ROLLER KENAR KIVIRMA SÜRECİNİN FİZİBİLİTE ÇALIŞMASI

SHADI SAFA

Bursa Uludağ Üniversitesi

Fen Bilimleri Enstitüsü

Konstrüksiyon ve İmalat Anabilim Dalı

Danışman: Prof. Dr. M. Cemal ÇAKIR

Kenar kıvırma, otomotiv endüstrisinde iç ve dış menteşeli parçaların panellerini (kaput, kapılar, bagaj kapakları vb.) birleştirmek için kullanılan bir teknolojidir. Dış panelin flanşının iç panelin üzerine plastik deformasyonla bükülmesi/katlanması işlemidir. Otomotiv endüstrisinde menteşeli parçalarının kıvırılması, gerekli iyi görünümlü araca ulaşmak için birçok parametreye bağlı karmaşık bir mühendislik sürecidir. Bu sonucu elde etme süreci, parça tasarımcıları, metal parça imalatçıları ve kıvırma ekipmanı imalatçıları ile ilgilidir. Ortak bir fizibilite çalışması yapılmadan, parçanın ve ekipmanın nihai tasarımının sorumluluğuna karar verilemez. Bu çalışmada, tercih edilen bir fizibilite çalışması matrisini kategorize etmek, ekipman için gereken yatırımı azaltmak, deneme yanılma süresini azaltmak, yüksek kaliteli bir ürün elde etmek, çevrim süresini optimize etmek ve hızlı devreye almak için alınacak her sorumluluğun teknik açıdan önemli ayrıntılarını vermek amaçlanmaktadır. Bu eylemler matrisinin fizibilite çalışması, her adımın sonucuna ve karşılaşılan zorluklara dayanmaktadır. Bir hata veya sorun fark edildiğinde, kök nedeni araştırılmalı, ardından analiz döngünün başından itibaren gözden geçirilmeli, her yönü yeniden kontrol edilmeli ve optimize edilmelidir.

Anahtar Kelimeler: Hemming, Flange, Roller, Hemming tool, Closures, Body in White**.**

2023, x + 49 pages.

ABSTRACT

MSc Thesis

FEASIBILITY STUDY OF THE ROBOT-ROLLER HEMMING PROCESS

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Hemming is a technology used in the automotive industry to join inner and outer closure panels together (hoods, doors, tailgates, etc.). It is the process of bending/folding the flange of the outer panel over the inner one by plastic deformation. Hemming of closure parts in the automotive industry is a complex engineering process that has a lot of parameters to reach the required well-looking vehicle trims. The process to obtain this result is related to closure parts designers, closure metal parts manufacturers, and hemming capital equipment manufacturers. The responsibility of the final design of the part and equipment cannot be decided unless a common feasibility study has been done. The study aims to categorize a preferred matrix of a feasibility study and give technical important details of each task to decrease the investment required for equipment, decrease trial and error, have a high-quality product, optimize cycle time, and acquire a fast-commissioning period. This feasibility study of the matrix of actions is relying on the result of each step and the difficulties faced within it. When an error or problem is noticed a root cause is done after which the analysis should be reviewed from the beginning of the loop, rechecking and optimizing each aspect.

Key Words: Hemming, Flange, Roller, Hemming tool, Closures, Body in White.

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Most importantly I dedicate this study and effort to my family and friends for their continuous trust in my pursuits, morally providing me the invaluable support making it possible to go after my dreams.

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SYMBOLS

Symbols	Description
σ	Sigma
Σ	Sum / total
$\pm$	Plus or minus

1. INTRODUCTION

Hemming is a technology used in the automotive industry to join inner and outer closure panels together (hoods, doors, tailgates, etc.). It is the process of bending/folding the flange of the outer panel over the inner one by plastic deformation (

Figure ***1.1***.). The accuracy of the operation significantly affects the appearance of the car's outer surfaces and is therefore a critical factor in the final quality of a finished vehicle.

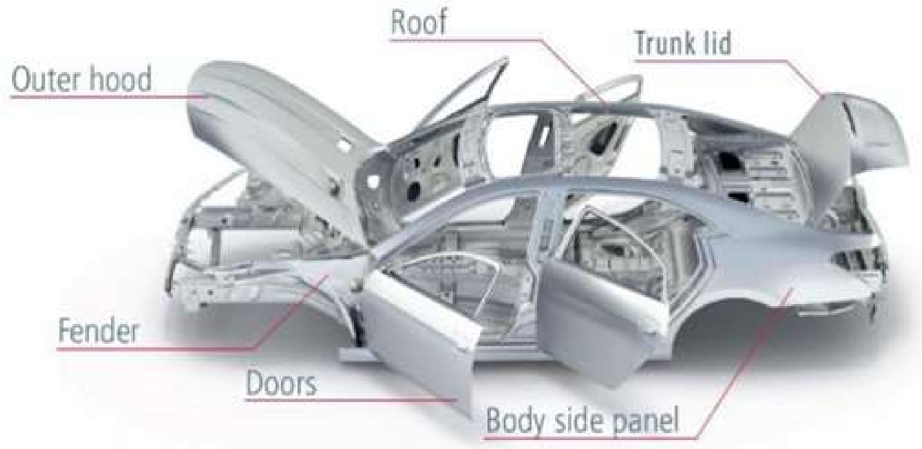

Figure 1.1. Body in white and closure parts.

Robot-roller hemming is utilized for the manufacture of low to high-production volumes. It uses a standard industrial robot integrated with a roller hemming head to provide a flexible method for forming closures. The flange of the outer panel is bent over the inner panel in progressive steps, by means of a roller-hemming head (

Figure ***1.2***.).

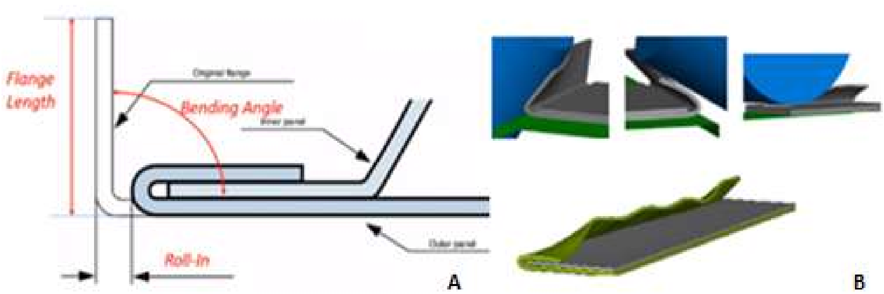

Figure 1.2. A) Flange sketch. B) Flange Illustrations.

One advantage of this process is that it can use the robot-controlled hemming head to hem several different components within a single cell. Another is that minor changes or fluctuations in panel-hemming conditions can be quickly and cost-effectively accommodated. If equipped with a tool-changing system, the robot could serve a variety of additional functions within the same assembly cell, such as operating dispensing equipment for adhesives and sealants, or carrying out panel manipulations, using a gripper unit.

1.1. Robot Hemming Features and Benefits

Robot roller hemming is a relatively new process (Figure 1.3). The process will be applied more and more in the future due to market demands and process development.

Figure 1.3. Robot Roller Hemming.

Too little fundamental process know-how is available. Achieving and maintaining the right product quality is therefore a trial-and-error process.

• The ideal solution for all volume production demands, via multiple robots and split operations.

• Overall quality is better than press or tabletop hemming technologies.

• Flexibility:

- Robot can hem various panel shapes that press, and tabletop can't achieve due to flange attack angles and physical accessibility.

- Can perform panel shape changes via quick program changes, while saving the original programs for future recall.
- Can perform other tasks by changing the hemming tool with another tool such as a dispensing nozzle.

• Low cost, simple and quiet in operation when used with standard industrial robot.

• Reduced mechanical effort for the try-out.

• The inner panel, outer panel, and reinforcement panel are manufactured and assembled by stamping, trimming, and flanging.

• The reinforcement is joined to the inner panel by spot welding, riveting, or clinching.

• The flanging of the outer panel to the inner panel is achieved by roller hemming and adhesive bonding.

• In the roller hemming process, a robot guides the roller along the product and bends the outer panel over the inner panel.

• Advantages are high quality and flexibility.

• Cycle times of 30s (120 units/hour) to 90s can be achieved.

• Servo-controlled rollers and hemming force can speed up cycle times and improve quality.

• In a typical robot hemming cell, the workpiece is mounted on a fixture that presents the panels and their edges to one or several robots.

• Bending is done step by step and the roller hemming may require three bending cycles to achieve the final closure of the hem.

• To achieve faster cycle times, two or more robots can be installed in one cell.

• Inserting and extracting the workpiece into/from the fixture is often done by robots.

1.2. Purpose of the Study

Hemming of closure parts in the automotive industry is a complex engineering process that has a lot of parameters to reach the required aesthetic vehicle trims. Automakers give a lot of importance to the gap between the closure parts and the body of the vehicle. However, the process to obtain this result is related to closure parts designers, closure metal parts manufacturers, and hemming capital equipment manufacturers. The responsibility for the final design of the component and equipment cannot be determined without a shared feasibility assessment. The goal of this study is to categorize a preferred matrix of a feasibility study and give technical important details of each task to decrease the investment required for equipment, decrease trial and error, have a high-quality product, optimize cycle time, and acquire a fast-commissioning period.

1.3. Scope of the Study

Robot roller hemming is a relatively new process. The process will be applied more and more in the future due to market demands and process development. Too little know-how about the fundamental of the process is available. Therefore, the right product quality can be achieved and maintained by a trial-and-error process. Finite element analysis of the robot roller hemming process helps to reduce this try-out phase. The goals are to create a more stable process and achieve the right product quality. The main targets are to create process-setting guidelines which control the dimensional and surface quality and reduce the overall process time (Figure 1.4).

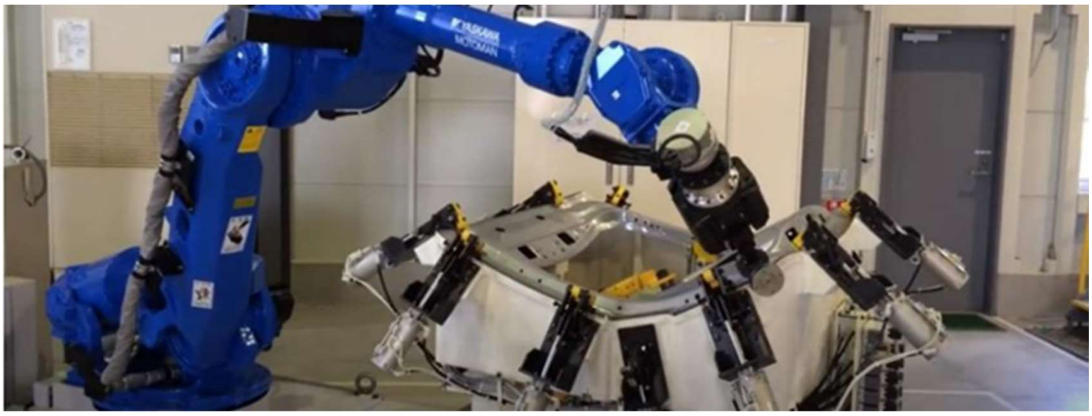

Figure 1.4. A Robot-Roller Hemming System.

Many of the studies and publications that have been done such as developing of a 3D robot-roller hemming simulation model and to analyse the reaction of the flange material during the hemming process (Jonkers et. all, 2006). Madhavi et. all. studied the correlations between the hemming parameters such as flange height, roller radius, pre-strain, rolling direction, and pre-hemming robot path on the hem surface with the help of Pamstamp2G software (Madvadi et. all, 2014). Babak Saboori and his colleagues made some simulations for the robot roller-hemming process and investigated how to reduce its cycle time by introducing a fast roller-hemming process (Babak et. all, 2009). In a study that takes the curved edge aluminium sheet as the research object, SPH (smooth particle hydrodynamics) was introduced to simulate the viscous adhesive, and the SPH-FEM (Finite element method) coupling model of adhesive and panels considering the viscosity-pressure effects (Li et. all, 2022). Other studies also are focused on the parametric optimization of geometric parameters of the hemming process. (Gomez et. all, 2012).

Several simulation models for roller hemming research have been developed (Pérez, 2016; Eisele, 2010), and the high-speed roller hemming process has been analysed (Baumgarten et al, 2005; Saboori et al, 2009). However, numerical analysis of the roller hemming process (Hu et al., 2012; Gurgen, 2019; Maoût et al., 2019) and techniques and applications for parametric optimization of the roll-hemming process for sheet metal have garnered the greatest attention and study (Raskaret al, 2014; Leyva, 2012).

In addition, a group of Chinese academics has examined a novel methodology and method for a roller hemming procedure without dies. (Huang, et al, 2021).

Only very few research has investigated the relationships and processes that connect all these findings. This information has been retained as proprietary knowledge, particularly by equipment manufacturers in an effort to reduce competition. Large technology companies such as KUKA, ABB, and Comau who have specific engineering teams in this area realize the importance of hemming equipment manufacture.

2. HEMMING QUALITY

Hemming is used mainly for the assembly of closures in automotive bodies. The outer appearance of the vehicle is therefore influenced by the outcome of the hemming process. It is therefore important to be able to predict the final shape and surface quality of the finished product and to determine the parameters which influence it. The quality areas can be divided into two: dimensional and surface quality.

2.1. Dimensional Quality

The dimensional quality is the geometrical tolerance between the hinges of the closure parts and the circumference of the part represents the dimensional quality of the part. The same datum referencing holes in the parts is carried out during part manufacturing and hemming to assure have stable fixed geometrical measuring criteria. The tolerance of the dimensions is specified by the car designer. A general trend in the automotive industry today is to try to reduce the gaps between the body parts.

The dimensional quality is mainly measured detailly by a laser CMM measuring device as the can be evaluated by the naked by two terms, the gap, and the flush of a panel/part. The gap and the flush are the most important terms related to hemming. They affect the appearance of the car unswervingly.

Gap: Closures create gaps in the outer skin of the car since they must be able to open/close properly. In Figure 2.1 three examples of panel gaps are given. gap.

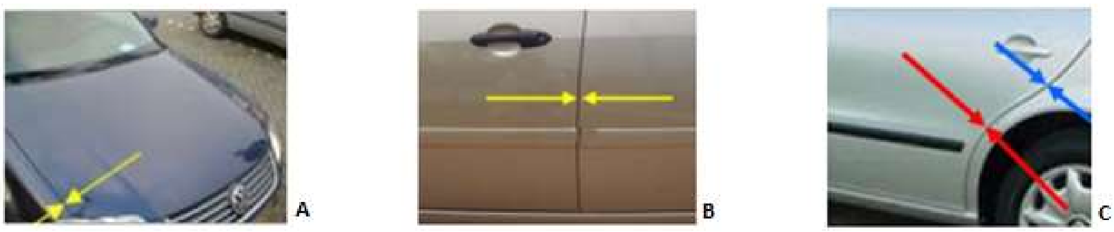

Figure 2.1. A) Hood/Front fender. B) Front/Rear door gap. C) Rear door/Rear fender gap.

Therefore, it is very important to be able to control/predict the roll-in of the hem (Figure 2.1) and to compensate for it. The roll-in of the hem is defined as the distance between the outer radius of the hem and the original flange of the panel.

They must create an evenly distributed gap between the closure part and the car body. It is therefore important to control the mechanism behind the roll-in. The hemming tools and applied hemming method will determine the working of this roll-in mechanism. Tabletop systems generally create a total roll-in of 0.6 ~ 0.8 mm. For roll hemming installations the total roll-in is 0.0 ~ 0.2 mm in general. This is likely caused by the different movement patterns of the processes.

Flush: The distance in the normal direction between neighbouring outer panels, the flush should also be precise (Figure 2.2).

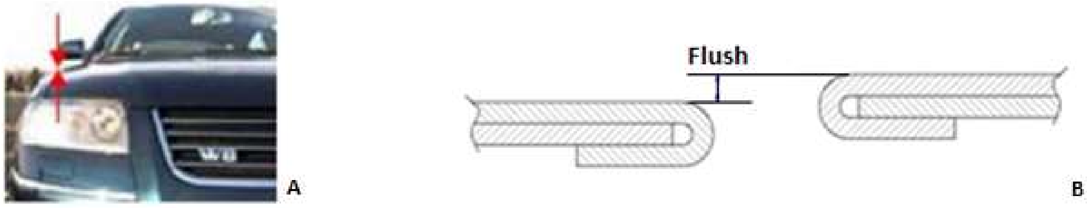

Figure 2.2. A) Hood/Front fender flush. B) Flush illustration.

A faulty flush will deface the appearance of the car and sometimes cause acoustic problems (for instance if the front side door surface is located outside of the front fender surface). A defect that can cause an incorrect flush is an assembled part of the wrong shape. The importance of hemming is to obtain a common homogenous dimensional quality to merge the closures to the body and obtain a common geometrical dimension.

2.2. Surface Quality

The surface quality of a hemmed product is related to three main areas depicted in (Figure 2.3).

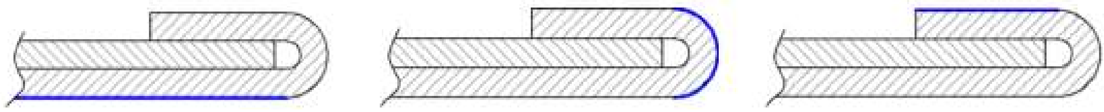

Figure 2.3. Surface areas. From left to right (order of importance): outer skin-, outer radius- and inner skin area.

The outer and inner skin areas can show ripples or a warpage around the product. They occur along the edge of the product (on the green areas in Figure 2.4). In the outer radius area cracks and fractures may occur.

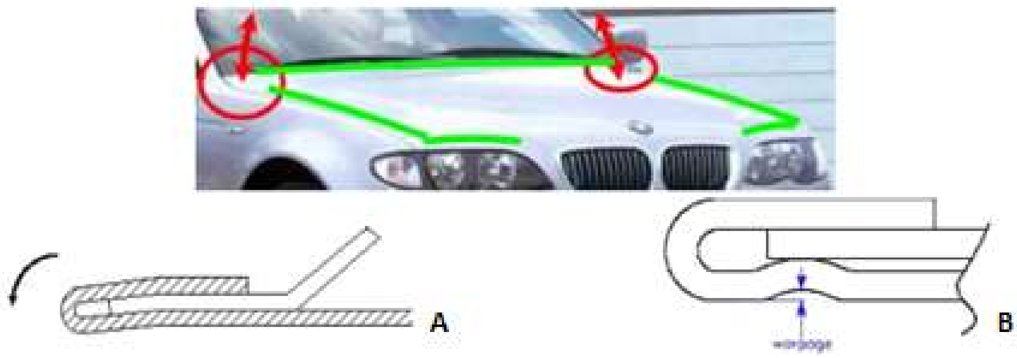

Figure 2.4. A) Recoil of the panel. B) Warpage of the panel.

Some other specific defects can occur on the corners of the product. The defects consist of an increased curvature of the panel close to the edge, known as a ski-slope or recoil of the panel (e.g., often occurring on corners of a hood, see the top picture of Figure 2.4 where the areas are encircled in red). The corners are not aligned with the rest of the car's body. Although some of these defects can be hard to detect directly after hemming, they can become visible once the part has been painted.

Some hemming defects are a combination of dimensional and surface quality problems. The recoil of a panel and an outer skin failure also create a dimensional flush failure. Essential tolerances should be considered in different groups to have a clear vision for the target quality needed.

2.2.1. Essentials Tolerances

1) Part tolerance

In the automotive world and most OEM standards require part tolerance to be 0,1 mm for the referencing pilot holes in the stamped parts and 0.2 mm on the surface areas. Because of the feasibility of the stamping process decreasing the tolerance to less than these values would require huge investments (Figure 2.5).

Optimizing the tolerances of the total hemming process by decreasing the pre-hemming part tolerance is not a feasible option. To decrease the tolerance of the parts, the dies must be machined with very low tolerances, and this would cause a very high cost compared to average machining. Yet, the tighter the tolerance of the part is, the better tolerance on the hemmed part can be achieved.

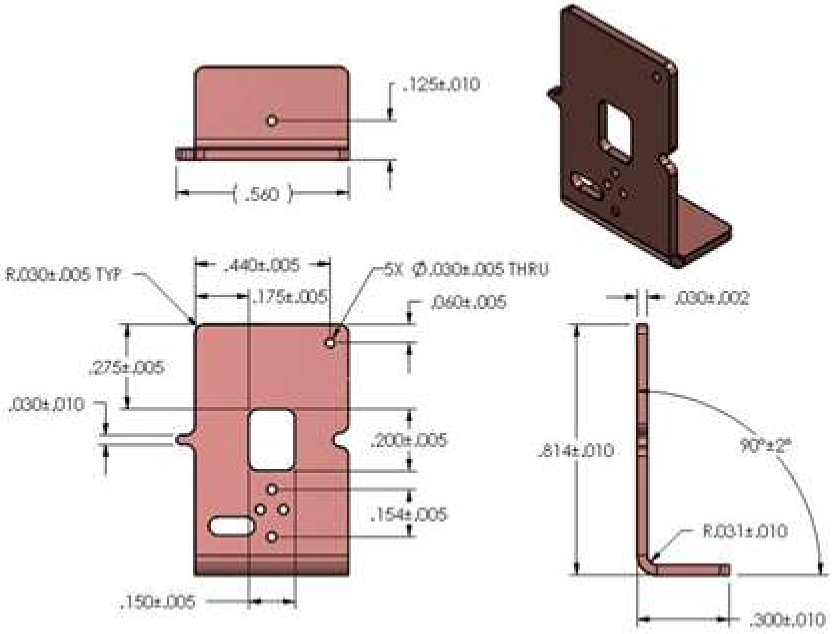

Figure 2.5. Parts Tolerances.

2) Welding tolerance

The inner panel which consists of stamped metal sheets and brackets is being welded together to form the inner supporting structure to hold the outer panel robust after hemming. The automotive standard and many OEMs require the tolerance after this process not to exceed +/-0.2 mm. Optimizing the welding process to acquire tighter tolerances is not feasible and is an expensive task to do. Yet, when the process is done automated by robots the outcome of the results is more stable than when it is done manually.

Figure 2.6. A) Robotic welding. B) Manual welding.

An automated robot welding process will give a more identical result every time which renders the hemming process to start by the same starting criteria. In manual operations acquired tolerances are +/- 0.2 but the results are non-sustainable. By automated robotic operations, +/- 0.2 sustainable tolerance results are achievable.

3) Hemming tolerance

The hemming tolerance is affected by a lot of parameters and criteria such as the hemming bed, fixation, robot pressure, roller surface, hemming angles, flange height, flange angle, etc.

The hemming process like any other equipment has a tolerance according to the process and accuracy of the equipment. This may vary from a minimum of 0.3 up to 1 mm or more.

Since the hemming bed is a CNC machined part, decreasing its tolerance can be quite expensive. CNC-machined parts used for referencing parts as well have their own manufacturing tolerances. The robot positioning has a defined tolerance identified according to the characteristic of the robot. All these factors summed up the hemming tolerance of the process.

2.2.2. Tolerance Add Up

The tolerance of the hemmed parts is added up from the components of the parts and tolerance gained from each stage of the process. The part tolerance itself is also an add up of the machining tolerances of the die, tolerances of the material, the stamping procedure, etc. For the equipment, it is the add-up of the CNC machining tolerance of the hemming bed, the clamping, the referencing pilot tolerance etc.

Calculation of the primary tolerance for the subassembly:

1. Calculation of assembly error (software-instrumental) consists of:
    1. Tooling error (stamp (part) + bed (equipment))
    2. Equipment error
    3. Other errors (welding, etc.)

$$\sigma\Sigma = \pm(\,\sigma part + \sigma equipment + \sigma hemming + \sigma others),$$

2. In this case, the calculation of the contour error is as follows:

$$\sigma part \; = \; Material \xrightarrow{\pm 0,001} CNC \xrightarrow{\pm 0,02} Punch\ /\ Die \xrightarrow{\pm 0,15} Stamping \xrightarrow{\pm 0,4}$$

$$\sigma equipment \; = \; Material \xrightarrow{\pm 0,001} CNC \xrightarrow{\pm 0,02} Bed \xrightarrow{\pm 0,15} Clamps \xrightarrow{\pm 0,001} Flanging \xrightarrow{\pm 0,3}$$

$$\sigma part = \pm\sqrt{0,0012 + 0,022 + 0,152 + 0,42} = \pm 0,427$$

$$\sigma equipment = \pm\sqrt{0,0012 + 0,022 + 0,152 + 0,0012 \; \times 8(*) + 0,32} = \pm 0,336$$

* * number of clamps. For example, let's take 8

$$\sigma\Sigma = \; \pm\,(0,427 + 0,336 + \overset{10\%}{\underset{base}{0,03}} \times 2 + \overset{30\%}{\underset{others}{0,1}} \times 2) = \; \pm 1,0$$

In general, the targeted tolerance is ±1,0, decreasing the tolerance of the assembly part less than that requires much more detailed analysis and special machines parts with lower tolerance for the dies and equipment.

3. THE METHOD

The proposed method in this study is a synoptic of actions to be taken according to the upcoming result of the feasibility studies. In parallel, the car designer, the part manufacturer, and the equipment manufacturer shall analyse the feasibility of their share in the general process. The process starts with the parts designer who would set the primary design of the car and its parts. Only this design would be revised and modified according to the feedback of the part manufacturer and equipment manufacturer optimizing the manufacturing process of the end product to be done in the best quality requested and in the simplest way possible.

3.1. Car Design Feasibility

The feasibility of the hemming process begins with the car's design, determined by the manufacturer's desired aesthetic, followed by the engineering team's selection of the scientific-technical specifications of the metal parts and the sealant applied between the internal and external panels (Figure 3.1).

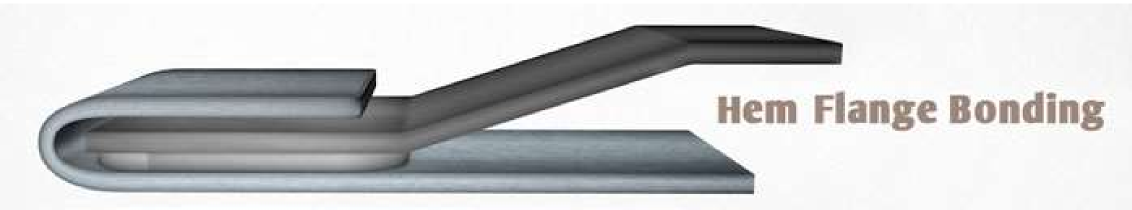

Figure 3.1. Applied sealer between the inner and the outer panel.

Most car designer companies avoid studying the flanges of the closure parts knowing that there are many parameters included in the process that they are not capable of controlling. Although part geometry, part form, metal part material, metal part thickness, and sealant are factors for a better hemming process, they are considered fixed, unchanging features due to their relationship to the automobile crash test and structure analysis.

Car structure analysis and crash tests are advanced engineering analyses done while designing all the car details. The structure of the body is analysed according to the ability of the car to carry the load of mass for a long period and be strong in accidents to keep passengers safe. The material of the metal is chosen to be an anticorrosion long-lasting material, and the thickness is specified for a part to be strong and last in good condition for a long period. Same as the choice of the sealers the assure the strong bonding of the parts and keeps the parts humid free and safe from corrosion.

Knowing that the engineering fee cost, the car design approval, and the crash test analysis are complicated expensive processes, parameter optimization for metal parts and hemming equipment is much more feasible compared to them.

3.2. Outer Panel Metal Part Manufacturer Feasibility

The feasibility analysis begins with the computation of the production stages of the metal outer panel by dies and press machines, where the pre-hemming angles of the flange and its height at each point are the most crucial characteristics for hemming initially designed. From the dies manufacturer's point of view, the angles of the hemming flanges are specified according to the ability of installing the inner panel inside it, the ability to curve the flange to the required angle, and the ability to form the curving line on the panel (Figure 3.2).

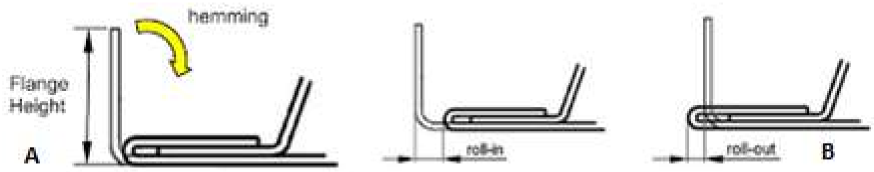

Figure 3.2. Flange Illustrations.

The height and angle of the flange are also vital for the manufacturer of hemming equipment, who should check and validate the ability of the equipment to apply hemming for all the parts before the outer panel's final pressing and cutting dies are manufactured.

3.3. Equipment Manufacturer Feasibility

The feasibility of the hemming flange height and pre-hemming angle can be analysed by Finite Element Analysis of the robot roller hemming process. To be able to do so, the equipment maker must produce a feasibility study of the rollers utilized and the robotic trajectory scenario of the hemming process, upon which the simulation of the feasibility of these scenarios will be performed. Here equipment designer and manufacturer have 2 phases of studies before submitting the input data required for the Finite Element Analysis.

Phase 1 is designing the hemming fixtures, choosing the hemming rollers and the hemming tool that can reach all the flange on the circumference of the outer panel from the pre-hemming angle to the required hemmed angle.

Phase 2 is the robot trajectory, position, and cycle time analysis. This analysis is done to choose the robot that is convenient to use for this process and make a robot trajectory analysis to check that the robot reaches all the hemming points. The robot must reach a convenient location. It should be ensured that the hemming tool can reach all flange locations on the fixture. Then, evaluate the robot's capacity to navigate the rollers or hemming tools to all required locations to apply the requisite force/pressure to all locations. And finally, examine the cycle time of the process, compare it to the required time, and decide what equipment must be improved to attain the required time, or increase the number of robots utilized for the task, if necessary. Since many of the feasible parameters for gaining a better final product are in these 2 phases, a more in-depth examination must be conducted.

Tooling feasibility:

- Designing robotic roller-hemming fixtures
- Designing robotic roller hemming head
- Simulation of robot for hemming trajectory using Robcad or Process Simulate software.
- Checking and analysing robot reachability, collisions, and cycle time to verify the robotic process.

3.3.1. Designing robotic roller-hemming fixtures

3.3.1.1 Hemming fixture

The hemming fixture's main component is a hemming bed (Figure 3.3). A hemming bed is a mold-like structure made of metal alloy that has been cast and machined to have the exact shape of the external panel, used as a fixing tool for the external panel of closures for two main reasons.

The first reason is, knowing that external panels in general do not have referencing holes on them, the bed is used to fix and preserve the shape of the panel while hemming.

The second reason is, the bed works as a push surface for the rollers to apply force on the flange to give it the form needed. The hemming bed should have the exact form of the external panel, especially on curves and areas with a form surface. The reason behind that is to stop the external panel from moving or dislocating when a force from the hemming roller is applied to it. The hemming bed should be covering all the circumference of the external panel for at least an area of 3-4 cm where it will hold the panel in place and be the surface on which the roller will apply the force.

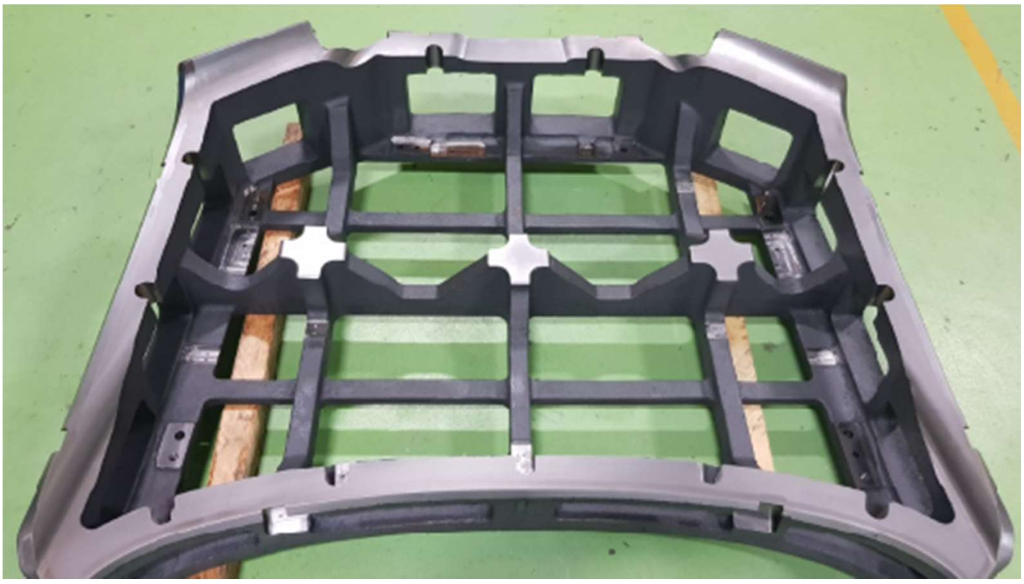

Figure 3.3. Hemming Bed.

The hemming bed should also contain open areas where some suction cups will be installed for the extra force applied on the external panel to fix the hemming bed. Some sensors are also installed for automated processes to ensure the presence of the panel and that is installed correctly to the hemming bed before starting the hemming process. In case the external panel has some referencing holes, referencing pins are installed with shim boxes (Kits) in 3 directions to insure the geometry of the panel.

The hemming bed circumference must be a surface like the angle of approach for the hemming roller in the first round of hemming (Figure 3.4). On this surface, the hemming roller will contact for a stable move during hemming and to form the curve line of the flange at the right place.

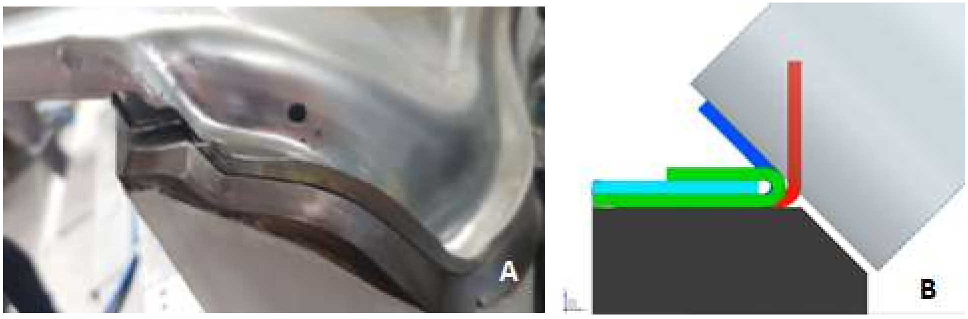

Figure 3.4. Hemming Bed Circumference Angle.

The referencing of the external panel is mainly acquired by the hemming bed, but in addition to it are referencing groups placed on the sides of the panel to insure the right position. They can be mechanical with springs to push down when the hemming roller passes to curve that area. Or can be attached to a pneumatic clamp or piston that opens when the hemming rollers passes by.

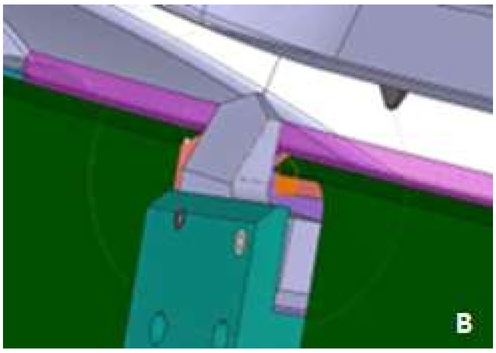

Figure 3.5. Referencing of the External Panel.

3.3.1.2 Down holder

During the hemming process holding the part in position without moving and applying equal force to each surface increase the quality of the part and achieve tighter tolerances. The most common application is a set of metal rods push the inner and outer panel together to the hemming bed on several points (Figure 3.6). To achieve a better result those metal rods should be replaced by a mold-like surface that would be placed on the inner panel and pressed vertically by clamps to insure equal force application.

This mold-like down holder can also function as a gripper to hold the inner panel that can be used for better handling of the part and down holding on the hemming bed.

Figure 3.6. Down Holder.

3.3.1.3 Inner fixation group

Since the process is robotic with automation, it is necessary to keep the inputs to the system constant in order to optimize hemming quality and change only one or two parameters all the time. By referencing the part, its position should be set with precision referencing groups that it is in the same position in every cycle (Figure 3.7).

Figure 3.7. Inner Power Fixation Group.

3.3.1.4 Referencing parts

Part referencing for hemming outer panels are done by a metal tongue-like mechanism placed on the circumference of the parts (Figure 3.8). These mechanisms establish a fine referencing tolerance, yet not very accurate for low tolerances expectations. Outer panel flange tolerance and angle affect the referencing accuracy.

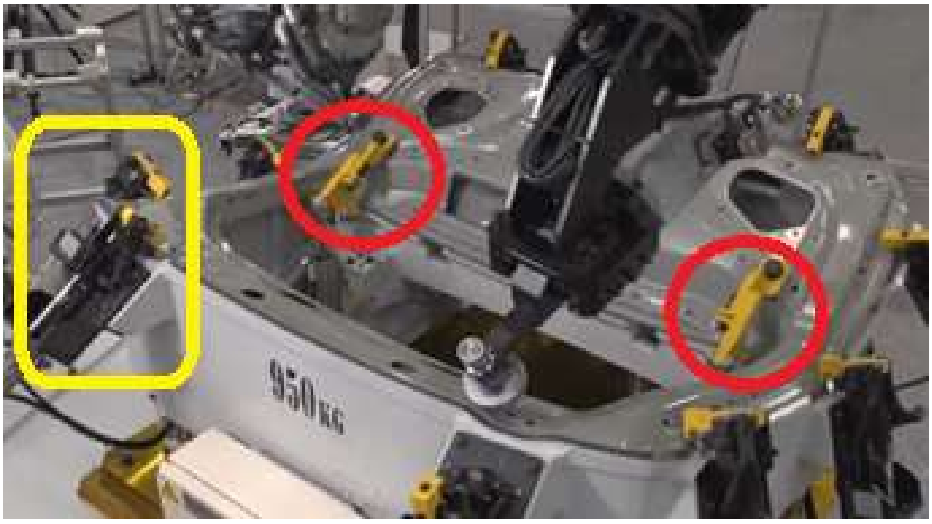

Figure 3.8. Part Referencing.

As for the inner panel, referencing is done by power clamps and long arms (Figure 3.8 in red) since their location has a limitation of accuracy.

As a solution for tight tolerance expectations, these should be optimized to referencing pneumatic moving clamps to obtain more accurate referencing. (Picture 3.8 in yellow).

3.3.1.5 Tool types

Hemming tools are connectors of the hemming rollers to the robot's 6th axis (Figure 3.9). It is connected to the robot axis and the hemming rollers are connected to it from the other side. A hemming tool has a piston-like structure inside with a spring to ensure the resistance when the pressure is exceeded and to give less harm to the hemming flange. Hemming tools can be of different heights that are determined according to the Robcad analysis and the need to reach the hemming area.

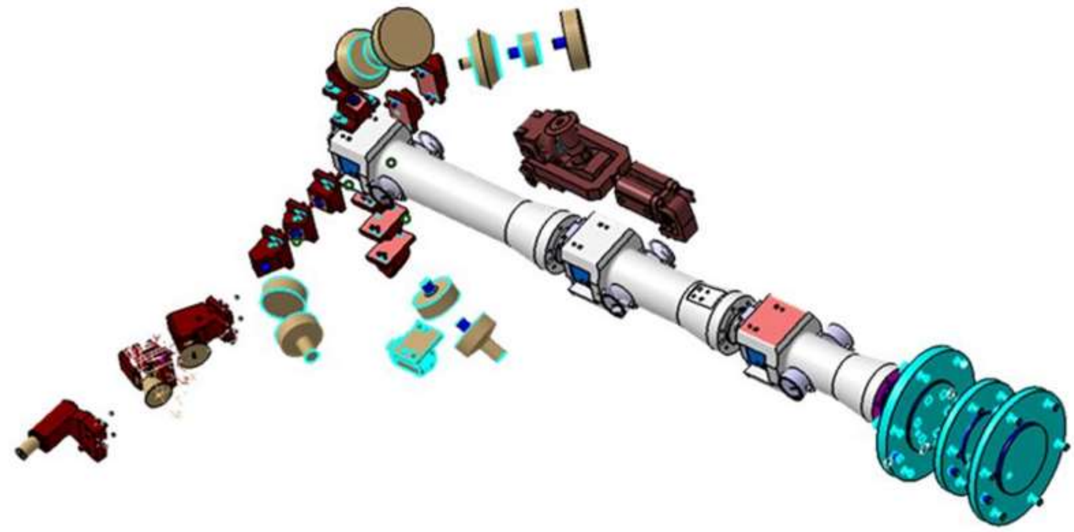

Figure 3.9. A Hemming Tool.

The hemming tool consists of a pressure measuring device, a roller or more depending on the process, a referencing pin on the peak, and in some cases some pneumatic or electrical mechanisms that give the ability to the rollers that are connected to it to move back and forth. In some cases, it includes a stick-like tool to push the flange in situations where the roller cannot reach.

3.3.1.6 Roller types

There is a big variety of rollers designed for different processes (Figure 3.10). The main target is always to use the least number of rollers to save time and decrease robot movements. The rollers mainly are 3 or 4 on a hemming tool. They are in 3 different degrees respective to the hemming tool: 90, 60 and 30 degrees, so the tool angle is always 90 degrees to the hemming part as much as possible.

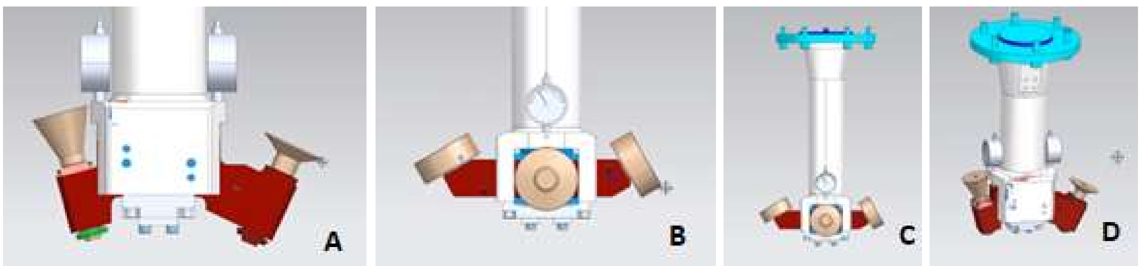

Figure 3.10. Roller Types.

3.3.2. Robot trajectory simulation

3.3.2.1 Robcad design

Phase 2 is the robot trajectory, position, and cycle time analysis. This analysis is done to choose the robot that is convenient for this process and make a robot trajectory analysis to check that the robot reaches all the hemming points (Figure 3.11). The robot must reach a convenient location. It should be ensured that the hemming tool can reach all flange locations on the fixture. Then, evaluate the robot's capacity to navigate the rollers or hemming tools to all required locations to apply the requisite force/pressure to all locations. And finally, examine the cycle time of the process, compare it to the required time, and decide what equipment must be improved to attain the required time, or increase the number of robots utilized for the task, if necessary.

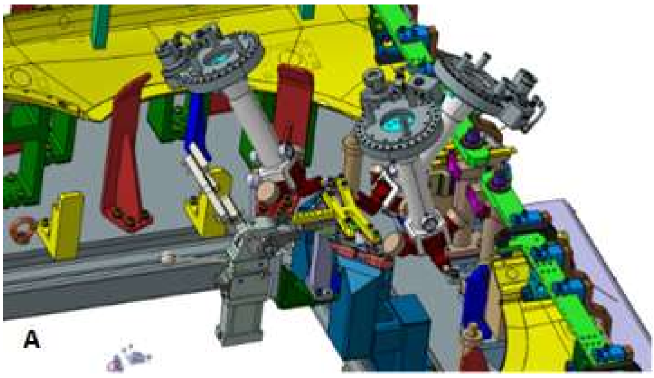

Figure 3.11. Tool Accessibility.

Based on this analysis, the analyst requests modification of the design of the fixtures. In some instances, pushing tools instead of rollers can be mounted on the roller, extra rollers with special shapes can be added, the positions of the power clamps can be altered, or the down holder can be modified.

The design of the equipment is evaluated based on the access locations of the hemming tool and the robot's capability to apply uniform pressure force to the part. After finalizing the control and ensuring that the rollers have access at all required angles, a comprehensive simulation of the robot's trajectory must be created.

3.3.2.2 Robot force application

After the fixtures, hemming tool, and rollers have been designed, an analysis should be conducted to select a suitable robot and position it appropriately relevant to the hemming fixture. The optimal angle for the robot to approach the hemming bed is 90 degrees (Figure 3.12). And operating the robot in its widest open position could produce vibrations during mobility that would degrade the part's quality. For highly complex component geometrical pieces, it may be essential to hem small flange portions at an inclination angle greater than 15 degrees (Figure 3.13). These parameters should be considered when analysing the procedure.

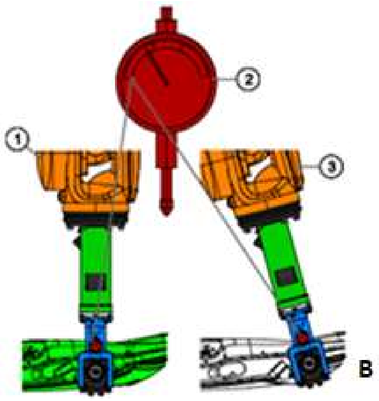

Figure 3.12. Hemming Head Angles.

The applied pressure is theoretically optimized in this analysis making sure the robot will be in 90 degree with the hemming bed as much as possible. Only the homogenous applied robot pressure required is optimized in the application phase. The tools have a pressure measuring device assembled to it (Figure 3.12), the robot programmer finalizes the robot trajectory by checking the pressure applied is equal and sufficient at all hemmed points.

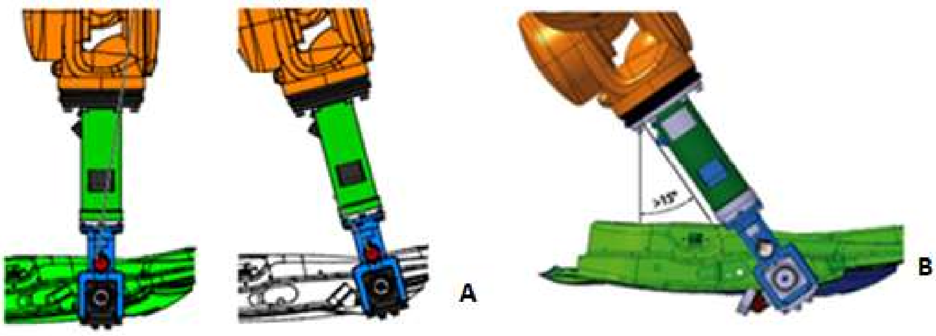

Figure 3.13. Robot Angle of Inclination.

3.3.2.3 Robot hemming tool accessibility.

One of the biggest handicaps of the hemming process is that while designing the equipment and before finalizing the final data of the inner and outer panels, all processes should be in parallel and done simultaneously. And in each stage, the equipment designers must continuously check the accessibility of the tool. They should check that the tool reaches all the sides of the parts that should be applied to hemming. They should check that the rollers have space and are able to move in all the tool's positions, forming an angle with the part of 90, 60, and 30 degrees (Figure 3.14).

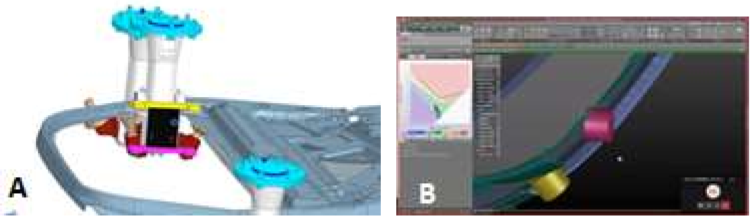

Figure 3.14. A) Robot Trajectory Simulation. B) Robot Positions.

According to this analysis, sometimes pushing tools instead of rollers are installed on the roller. In some cases, extra rollers with special forms must be added. Equipment design is reviewed according to the access points of the hemming tool.

3.3.2.4 Robot hemming head.

The stages of the hemming process start with Pre-hemming 1, One or more hemming rollers move around the open flange of a panel, along a programmed hemming path. The hemming roller, rotated by friction between the roller circumference and the flange, bends the flange to the planned new angle.

Pre-hemming 2, in a second pass (preferably in the opposite direction) along the rolling path, the flange is formed further.

In final hemming, the last pass along the hemming path, the flange is formed into a so-called final hem and encloses an inner panel in a positive-locking manner. In the case of the hemming head with an optional drive, the last forming stage is carried out with a rotating final-hemming roller in synchronization with the roller. The number of hemming paths required is dependent on the flange and component geometry. It is recommended that the direction of motion be changed after each pass in a multi-stage hemming process (Figure 3.15).

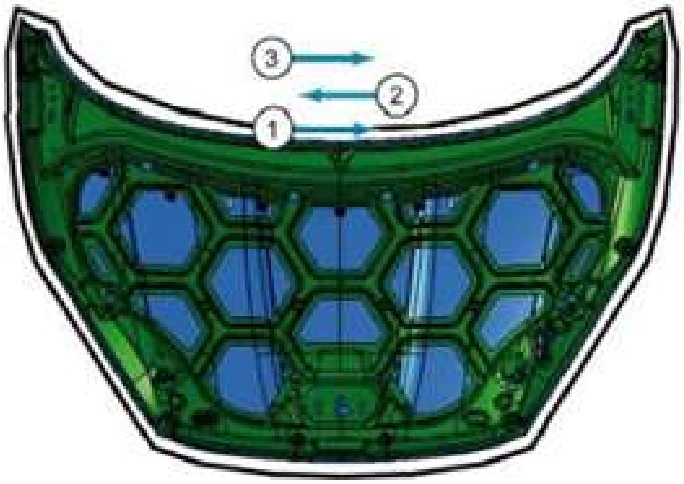

Figure 3.15. Hemming Process in Three Passes.

3.3.2.5 Cycle time

Based on this simulation's study, the approximate cycle time of the process will be the optimum scenario closest to a realistic one (Figure 3.16). If the obtained cycle time is longer than expected, the time loss will be analysed by optimizing the robot pathways and, if necessary, revising the fixture design to reduce the robot's motion. If the cycle time could not be optimized to the required time, more robots would be evaluated, and the fixture design for a two-robot situation would be revised.

Figure 3.16. Robot Trajectory Cycle Time Analysis.

3.3.3. Finite element simulation

When the design process is finalized all the technical details like hemming bed surface, suction cups, referencing points, down holder pressing points, along with the technical characteristics of the part and sealer are inputted into the finite element analysis program.

3.3.3.1 Hemming feasibility

The analysis of the reaction of the flange according to the designed equipment and process serves to enlighten about the:

- Bending simulation of the closed flange from the open flange.
- Deformation of hemmed areas with spring back influence on the surface.
- Evaluation of material deformation from hemming.
- Defining heights, angles, and transitions of flanges
- Developing more reliable car data.

First, a quick hemming analysis can be done showing the major clear mistakes, then a detailed long analysis can be done to assure the result required is achievable (Figure 3.17).

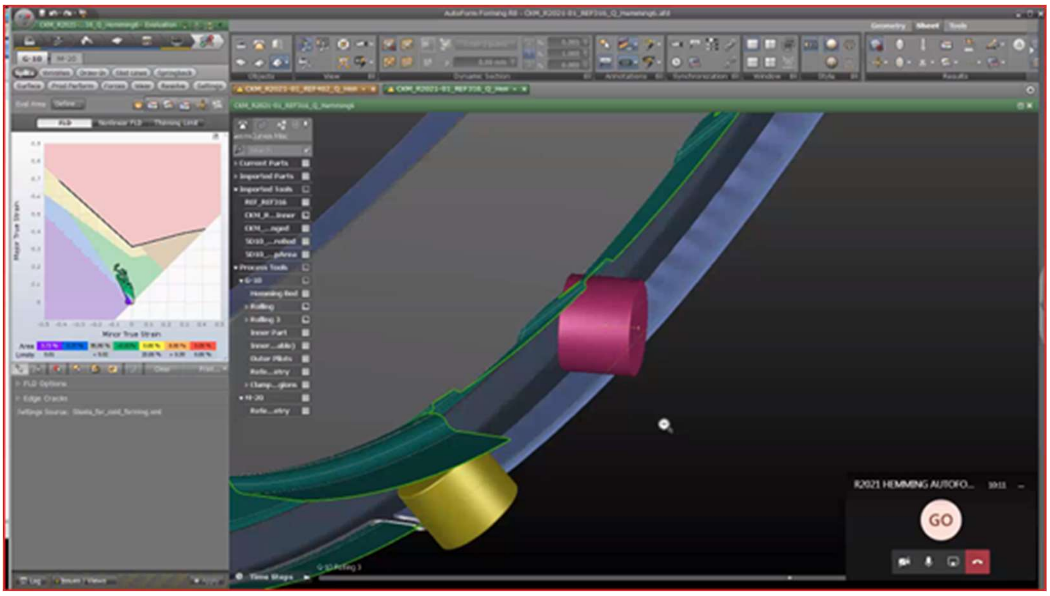

Figure 3.17. Flange Material Reaction Analysed in Auto-form Program.

This analysis allows rapid definition and optimization of the hemming process and the creation of necessary tool geometry for simulation. The program assists in evaluating the deformation of the hemmed area and the influence of spring back on adjacent surfaces. It aids in evaluating the material's deformation and reveals the flange's shape after hemming. It indicates if the flange is wavy and has excess material or has the propensity to crack due to a lack of material (Figure 3.18).

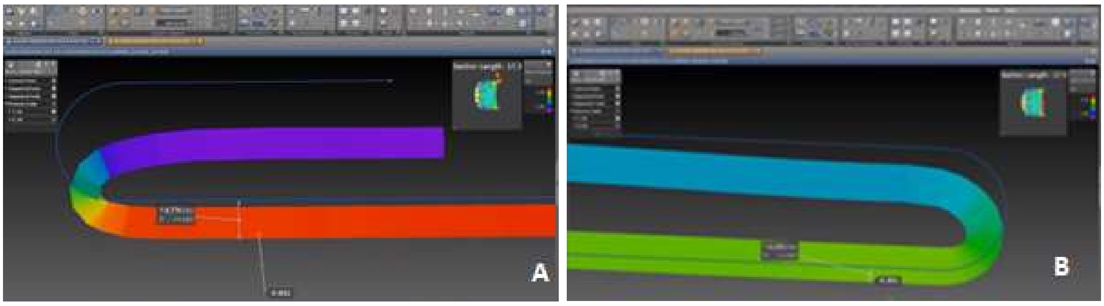

Figure 3.18. Closed Hemming Spring Back Analysed in Auto-form Program. A) Out of tolerance. B) Tolerance ok.

The analysis would reveal the reaction of the flange material during the procedure, and the outcome of this study would be assessed following the identification of its root cause. According to the root cause, the equipment design can be optimized, a roller can be added, removed, or redesigned, or, most importantly, the flange height can be altered. Under precise equipment design, the significance of this analysis is to reduce the error factor of the equipment so that the response result of the flange can be observed, and in the case of a NOK result, the height of the flange may be altered and reanalysed (Figure 3.19).

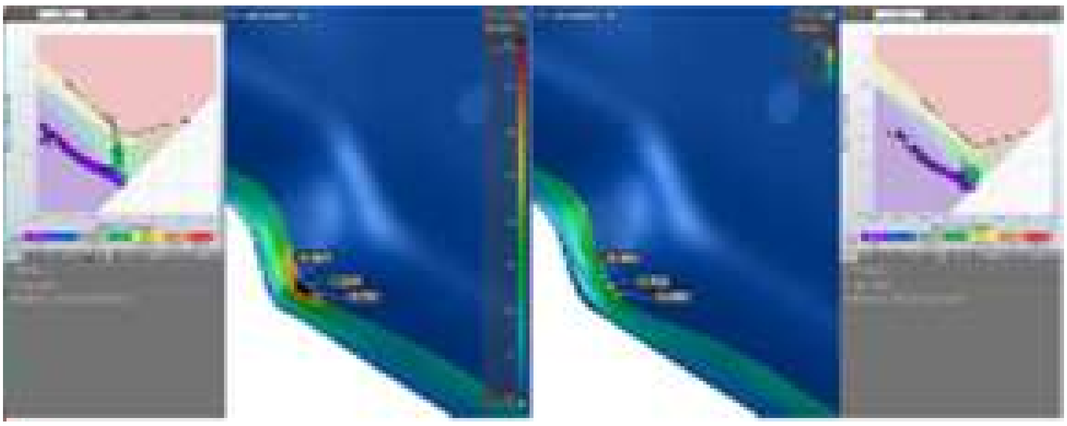

Figure 3.19. The Analysis Results of Auto-form Program Showing the Excess Material after Hemming Reaction.

4. CASE STUDY

4.1. The Design

The sample part considered to show the purpose of this thesis is a car hood. The hood outer panel has no referencing holes; thus, a wide hemming bed has been designed. 10 small 20 mm width rubber suction cups and 4 big 80 mm width rubber suction cups were used to fix the part to the hemming bed. Besides this, extra referencing mechanisms were added to the circumference of the hemming bed (Figure 4.1).

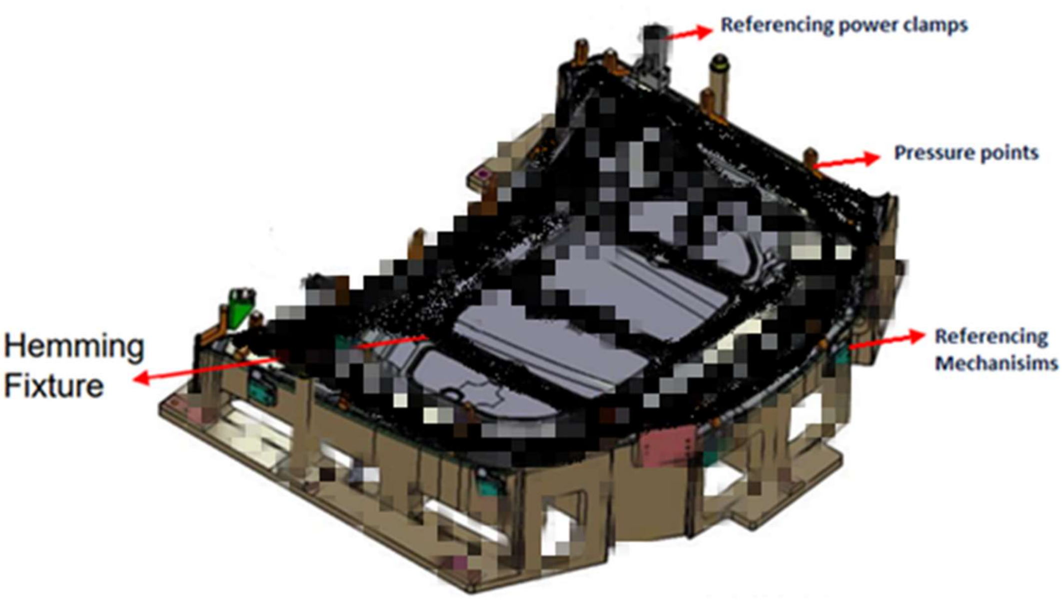

Figure 4.1. Hemming Fixture Design.

As for the referencing of the inner panel 2 power clamps with long course referencing pilots were designed. And for fixation of the inner panel, a down holder attached to a pneumatic 80mm piston was designed. Attached to the down holder 20 rod-like pressure points were added to the circumference of the part to insuring tight hemming.

4.2. Roller Specification

Roller approach angles result in better quality when the hemming rollers approach the flange with the least possible angle in each turn while bending the flange. But for an optimized cycle time, it is suitable to bend the part with three turns or less.

• Ø60mm Roller

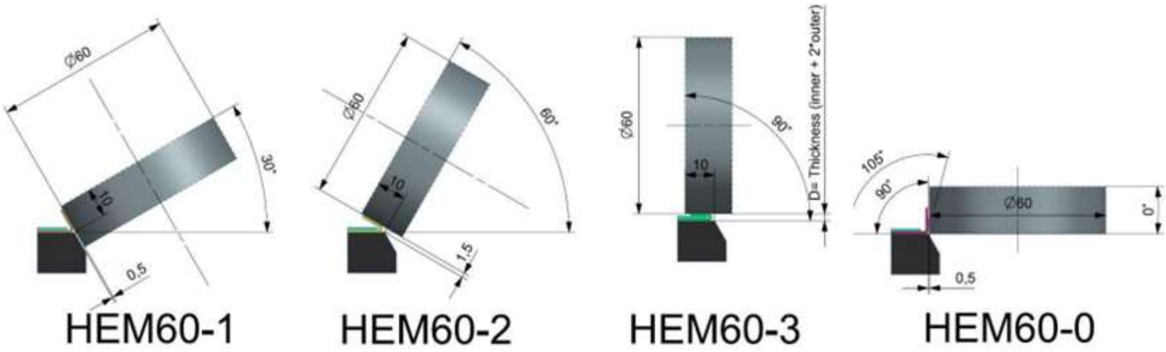

Figure 4.2. Hemming Rollers Angles.

Hem60-1: Pre-Hemming will be done at 60 degrees first. The roller's position should be in the values given in the picture.

Hem60-2: flange will be bent to 30 degrees in the next operation. 1.5mm approach distance is the maximum value. This value is up to 0.5mm and can be lowered. However, we will use 1.5mm for quick hemming.

Hem60-3: flange will be bent at the finish operation to 0 degree as indicated in the picture.

Hem60-0: If the flange angle is over 105 degrees (up to 110 degrees) pre-bending with the roller at the start of the operation should be done (Figure 4.2).

• Ø20mm Roller

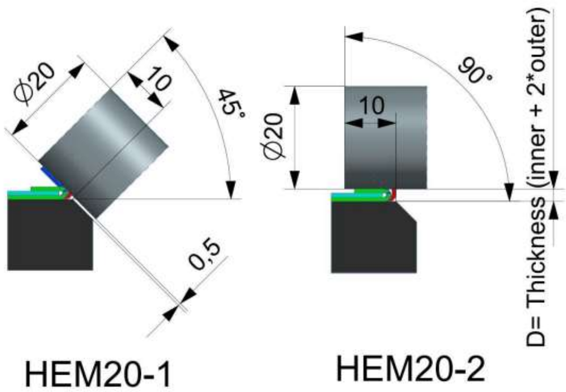

Figure 4.3. Hemming Rollers Angles.

With Ø20mm diameter rollers in 2 moves, respectively 45 degrees and 0 degrees to do (Figure 4.3). In areas where form transitions are hard, pre-bending should be done by approaching a 60 degrees angle (Figure 4.4).

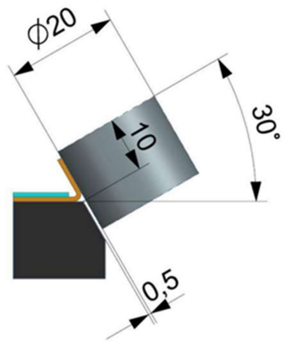

Figure 4.4. Hemming rollers angles.

After, standard operations (HEM60-1, HEM60-2, HEM60-3) will be performed by bending the flange 60, 30, and 0 degrees respectively from the same area with Ø60 mm rollers. Finally, these areas will be finished with a Ø20mm roller.

4.3. Roller Selection and Accessibility Control

Analysing the flange of the part, the radius of the curves, and the accessibility of the roller to the part, it was confirmed that the process can be done using 6 different rollers. 3 of these rollers are 60 mm radius rollers each with a different angle relative to the tool, 30, 60, and 90 degrees. A 20 mm roller to reach low radius flanges. A 40 mm roller and a roller with 45 degrees angle to reach farthest points relative to the robot. The rollers are specified in the pictures below. Those rollers were mounted to 2 different hemming tools. The tools were attached to a tool changer mechanism for which the robot will be able to switch between them during the process (Figure 4.5).

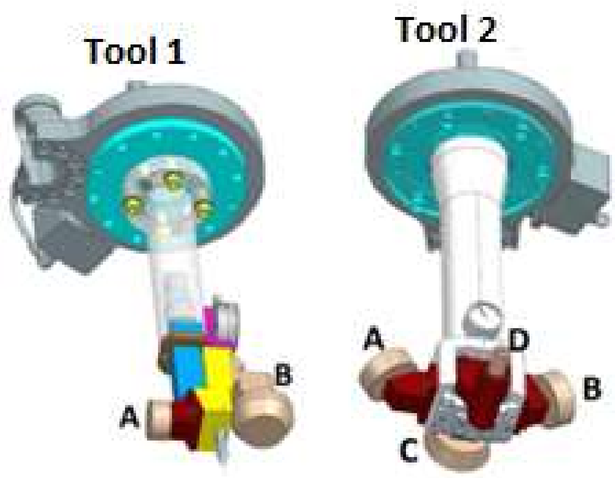

Figure 4.5. Hemming Rollers Tools.

The chosen rollers for the process:

- Roller A, Tool 1: is a 40 mm radius roller with 90 degrees with the tool.
- Roller B, Tool 1: is a 60 mm radius roller with 180 degrees with the tool. Only the roller has a 45-degree.
- Roller A, Tool 2: is a 60 mm radius roller with 30 degrees with the tool.
- Roller B, Tool 2: is a 60 mm radius roller with 60 degrees with the tool.
- Roller C, Tool 2: is a 60 mm radius roller with 90 degrees with the tool.
- Roller D, Tool 2: is a 20 mm radius roller with 90 degrees with the tool.

The process was analysed accordingly:

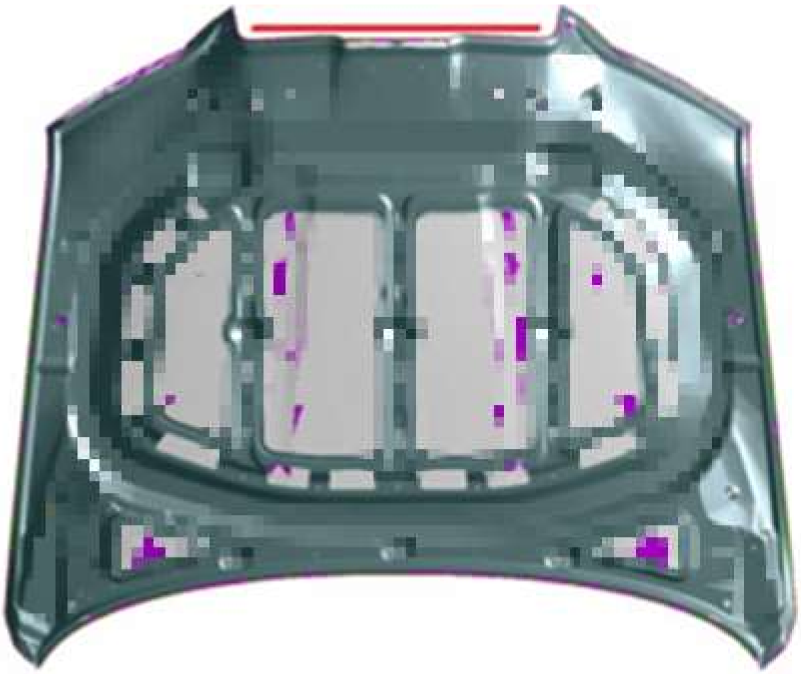

Figure 4.6. Analysed Area.

Knowing that the flanges in the red area (Figure 4.6) are bigger than 90 degrees, using roller-B of tool 1, the flange of the area marked in red will be bent to 90 degrees.

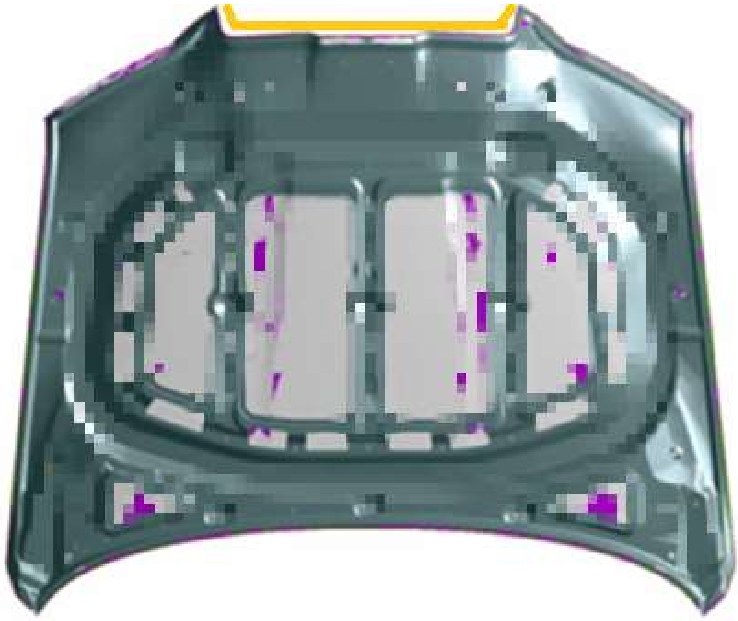

Figure 4.7. Analysed area.

Using roller-A of tool 1, the flange of the area marked in orange (Figure 4.7) will be bent from 90 degrees to 60 degrees, then to 30 degrees and finally to 0 degrees respectively.

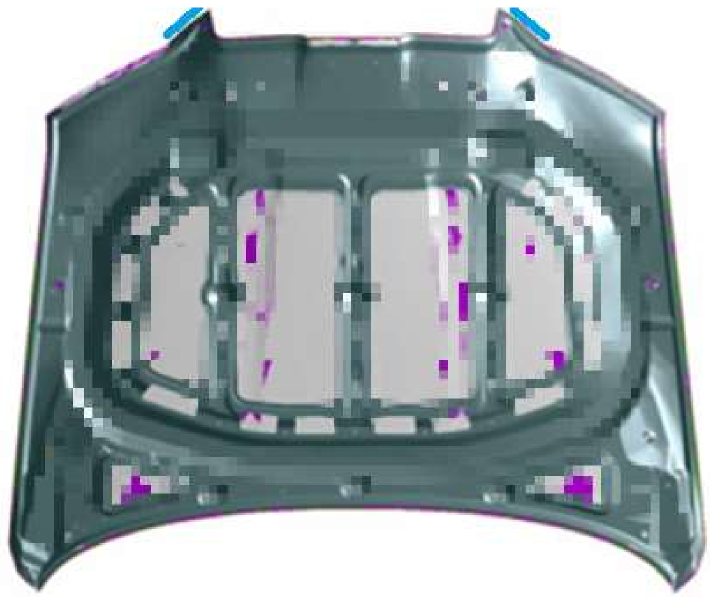

Figure 4.8. Analysed area.

Using roller-A of tool 1, the flange of the area marked in blue (Figure 4.8) will be bent from 90 degrees to 60 degrees, then to 30 degrees. After that the tool is changed and using roller-C of tool 2, the flanges are folded to 0 degrees.

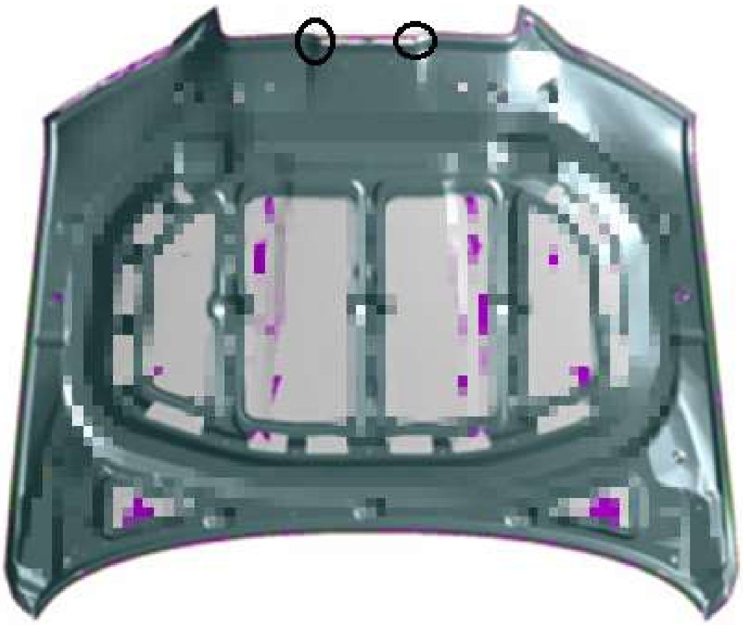

Figure 4.9. Analysed Area.

Using roller-D of tool 2, the flange of the area marked with black circle (Figure 4.9) a pressure is applied to ensure tight hemming.

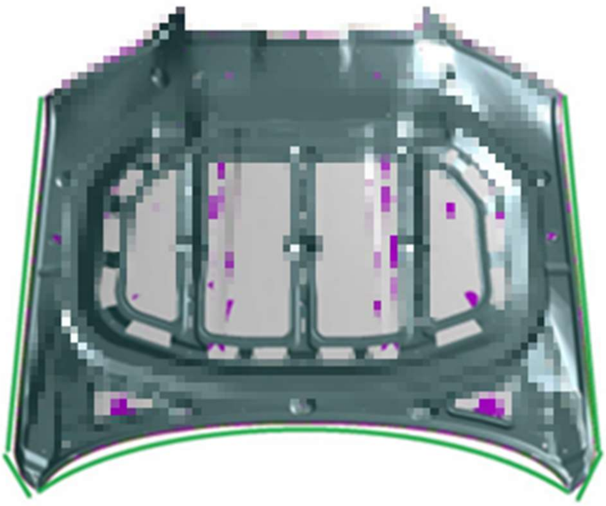

Figure 4.10. Analysed Area.

Using roller-A of Tool 2, the flange of the area marked in green (Figure 4.10) will be bent to 60 degrees then using roller-B the flanges are bent to 30 degrees. Then by using roller C, the final hemming is to be done by bending the flange to 0 degree respectively. According to the result acquired, if necessary, an extra turn can be done using roller-C to ensure better surface quality.

4.4. Robot Trajectory Analysis

The designed fixture and tool were introduced as input data for Robcad program in which the position of the robot was set. The accessibility of the tool to the flange in all positions was checked (Figure 4.11). And finally, the trajectory cycle time of the robot was checked and found sufficient to the process using only one robot (Figure 4.12).

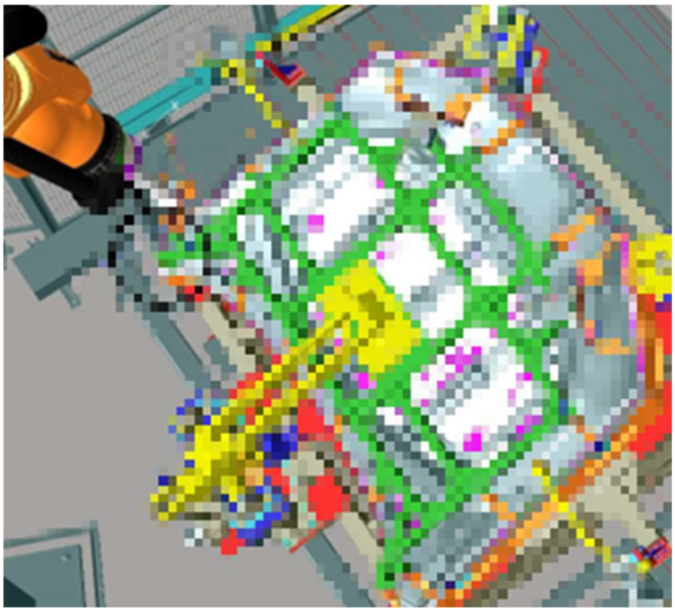

Figure 4.11. Robot Tool Accessibility.

Figure 4.12. Robot Trajectory Analysis.

4.5. Finite Element Analysis

After the Robcad study, the final designs were introduced as input data for the Autoform program. The material technical specifications, the referencing points and pressure points on the part were specified. A detailed simulation accordingly was done (Figure 4.13, 4.14).

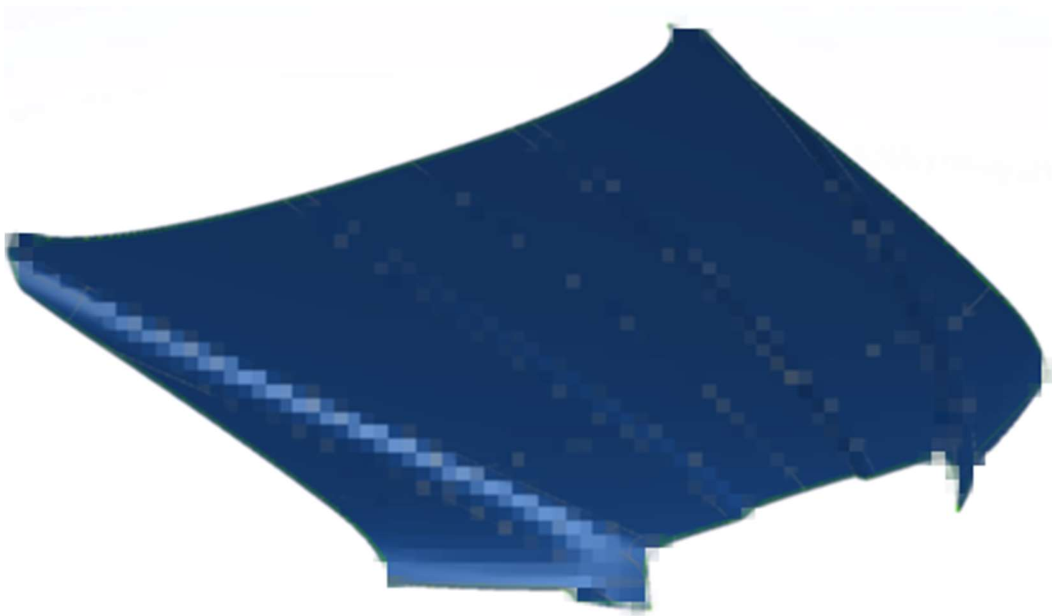

Figure 4.13. Application Test Part.

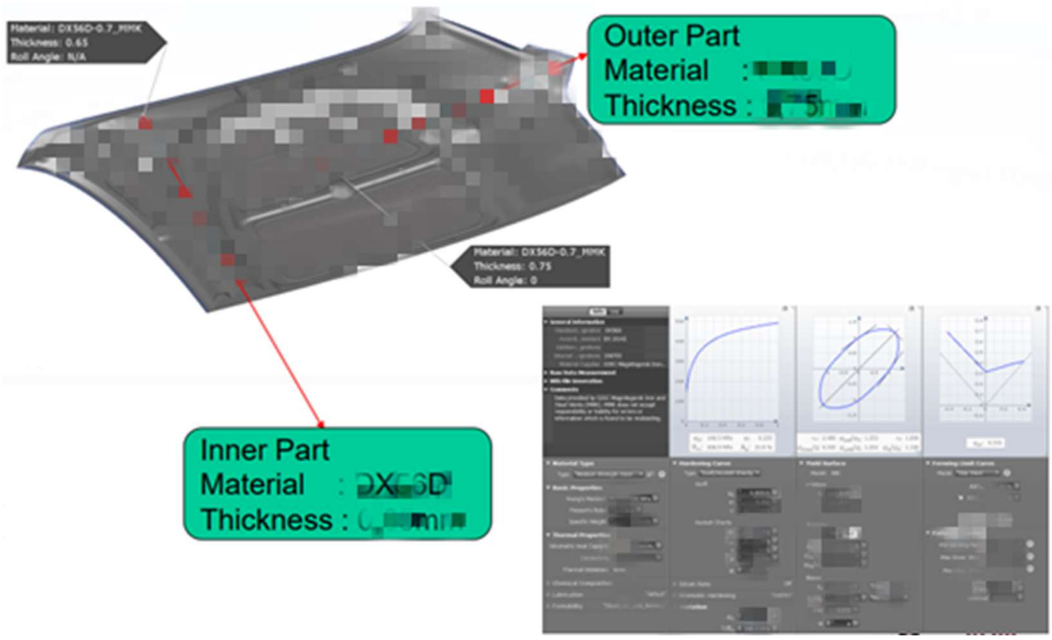

Figure 4.14. Part Technical Specifications.

To start the hemming simulation phase, the location of the outer panel on the hemming bed, the suction cups on the outer panels, the location of the referencing pins and the clamping on inner and outer panel's locations are specified (Figure 4.15).

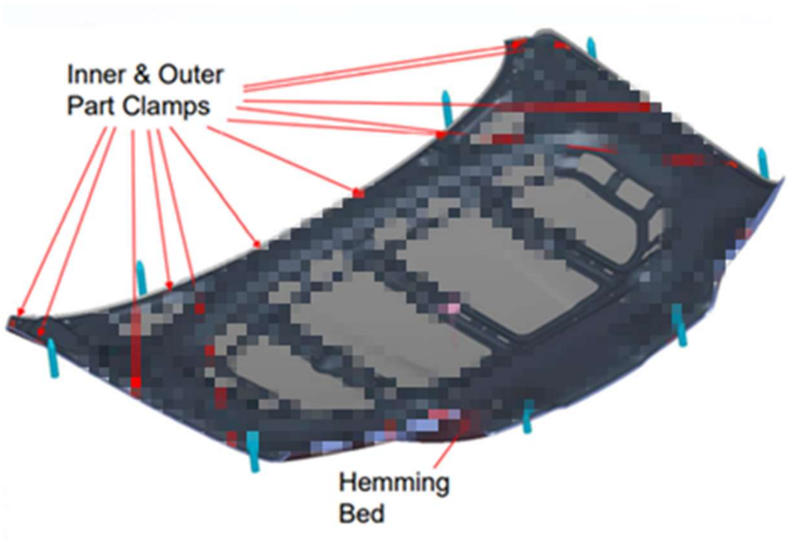

Figure 4.15. Location of Clamps and Referencing Pilots of the Part.

Roll Hemming Process Steps were specified to Autoform according to the simulations done in RobCAD. The starting points of the rollers are specified, and trajectory simulations start by analysing the approaching angle and the existing position. For this case the first starting points are for the areas that have pre-hemming angle more than 90 degrees. Starting from there, the rollers bend those angles to around 90 degrees (Figure 4.16, 4.17).

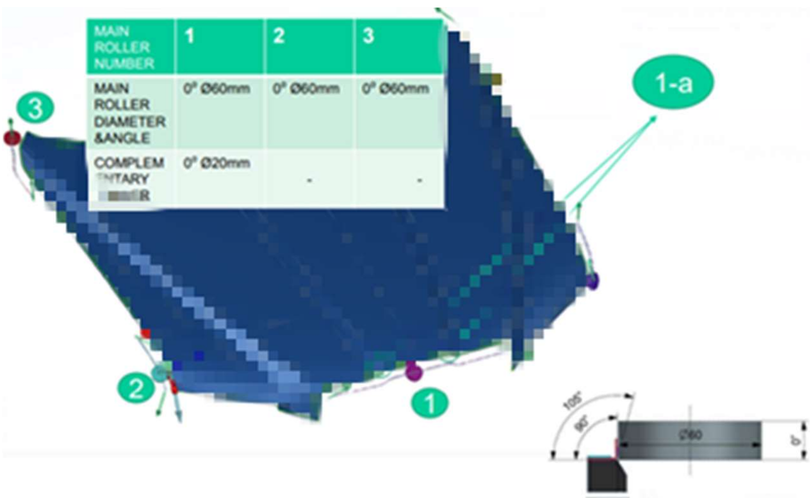

Figure 4.16. Analysed Area.

As shown in the figure (Figure 4.16), there are 3 specified starting points for the roller for each side of the part respectively. The flange angles at these 3 locations are bigger than 110 degrees. Thus, the process starts from those points using the 60 mm roller.

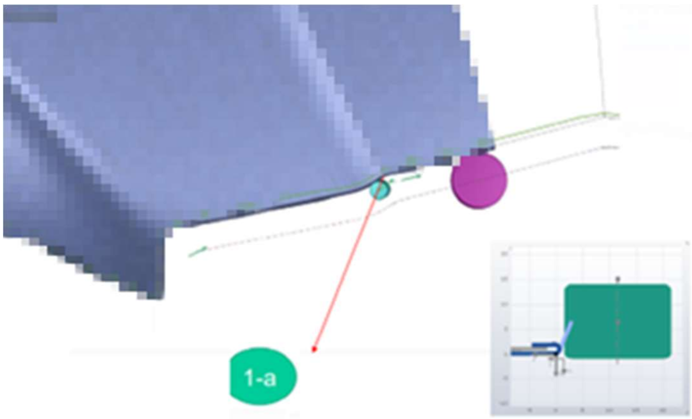

Figure 4.17. Analysed Area.

Only for location 1, a 20 mm roller is used because the radius of the angle at that point is around 20 mm (Figure 4.17). Then respectively 30, 60 and 90 degree, rollers moves on the part, a pass with 20 mm roller should be done complementary (Figure 4.18). Some geometrical locations do not allow 60 mm roller to enter, for those locations the smaller 20 mm roller are used to complete the hemming process (Figure 4.19).

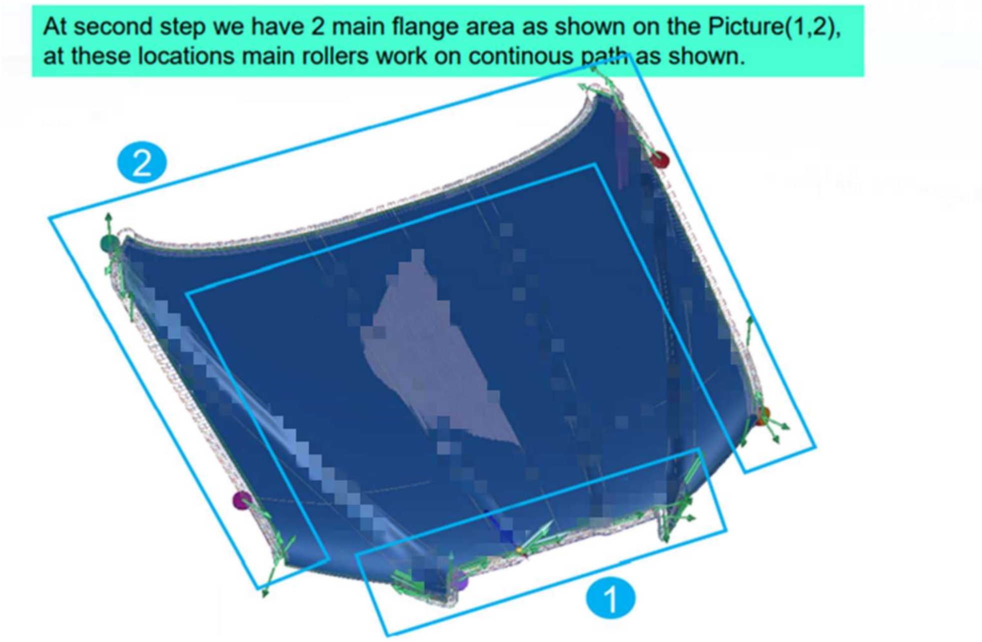

Figure 4.18. Analysed Area.

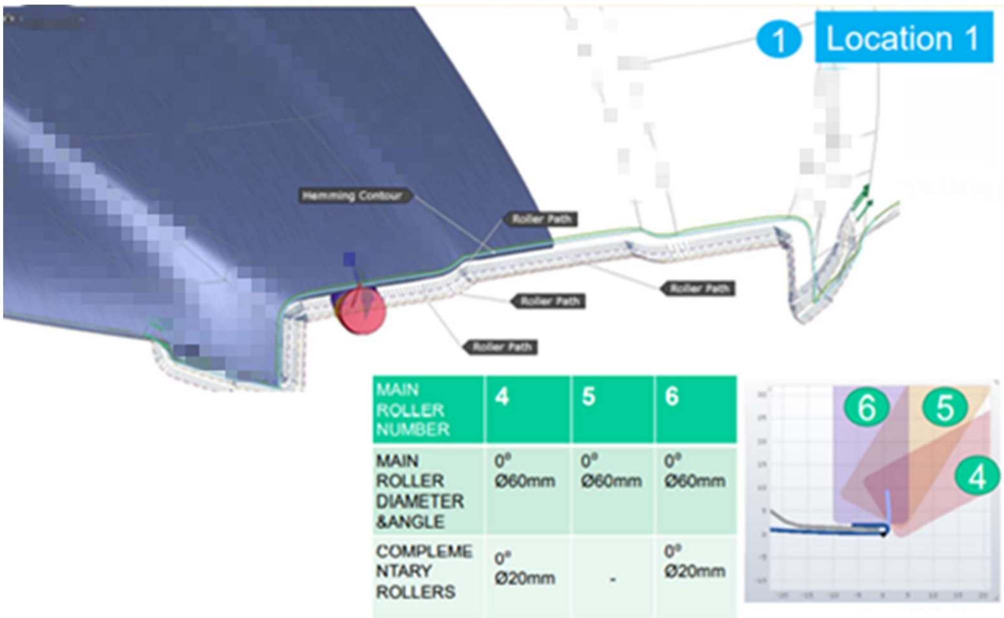

Figure 4.19. Analysed Area.

4.6. Roll Hemming Optimized Simulation Results

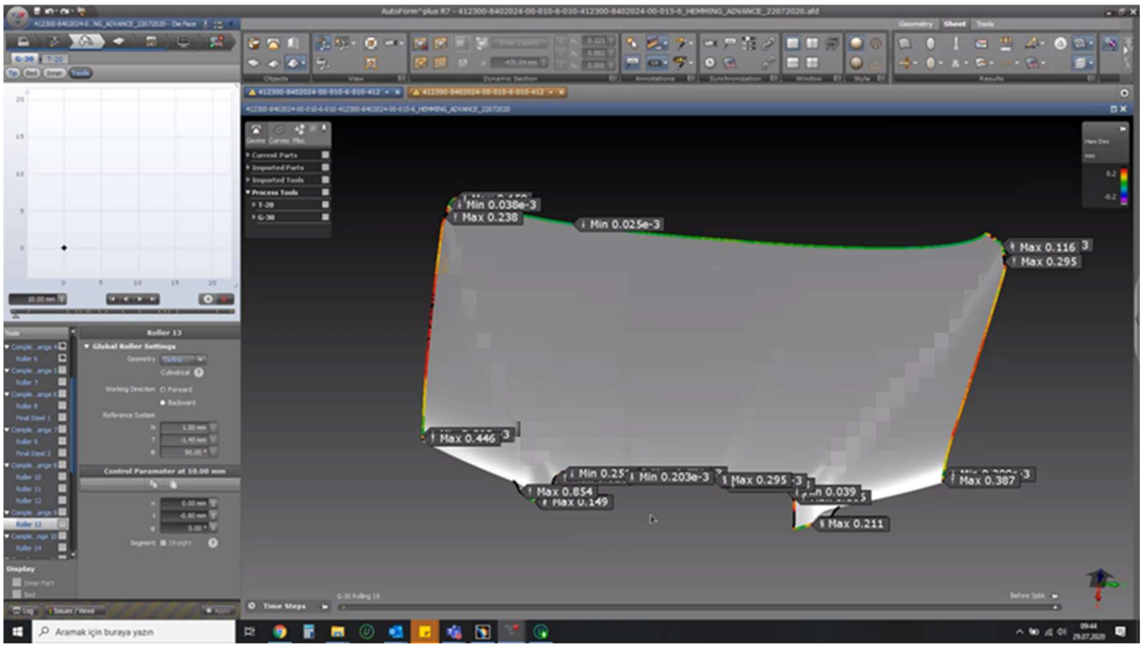

Figure 4.20. Quick Hemming Spring Back Effect Analysis Results.

After the quick saving (Figure 4.20), it was noticed that the spring back effect on the part left and right of the part were present (Figure 4.21). To reduce this, adding extra pressure points on the down holder was requested to the fixture designer and the following analysis has been done after modification.

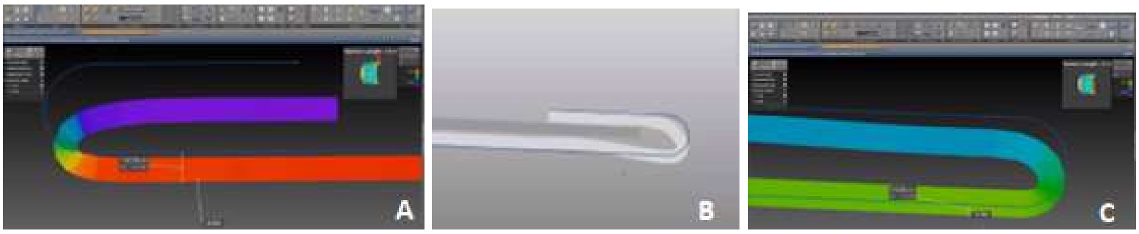

Figure 4.21. Quick Hemming Spring Back Effect Analysis Results.

Following the quick saving, the new design revised fixture data is introduced and now a more detailed analysis should be done. The results of that analysis were as following (Figure 4.22, 4.23):

During bending, the flange sheet has the appropriate height according to the situation. Long enough to press on the inner lining, and short enough that the material doesn't clump after curling. Short in corners and curved (formed) places. It is evaluated by making regional analyses.

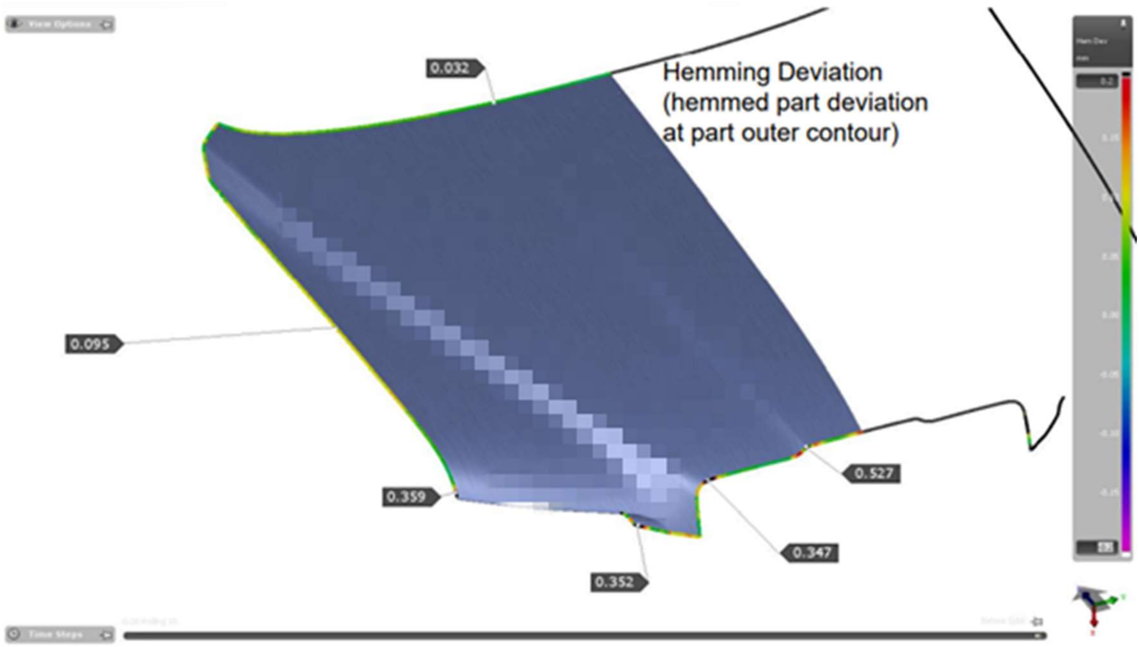

Figure 4.22. Analysis Result.

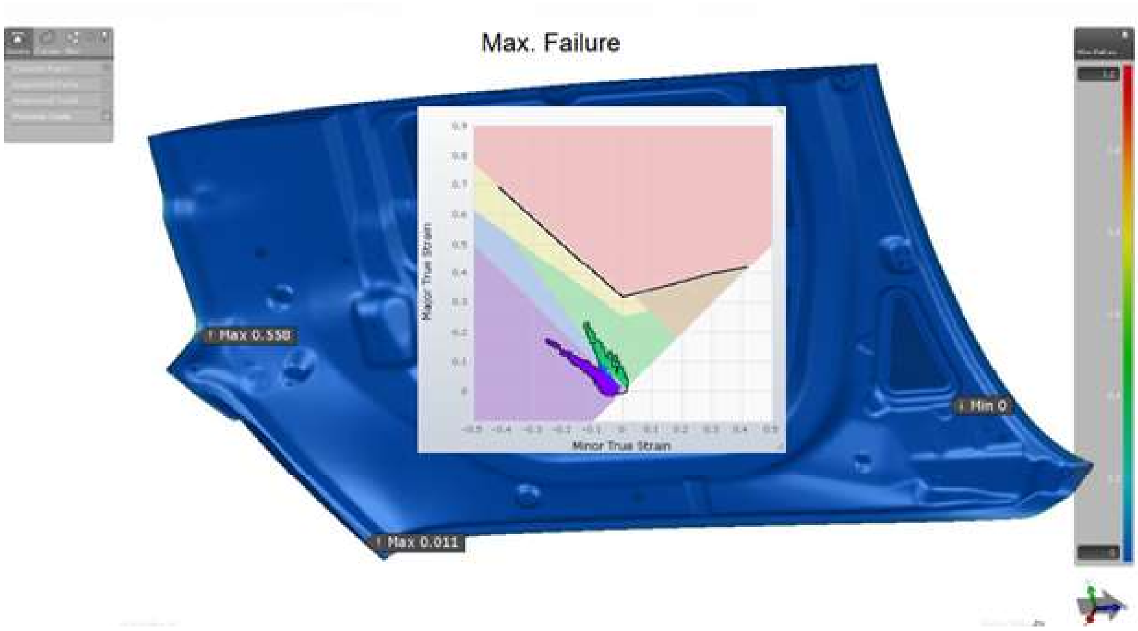

Figure 4.23. Analysis Result.

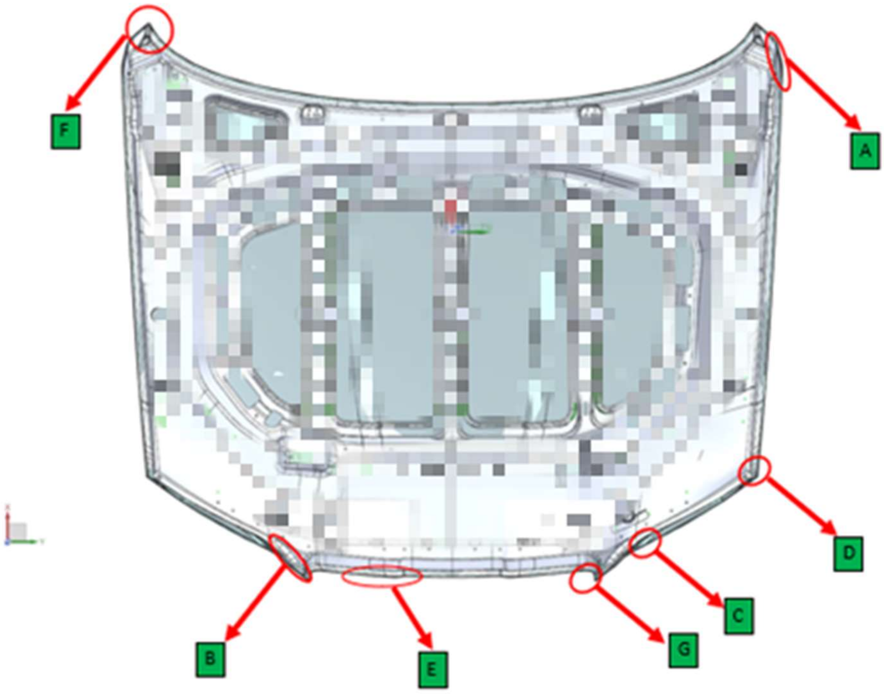

Figure 4.24. Analysed Area.

In zone A and E of the part, because of the form of the hood, the pre-hemming angles are around 133 degrees, this means the flange must be bent first around 45 degrees at once to obtain the 90 degrees for a good hemming process. Bending the flange 45 degrees at once may cause the flange to bend away from the bending line, the material to become thinner and a risk of crack of the flange (Figure 4.24).

The outer panel manufacturer was requested to decrease those angles at least to less than 120 degrees (Figure 4.25). However, forming these angles by the manufacturer requires extra moving mechanisms on the die to continue bending the angle to less than the present angle. The cost of this was evaluated as 150+ K€.

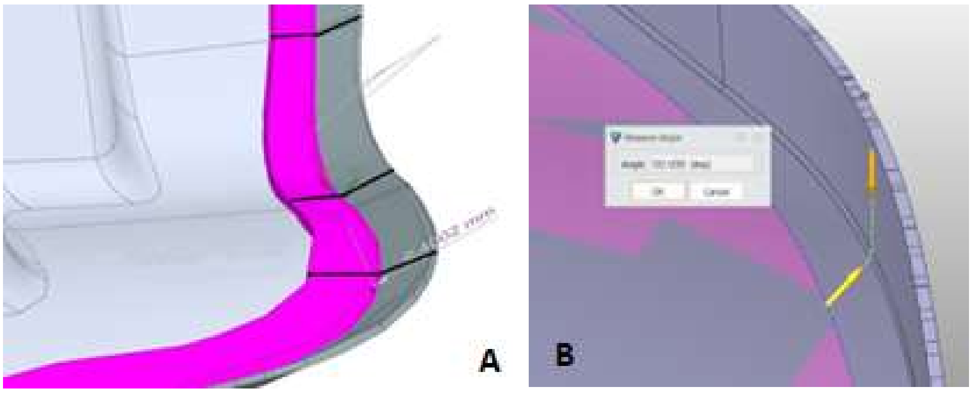

Figure 4.25. Analysed Area.

For this reason, as a more feasible solution, two less expansive modifications were done. First, the equipment manufacturer has to add extra pressure points to the curve to support the roller bend the flange on the curving line. The request was applied to the design, the roller access was reviewed, and the robot trajectory analyses were checked to ensure those extra pressure tools to not limit the accessibility of the tool during the process.

Second, the part manufacturer has to sharpen the curving lines on the part making it easier it to bend when force is applied. In the pre-hemming analysis part, the radius along the line where the flange should bend was not very clear and not marked by the press, so the roller tends to bend the material on a different line. The part manufacturer in this case study did not finalize the machining of the last form making dies and cutting dies. This gives them the ability to apply the requests from the feasibility studies if needed. So, in this case, the request was approved by the part manufacturer, knowing that they were waiting for the feedback on the feasibility of the equipment manufacturer, they reviewed the die's design and finalized the machining accordingly.

For zone B, the same request was done to decrease the angle below 115 degrees (Figure 4.26). For this zone, it was possible for the part manufacturer to apply this modification by reviewing the design of the dies. This modification too was applied to the dies. Here the robot trajectory and tool accessibility should be checked as well, but mainly decreasing the angle may cause major problems.

Figure 4.26. Analysed Area.

For zone C, the material on the corner shows an overlap of flange material after hemming (Figure 4.27), so it was requested from the part manufacturer to decrease the height of the flange in this area. This request was accepted and the cutting dies design was reviewed and machined accordingly. Only to check the ideal high of the flange the finite analysis was redone by analysing the reaction of the material in each height. The acceptable result was to decrease the flange height by 2 mm.

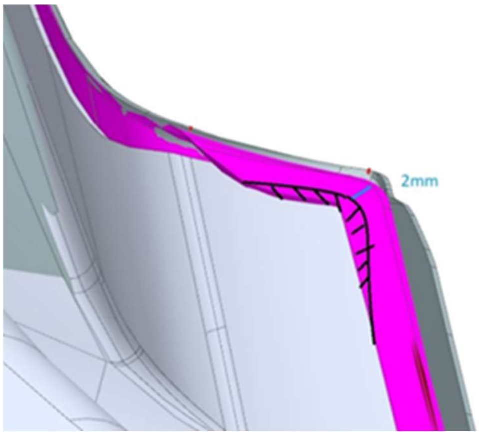

Figure 4.27. Analysed Area.

For zone D, the analysis shows that the roller exiting the part can reach enough this area and the applied pressure is not equal. For this reason, the height of the flange was decreased according to the accessibility of the roller (Figure 4.28). Here the roller accessibility is was analysed and reviewed to assure the full path over this area and homogenous pressure. After the data modification, this area again had to input to finite element analysis to see the reaction of the material and to make sure the flange closes completely after part data modification.

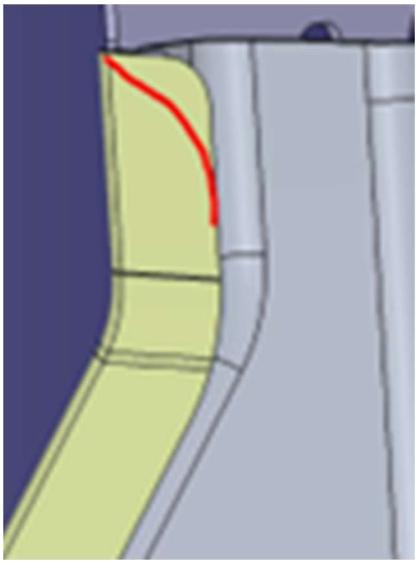

Figure 4.28. Analysed Area.

4.7. Material Behaviour

In zone A, wrinkles were observed in the analysis, the roll-in value was brought closer to the nominal. The wrinkle value was observed again, and accordingly, it was requested to decrease the height of the flange to avoid the curvy form of the flange (Figure 4.29).

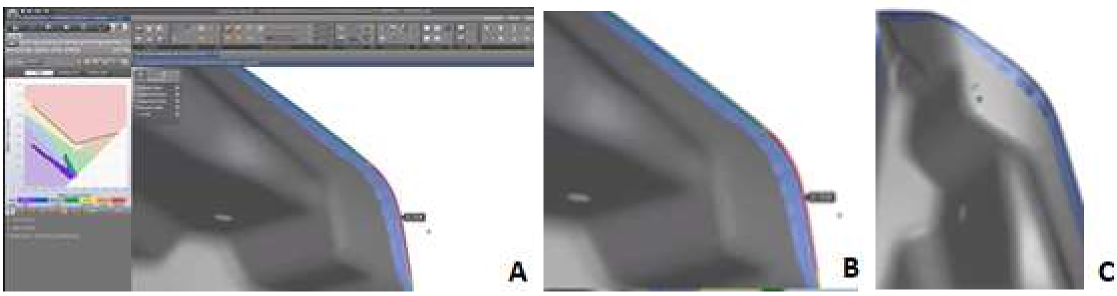

Figure 4.29. Analysed Area.

In zone G, where failure occurs after hemming on the flange, a check was made after the quick hemming. The analysis shows a lack of material after bending and the risk to have a material crack (Figure 4.30). For this reason, it was requested to increase the height of the flange in that area by 1 mm.

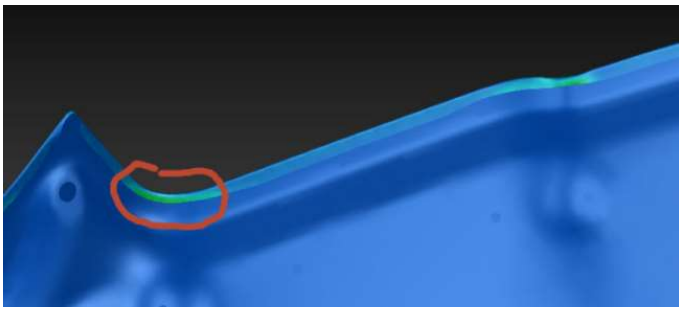

Figure 4.30. Analysed Area.

For zone F, the analysis showed an overlap of material after bending due to the excess material (Figure 4.31). For this reason, the height of the flange on this corner was decreased gradually to reach 1 mm on the peak and then increasing the height to the ordinary length after.

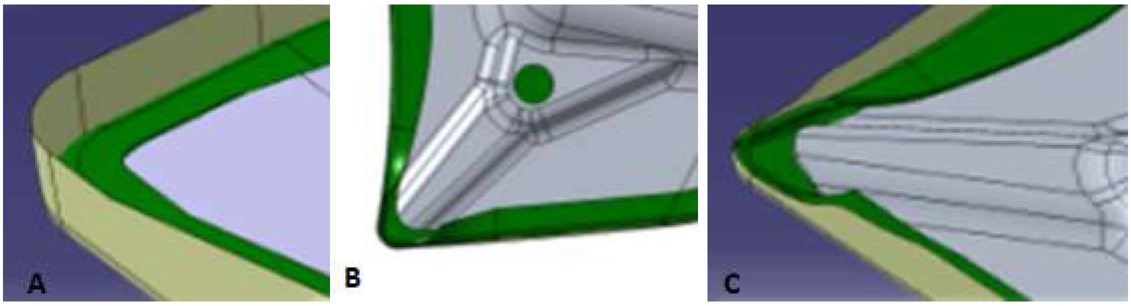

Figure 4.31. Analysed Area.

The requests for modifying the flange height were accepted by the part manufacturer as well as the car designer approved the form of the corners and how they will look. The design of the cutting dies was modified according to the request and machined accordingly.

4.8. Inner Panel Analysis

And finally, the inner panel that plays a role in extra pressure during hemming was analysed. The corners where the results were out of tolerance were analysed. It was observed that in zones D and G the inner panel are a bit far away from the curving lines.

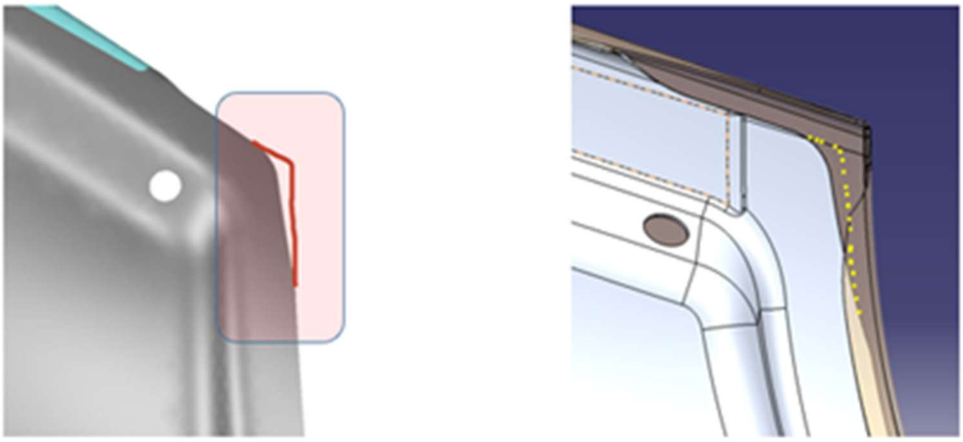

Figure 4.32. Analysed Area.

As shown in Figure 4.32, the area of contact between the inner panel and the flange when closed is very short. The roller presses the inner panel flange on its outer surface because the inner panel does not fill that area. For this reason, a data modification on the part design was requested to elongate the inner panel in those areas as shown in Figure 4.33.

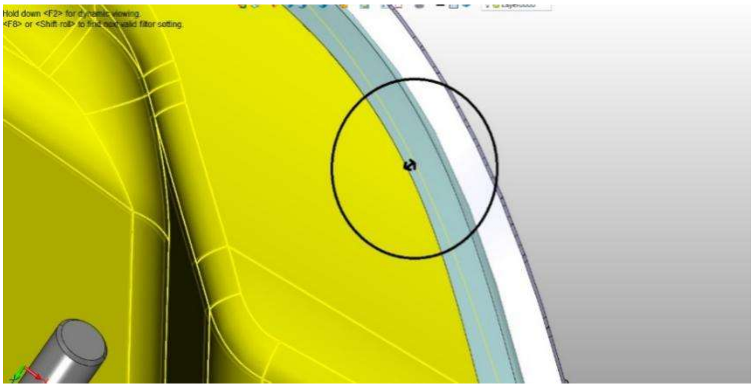

Figure 4.33. The Gap Between the Inner Panel and the External Panel.

The inner panel should be elongated to the outside so that the gap between it and the radius is between 2.5 mm and 1 mm. The request was approved by the part manufacturer for the manufacturing feasibility, the cutting dies of those parts were modified and machined accordingly. Here the part designer had as well to approve the request and to re-evaluate the technical parameters of the part, the extra material effect on the design. Knowing it is a small modification, it was informed that it would not affect their analysis in this case.

5. CONCLUSION

The hemming process is a delicate topic that is now under investigation; Considering all its benefits, the roller hemming procedure is desirable for the body in white closures due to its practicability. The feasibility study for manufacturing closure parts by robot roller hemming is a complex process that has a lot of parameters. The variations in those parameters affect the part design itself and the equipment. And the most feasible way to do that is for the parties of the process, part designer/part manufacturer/equipment designer, to run their feasibility studies in parallel to achieve common feasible solutions for the problems upcoming during the process. There are typically multiple solutions to a problem, but the least expensive one is always requested.

The feasibility analysis of the matrix of activities depends on the outcomes of each phase and the challenges encountered at each step. When an error or problem is identified, a root cause analysis is conducted, and then the analysis should be revisited from the beginning of the loop, with each aspect rechecked and optimized. The hemming fixture will be evaluated based on the analysis of the robot's trajectory. According to the simulation of the flange reaction, the pressure locations on a down holder will be evaluated. To access specific flange locations, it may be necessary to add new rollers. If the cycle time was longer than anticipated, the design would be revised, or an additional robot would be installed. The pre-hemming angles and flange height will be modified based on the flange reactivity analysis, and the rollers' accessibility will be re-evaluated.

For the case study evaluated in this paper, the hood equipment cycle time was enough to use 1 robot and 2 tools with 6 rollers were sufficient for the process. The down holder pressure points were not enough, in the beginning, knowing the part size is big. A supportive suction cup set was applied on the fixture for better fixation and better referencing supporting the referencing mechanisms. The design of the roller tool was reviewed and finalized according to the reachability of the robot and the accessibility of the rollers.

The results of the finite element analysis done with the equivalent design showed many nonconformities, their root causes were analysed, and modification requests were sent to relevant parties. The main challenge in the process was to define the process for the flanges with more than 120 degrees and the second problem was the length of the flange in some areas. Extra pressing points were added in that area for better fixation during the process. And a pre-hemming cycle was introduced to decrease the angles of the flanges. For some areas, it was possible to decrease the flange angles by the part manufacturers and for some areas it was accepted to decrease the height of the flanges. To apply those requests the dies design was modified and machined accordingly. It was also seen that the inner panel in some areas does not apply enough pressure on the outer panel, for that a modification request was sent to the part designer and approved. The part designer analysed the requests according to the technical analysis they formally did and checked if it affects them or not.

In case those feasibility studies have not been done in parallel and it would not have been possible to modify the parts. And then the equipment manufacturer will have to design extra equipment, add roller or even extra robot to resolve the upcoming issues. Those extra equipment means extra components costs, extra engineering hours cost and means extra financial cost. And knowing that the add up tolerances of the many parameters of the hemming process affect the end product, it would be essential to resolve all the upcoming small defects in the most efficient way to be able to have a feasible good product.

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APPENDICES

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APPENDIX Curriculum vitae

RESUME

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