DIFFERENT METHODS IN ANALYZING ROLL FORMING PROCESS OF AUTOMOTIVE COMPONENT

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Abstract: *In Finite Element Analysis of the Roll Forming (RF) process of automotive component, there are two methods for numerical simulation. The first one is general analysis, and the second is a specific analysis. The general approach is a deeper investigation but takes a long time for simulation, while the specific approach uses many assumptions for RF, takes less computer time and can analyze many special processes quickly. This paper investigates many RF processes of automotive components by using both methods, in order to identify differences between them as well as build the foundation for using the combination of different methods in analyzing and designing RF process. A realistic application in analyzing and designing is developed and shows the good efficiency in comparison with the previous procedure.*

Key words: *roll forming, finite element analysis, numerical simulation, automotive component*

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1. Introduction

RF is currently used in manufacturing of many automotive components, such as a car hood, car canopy or car door-belt. In Finite Element Analysis of RF, there are two methods for the numerical simulation of a process. The first one is general analysis, which uses general analysis programs and considers almost all factors that affect the process for simulation. The second one is the specific analysis, which uses many assumptions for RF and only considers some main factors in the process.

In RF, the metal sheet has large deformation by contact with rolls over a long period of time. The results of the process depend on many factors: the number of pass, the geometry and rotation velocity of each roll, the mechanical properties of material, and the friction coefficient.

A number of researches on RF using the general analysis have been done. Heislitz *et al.* (Heislitz *et al.*, 1996) used a 3D FEM code PAMP STAMP to simulate the U channel RF process with three roll stands. Computer time was 250 hours and longitudinal strain from the simulation result is close to the experiment. Lindgren (Lindgren, 2007) used an FE package MARC/MENTAT to simulate the RF process of U channel made of high strength steel with 4 roll stands. Simulation results by general analysis showed a variation of longitudinal strain and deformation length for material with high yield strength. Bui and Ponthot (Bui & Ponthot, 2008) used an FE code Metafor to simulate RF process of U channel. Useful results like stress and strain distribution have been obtained by the general approach. However, most of them only worked with RF process of simple sections.

In order to simulate the RF process of complicated profile as well as reduce complexity and computer time, many studies set specific assumptions on the deformation of the sheet; many specific RF programs have been built with these assumptions. Brunet *et al.* (Brunet *et al.*, 1998) developed a specific FEM code PROFIL, that simulation is done by combination of 2D analysis at cross section and 3D analysis between 2 or 4 roll stands. Duggal *et al.* (Duggal *et al.*, 1996) developed a computer aid simulation program RF PASS for the RF process. They assumed a "shape function" to describe movement of the sheet between 2 passes and set constraints for force and strain at cross section. These studies with others have set the foundation for the development of many specific RF programs later.

Each analysis method has its specific strong points. The combination of different analysis methods to take full advantage of them shows the great applicability in analyzing and designing RF process of automotive component. However, no previous study evaluated and clarified their characteristics and differences; and no application of combination of different analysis methods in RF has been developed till now.

In this paper many RF processes of automotive components are simulated and analyzed by different analysis methods to clarify their characteristics and the differences between them. The application of different analysis methods in analyzing and designing RF process of automotive component is developed. The current procedure for designing RF process is mainly based on experiment with the aid of specific RF tools. It takes a long time for analyzing and cost for producing prototype.

The analyzing and design procedure based on the combination of different analysis methods can result in obtaining the optimum design of forming process with less time for analysis and less cost for producing prototype.

2. Simulation of RF process by general and specific analysis

With specific analysis, this paper focuses on the most common approach, rigid plastic FEM with the generalized plane strain condition. The rigid plastic FEM is widely used for analyzing many processes, such as RF (Sheikh & Palavilayil, 2006; Hong *et al.* 2001), tube forming (Ko *et al.*, 2005), blanking (Hein *et al.*, 2008), or forging (Kim *et al.* 2009). Many RF programs have been built and used in RF industry as well as in many studies by this approach.

In the simulation of the RF process by general analysis, only some basic assumptions are used for modelling and the simulation is done with three dimensional FE model. By specific analysis, the three dimensional rigid plastic FEM combines with the initial guessing algorithm is used (Sheikh & Palavilayil, 2006; Hong *et al.* 2001)

With the metal sheet, the general analysis considers almost all affecting factors, while specific analysis set condition on deformation of the sheet. In the cross section which perpendicular to the rolling direction, the general plane strain condition is used. Therefore longitudinal strain rate is uniform in all cross sections in specific analysis.

In the modelling of a process by general analysis, all rolls are considered as rigid bodies, the sheet contacts with rolls and is moved by friction force, contact pairs are defined manually for each pass. With specific analysis contact pairs are defined automatically and in each pass the initial guessing algorithm finds the steady state solution from 2D FE model (Sheikh & Palavilayil, 2006).

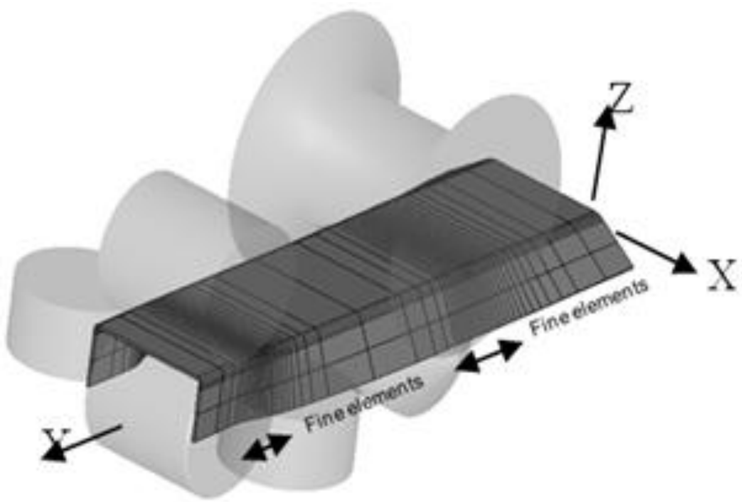

Fig. 1. Computational mesh by real time re-meshing technique

Besides using basic meshing rules, many RF programs are equipped with a special meshing technique for RF, called real time remeshing. With this technique, the computational mesh for analysis has fine elements in contact areas between sheet and rolls, and coarse elements elsewhere (Fig. 1). By this technique, the simulation time is significantly reduced, while the accuracy of results is acceptable (Alsamhan *et al.*, 2004). On the contrary, with general analysis it is hard to apply this technique to the simulation of RF. Therefore, in most studies, the computational mesh in general analysis has fine elements over the entire sheet (Park & Pham, 2009).

3. Modelling and simulation of different RF processes

Different RF processes of automotive components are simulated by general and specific approaches. Value of longitudinal strain at the edge of the sheet is the main factor for comparison since it is the major factor related to quality of RF product. In all simulations, the general analysis program ABAQUS is used with the general approach, the specific RF program SHAPE-RF is used with the specific approach.

Mechanical behavior of material is assumed to follow Swift's isotropic strain hardening law: $\sigma_v = K.(\varepsilon_0 + \varepsilon_p)^n$. Where σ_v is the flow stress, ε_0 is the initial strain, ε_p is the plastic strain, K is the strength coefficient, and n is the strain hardening exponent.

3.1 RF process of U channel section

The U channel RF process is the most popular model of many studies because of its symmetrical profile and because the number of pass is small. This process also is used in manufacturing of many automotive components. In this paper, the RF process of a U profile which was numerically modelled by (Heislitz *et al.*,1996) is simulated again and the experimental result extracted from (Heislitz *et al.*,1996).

The forming process includes 3 steps; bending sequence is 300, 600, and 900. The sheet has an initial thickness of four mm. Mechanical properties of the material are: E = 210 GPa, K = 1015 MPa, $\varepsilon 0$ = 0.001292, n = 0.143.

The deformed shape of the sheet (Fig. 2) and the values of peak longitudinal strains from simulation results of both approaches are similar (Tab. 1) and are in good agreement with experimental results (Fig. 3). However, the values of longitudinal strain between roll stands from general and specific analysis are different. Specific analysis has a larger value than the general analysis. The reason comes from the spring back phenomenon which cannot be correctly simulated by rigid plastic model of the specific analysis. By result in this paper and from results of (Bui & Ponthot, 2008) and (Hong *et al.* 2001), it is clear that the simulation of general analysis is very close to reality.

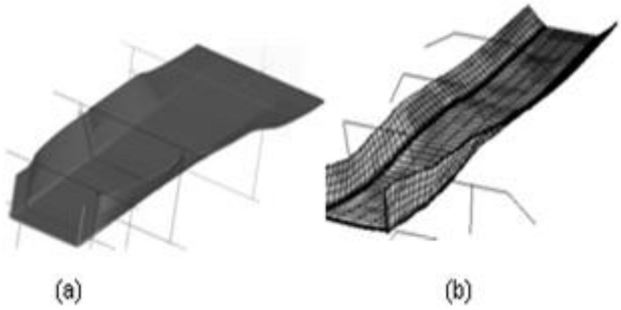

Fig. 2. Deformed shape of sheet by: a) the specific approach, b) the general approach

Peak Long.Strain	RS1	RS2	RS3
General analysis	0.0153	0.0143	0.0245
Specific analysis	0.0150	0.0126	0.0240

Tab. 1. Result of peak longitudinal strains by general and specific analysis in RF of U channel section

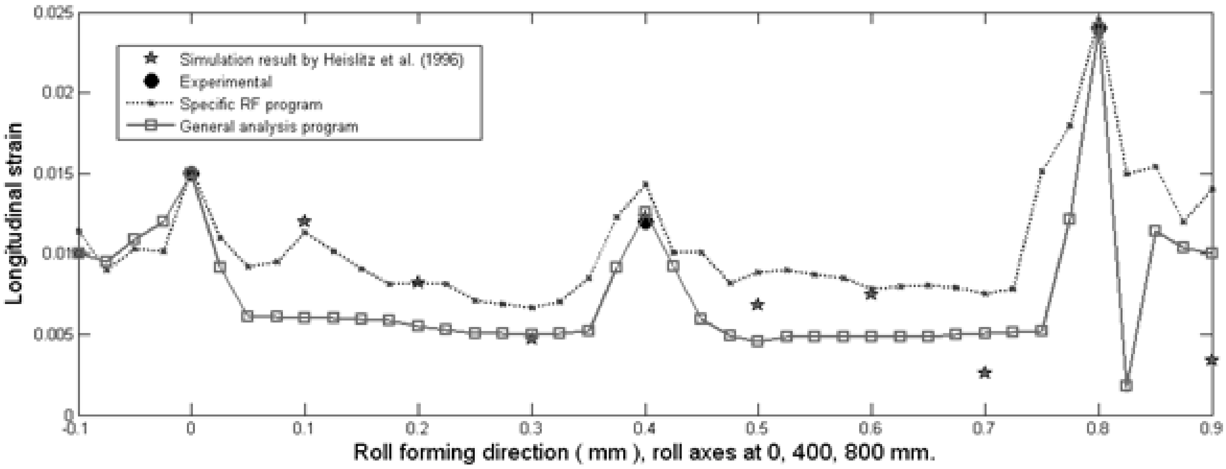

Fig. 3. Contour of longitudinal strain at a distance 2 mm away from the edge of sheet

Next, an unusual RF process of U channel section is analyzed. Forming line includes 3 steps with the bending sequence is 200, 400, and 600. The material is the same as RF process above. At roll stand number 2, the area that contacts with the sheet of top roll is smaller than bottom roll (Fig. 4). Rotation velocity of rolls is increased to enlarge the defect.

Simulation results from the general and specific approach are different. The specific RF program shows a good process while the general analysis program shows an unusual moving of the sheet (Fig. 4). Moving direction of the sheet tends to be upward instead of straight and causes unusual impacts with rolls.

The reason of this phenomenon comes from the difference between areas which contact with the sheet of top and bottom rolls. This difference causes an unbalance between friction force on top and bottom surfaces of the sheet, therefore, causing unusual moving direction. Because of this unbalance, the longitudinal strain of cross section at roll stand number 2 is not longer uniform, while specific analysis uses generalized plane strain condition for simulation, so it does not recognize this phenomenon.

It can be seen in Fig. 5 that in normal cases the difference between the length of longitudinal fibers in the flange zone and the web zone causes a little downward defection of the sheet. Nevertheless, when the contact areas are different the sheet movement tends to be upward.

From the simulation result of the general analysis, it can be concluded that the roll design in this case is not good. This result is close to problems in reality.

This defect depends on many factors but the main is the ratio of the contact area between top roll and bottom roll. As can be seen in Fig. 5, when this ratio decreases the upward displacement increases. The friction coefficient and rotation velocity can also affect this defect. When their values are large, only small differences between the contacting areas can causes large upward displacement.

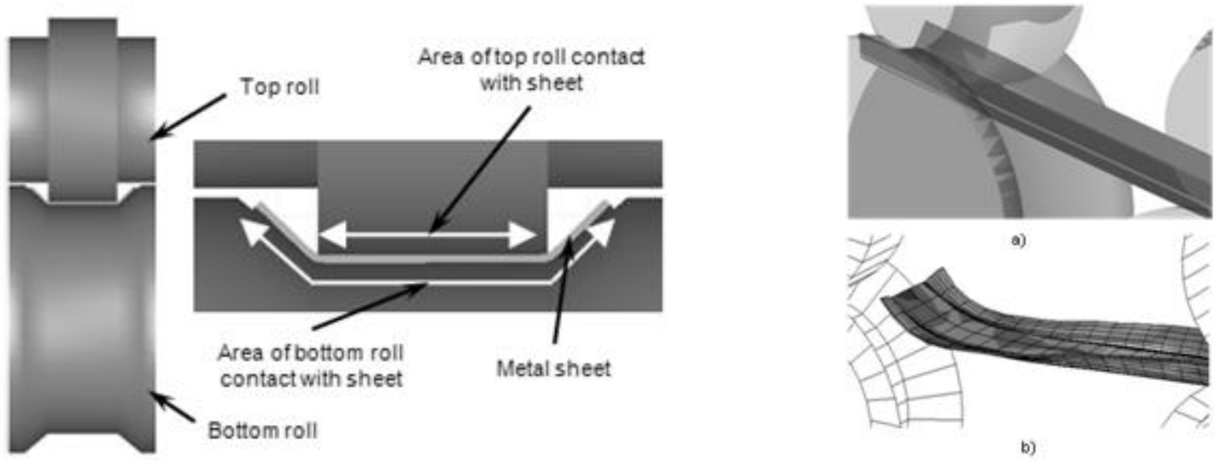

Fig. 4. Top roll and bottom roll of roll stand number 2; and deformed shape of sheet by: a) the specific analysis, b) the general analysis

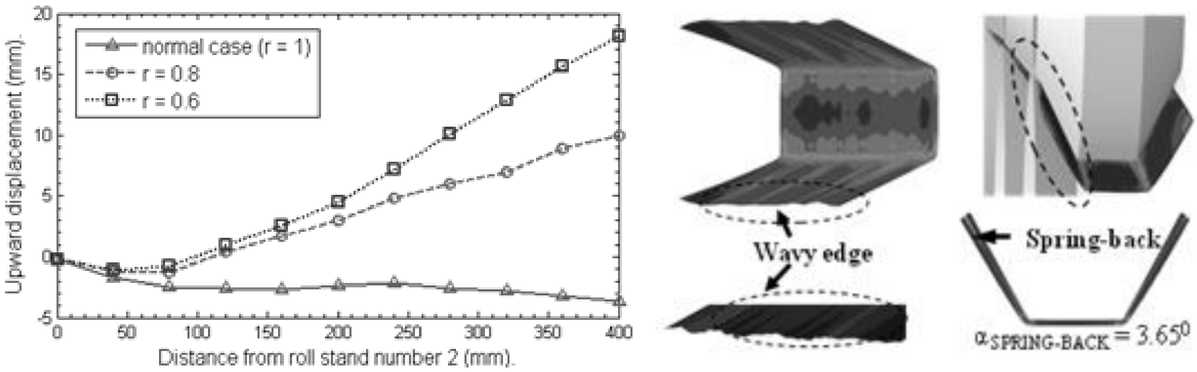

Fig. 5. Vertical displacement of a point on the centre line of the sheet, with r is the ratio of the contact area between top roll and bottom roll; and the wavy edge and spring back phenomenon in RF process of U channel

Other defects such as the spring back phenomenon or edge wave also can be analyzed clearly by the general analysis. The spring back angle and the overbending angle can be obtained. The spring back angles of RF process of U channel are shown In Fig. 5. These defects affect directly to quality of product. However, they cannot be simulated by rigid plastic FEM and the prototype must be produced to check for defect when specific RF analysis is used.

3.2 Edge bending and hemming process

Bent edge and hemming are widely used in manufacturing of many components of a car, such as a car hood or car door. Bending the edge of sheet is more difficult than the middle. The effect of spring back at the edge of the sheet easily leads to buckling, and besides spring back the contact definition can also cause simulation failure in the FE analysis of the process.

The specific RF analysis uses an initial guessing algorithm to find the steady state solution from the 2D FE model of the pre-estimated section and automatically defines contact pairs based on the geometry of the rolls. However, the guessing algorithm can provide different simulations with respect to different geometries of the roll. Simulation of edge bending is often wrong at the edge of sheet where there are many contact pairs and hard to find steady state (Fig. 6). On the contrary, contact pairs in general analysis cannot be manually defined so the simulation results of edge bending are more stable.

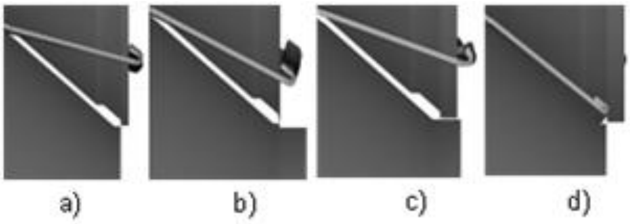

Fig. 6. Different simulation with respect to different roll geometries: a) change top-roll, b) change bottom-roll, c) change both rolls, d) good result

The most severe case of edge bending is hemming. Hemming is used to make a smooth edge by folding the edge of the sheet. (Svensson & Mattiasson, 2002) used the general analysis by LS-DYNA to simulate automobile hood hemming. (Thuillier *et al*., 2008) also simulated roll hemming process by general analysis through ABAQUS software. All of them analyzed the normal case of hemming where complexity is reduced by supporting of the inner panel (Fig. 7). However, in RF roll design does not allow the participation of the inner panel, the process is done by the self contact of sheet.

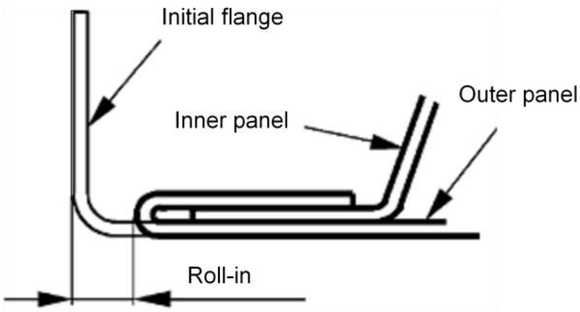

Fig. 7. Initial flange and final hem in hemming with inner panel

A hemming process in RF is simulated by both approaches for comparison (Fig. 8). Process includes five steps with bending sequence is 400, 750, 1100, 1450, 1800. The material is aluminium with mechanical properties: K = 950 MPa, ε0 = 0.024, n = 0.35, E = 70 GPa. The sheet has an initial thickness is 0.4 mm.

Specific RF programs define contact pairs automatically but easily have incorrect simulations such as self intersection. On the contrary, general analysis program simulates the process fluently by manually defining of contact pairs. With successful simulations (Fig. 8), the values of peak longitudinal strains from both approaches are similar (Tab. 2). In hemming longitudinal strain between roll stands from general analysis and specific analysis are different as with the U channel case above (Fig. 9).

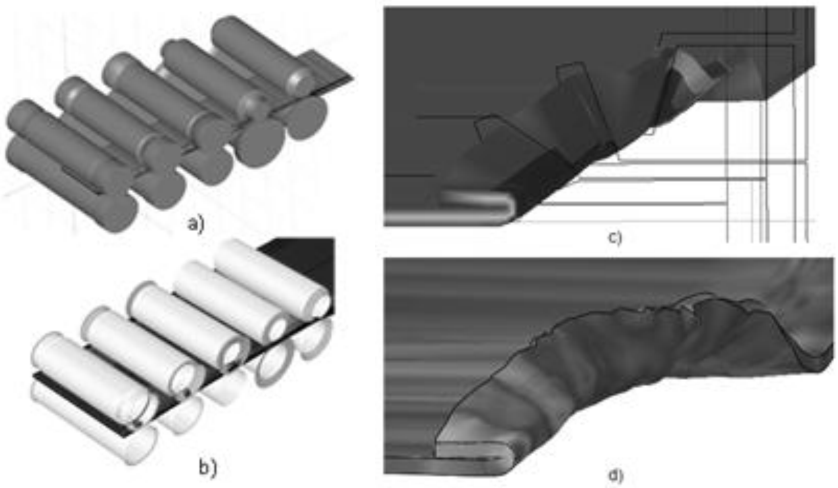

Fig. 8. Hemming process by: a) the specific analysis program, b) the general analysis program; and deformed shape of sheet in hemming process by: c) the specific analysis, d) the general analysis

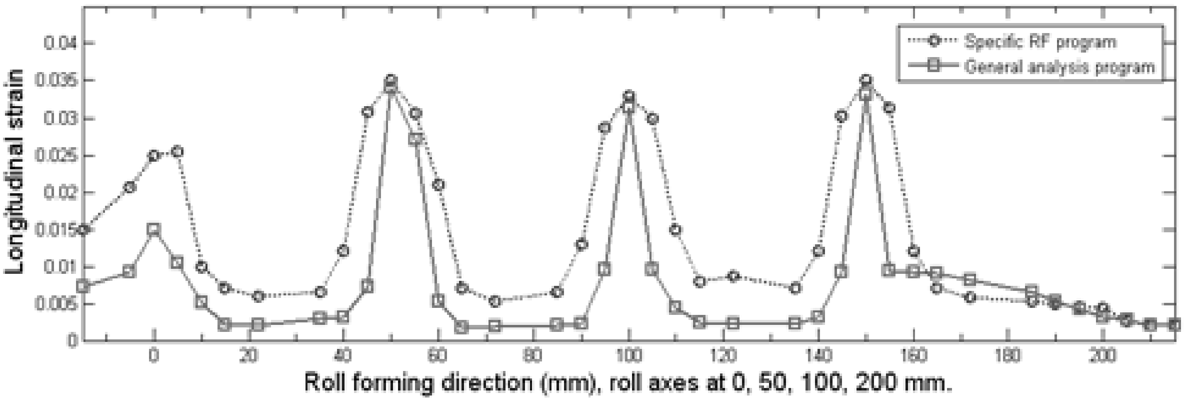

Fig. 9. Contour of longitudinal strain at a distance 0.5 mm away from the edge of sheet

Peak Long.Strain	**RS1**	**RS2**	**RS3**	**RS4**	**RS5**
General analysis	0.0315	0.0350	0.0336	0.0353	0.0300
Specific analysis	0.0285	0.0344	0.0313	0.0320	0.0318

Tab. 2. Result of peak longitudinal strains by general and specific analysis in hemming process

The deformed shapes of the sheet from the simulation of the general and the specific analysis also are different. The edge of the sheet in simulation of general analysis is not smooth as specific analysis and is close to the phenomenon, in reality. This defect is caused by an excessive large longitudinal membrane strain. At the initial stage of forming, the edge portion of the sheet has longitudinal elongation. After exiting the roll gap, in order to keep the sheet straight the elongated edge portion must shrink again. However, because of the excessive large longitudinal membrane strain, it cannot shrink smoothly and leads to the wavy edge.

3.3 RF process of an asymmetric profile.

In RF of the asymmetric profiles, especially when the number of pass is large, process easily has many undesirable effects such as sweeping, bowing, twisting, or buckling. In this paper, the unusual transversal movement of the sheet is analyzed since the position of rolls can be adjusted by this result. One of the main reasons for this defect comes from the existence of transversal force, which is caused by impacts between the sheet and the roll. Because of the asymmetric profile, there is a difference between the values of transversal force at two edges of the sheet. This difference increases by each pass and can cause defects in the process when the number of pass is large.

At first, the effect of an asymmetric profile with the small number of passes is investigated by the RF process of car canopy. The flower diagram is shown in Fig. 10. The number of pass is 4, the material is aluminium with mechanical properties: K = 858 MPa, ε0 = 0.0221, n = 0.365, E = 70 GPa.

The deformed shapes of sheet and the values of the peak longitudinal strains from general analysis and specific analysis are similar (Fig. 11 & Tab. 3). The defect in this case is transversal movement of the sheet and is analyzed clearly in Fig. 12 by the general analysis. When the number of pass is small product profiles usually are simple. It can be seen from the canopy RF process that defect when number of pass is small can be neglected. Therefore, specific analysis should be used to reduce time for simulation.

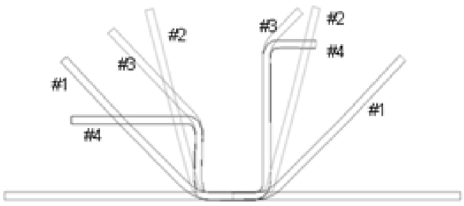

Fig. 10. Flower diagram of RF process of canopy

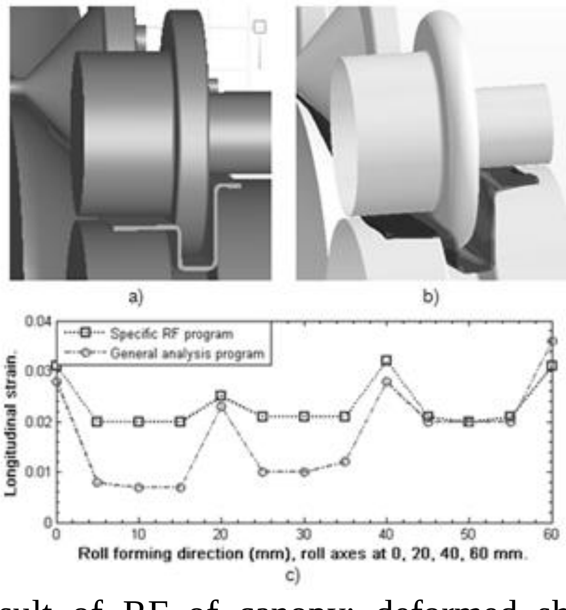

Fig. 11. Simulation result of RF of canopy: deformed shape by a) the specific analysis, b) the general analysis; and c) contour of longitudinal strain at the edge

Peak Long.Strain	RS1	RS2	RS3	RS4
General analysis	0.0284	0.0233	0.0285	0.0317
Specific analysis	0.0310	0.0251	0.0320	0.0365

Tab. 3. Result of peak longitudinal strains by general and specific analysis in RF of car canopy

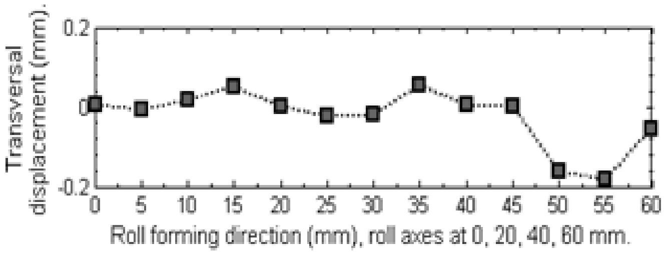

Fig. 12. Transversal displacement of a point on centre line of sheet

Next, the RF process of a car door-belt is simulated to clarify the effect of asymmetric profiles with a large number of pass (Fig. 13). Process includes 16 steps. The flower diagram is shown in Fig. 13. The sheet has an initial thickness of 0.4 mm. The material is aluminium with mechanical properties: K = 858 MPa, $\varepsilon 0 = 0.0221$, n = 0.365, E = 70 GPa.

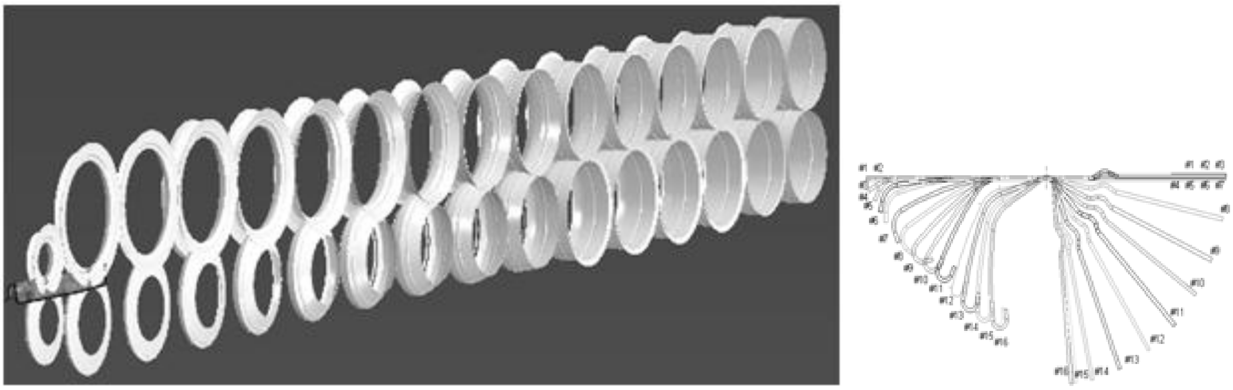

Fig. 13. Modelling in FE tool and flower diagram of RF process of car door-belt

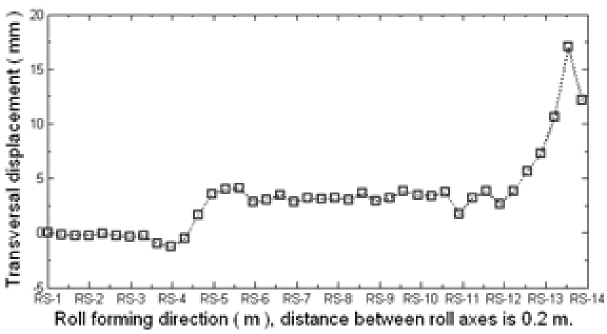

Fig. 14. Transversal displacement of a point on centerline of the sheet

In the specific RF analysis, the three dimensional FEM simulation starts with geometry and boundary conditions determined by two dimensional FEM simulation.

It is assumed that direction of friction force vector at a material point is opposite to the direction of the relative velocity on the contacting roll surface. Therefore, the specific RF analysis neglects the existence of transversal force and shows a good process while the general analysis program shows the failure and analyzes the defects clearly. The sheet has transversal movement shown in Fig. 14; that is caused by transversal force. This simulation result is close to the phenomenon in manufacturing. Accumulated transversal force increases with respect to number of passed roll stand causes an increasing of transversal displacement.

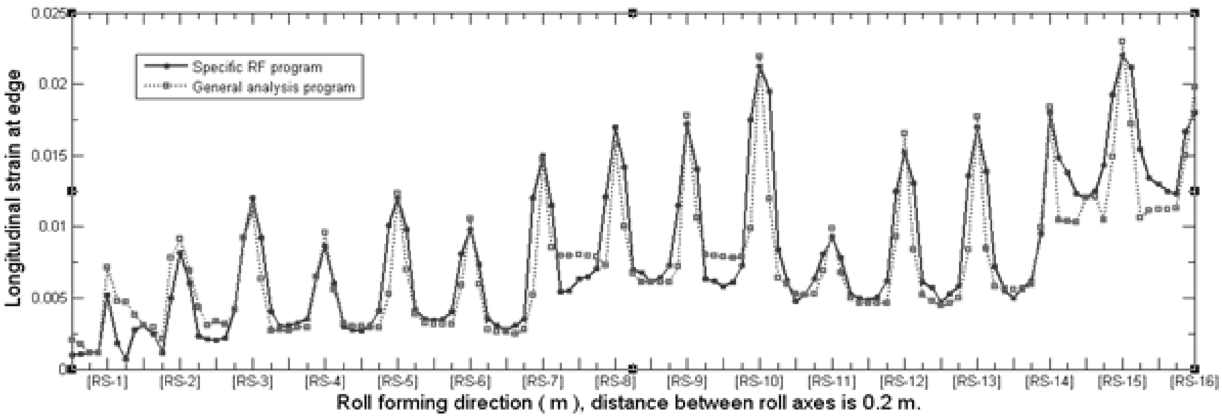

Fig. 15. Contour of longitudinal strain at a distance 0.5 mm away from the edge of sheet

Peak Long.Strain	**RS 1**	**RS 2**	**RS 3**	**RS 4**	**RS 5**	**RS 6**	**RS 7**	**RS 8**
General analysis	5.20 e-3	8.20 e-3	1.20 e-2	8.70 e-3	1.25 e-2	9.86 e-3	1.52 e-2	1.73 e-2
Specific analysis	7.12 e-3	9.15 e-3	1.11 e-2	9.56 e-3	1.23 e-2	1.05 e-2	1.46 e-2	1.57 e-2
Peak Long.Strain	**RS 9**	**RS 10**	**RS 11**	**RS 12**	**RS 13**	**RS 14**	**RS 15**	**RS 16**
General analysis	1.72 e-2	2.13 e-2	9.20 e-3	1.56 e-2	1.70 e-2	1.83 e-2	2.26 e-2	1.87 e-2
Specific analysis	1.78 e-2	2.19 e-2	9.89 e-3	1.65 e-2	1.77 e-2	1.84 e-2	2.30 e-2	1.98 e-2

Tab. 4. Result of peak longitudinal strains by general and specific analysis in RF process of car door-belt

The value of transversal force depends mainly on the geometry of the rolls and the friction coefficient. It is hard to estimate the variation of transversal force because the geometry of the roll is changed with respect to each pass. Therefore, the general analysis should be used first to detect and analyze defects of the process. From these results, roll design can be improved.

In RF of the car door-belt, the defect can be eliminated by adjusting the position of the rolls or eliminating the transversal force by general analysis. After adjusting, the simulation is done again. The values of longitudinal strains in simulation results of general and specific analysis are in good agreement (Fig. 15 & Tab. 4). The final shapes of sheet from simulation of both approaches are also similar with the product, in reality (Fig. 16). As the results from both approaches are similar, the specific analysis should be used in order to reduce computer time.

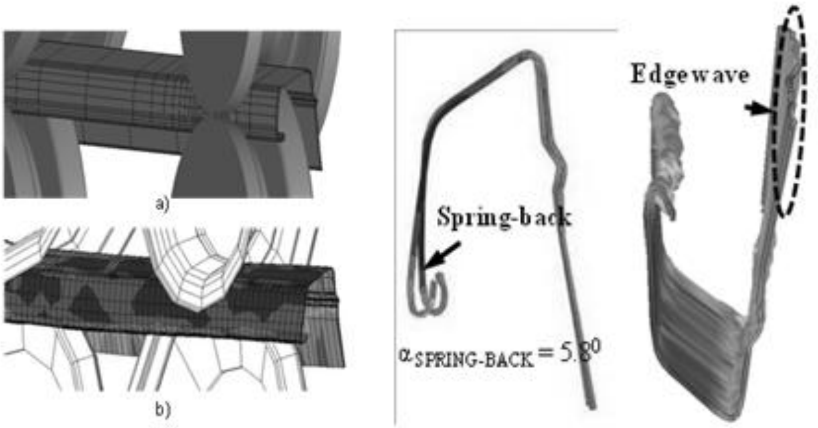

Fig. 16. Deformed shape of the sheet by: a) the specific RF program, b) the general analysis program; and wavy edge and spring back phenomenon in RF process of car door-belt

The spring back phenomenon and the existence of waviness also are analyzed by general analysis (Fig. 16). With spring back of complicated section like car door-belt, the prototype must be produced or the general analysis must be performed. The result from simulation is in good agreement with the result measured in prototype.

4. Application of different analysis methods in analyzing and designing RF process of automotive component

There are two major requirements in designing RF process must be satisfied. The first is ability to manufacture. The metal sheet has to pass through all rolls and form to desired shape. All effect factors have to be considered for adjusting the forming line correctly. The spring back angle also has to be calculated for overbending at final step. The second requirement is ensuring flawless process and increasing the quality of product by optimizing process parameters. As mentioned above, the major factor related to defect in RF is longitudinal strain. The defect occurs when value of longitudinal strain is greater than buckling limit. Therefore, the optimum configuration of process parameters has to minimize the maximum value of longitudinal strain in process in order to increase product quality.

The analyzing and design procedure using combination of different analysis methods can be developed based on the investigation of different analysis methods as in Fig. 17.

The number of step and bending angle increment at each step are determined by empirical formulas based on the desired section and material properties. The flower diagram and CAD data of rolls are created. The specific analysis cannot obtain results for adjusting the forming process as mentioned in previous section. Therefore the general analysis is carried out at initial. Many important results in process are obtained although the time for running simulation is long. The first result is the movement of metal sheet during forming process. From the vertical and horizontal displacement of sheet, the positions of rolls can be adjusted of the side rolls can be added to correct the forming line. The second result is the stress and strain analysis. The buckling limit strain of process is obtained by the distribution of longitudinal strain and deformed shape of sheet. This limit will be the constraint on maximum longitudinal strain in the optimization of process parameters. The fracture investigation also can be done in this analysis to ensure the quality of final forming product. If the fracture occurs by excessive bending, the bending angle increment has to be decreased. The third important result is the spring back angle. The overbending angle at final step can be estimated based on spring back angle in this analysis.

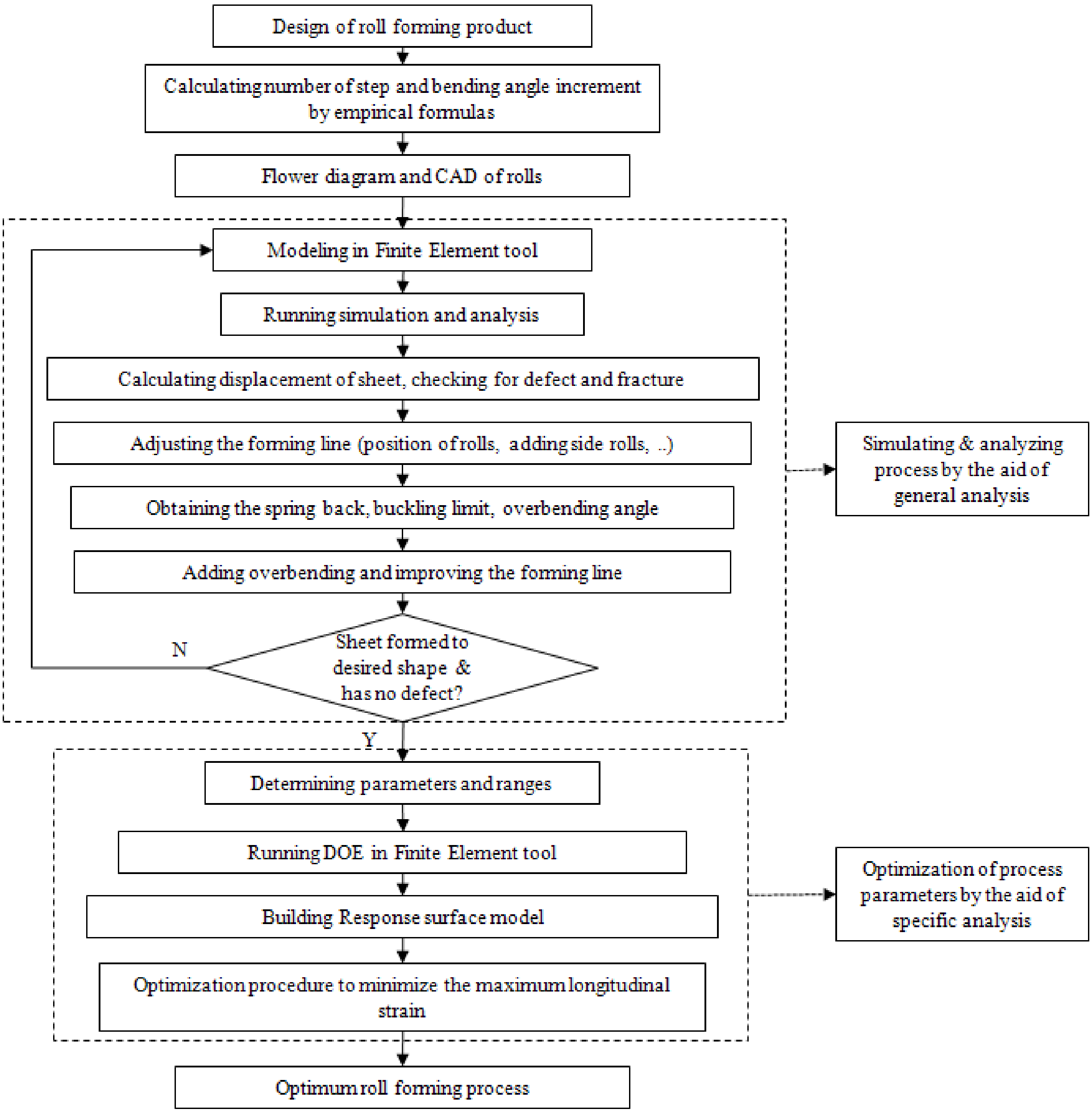

Fig. 17. Analyzing and design procedure using different analysis methods

The forming process has been adjusted and is able for manufacturing after the general analysis. The next step is optimization process parameters for keeping the flawless process and increasing the quality of product. The objective of optimization is minimizing the maximum value of longitudinal strain. The design factors are process parameters such as the roll forming line velocity, the inter-distance between roll stations, the roll gap, and the diameter of the rolls. The ranges of parameters are taken from the factory and the buckling limit is set as the constraint on longitudinal strain. The RSM is employed to build the approximation model that represents the relationship between design factors and objective function. One characteristic of this method is that the number of simulation for calculating longitudinal strain at the experiment point is large. The longitudinal strain results from specific and general analysis are similar and are in good agreement with experiment, while the time for running simulation in the specific analysis is very less than general analysis. Therefore, the specific analysis is used in this step. The saved time is very considerable while the accuracy of results is acceptable.

The optimum configuration of process parameters is obtained after optimization. The final product of this design procedure satisfies both major requirements in designing RF.

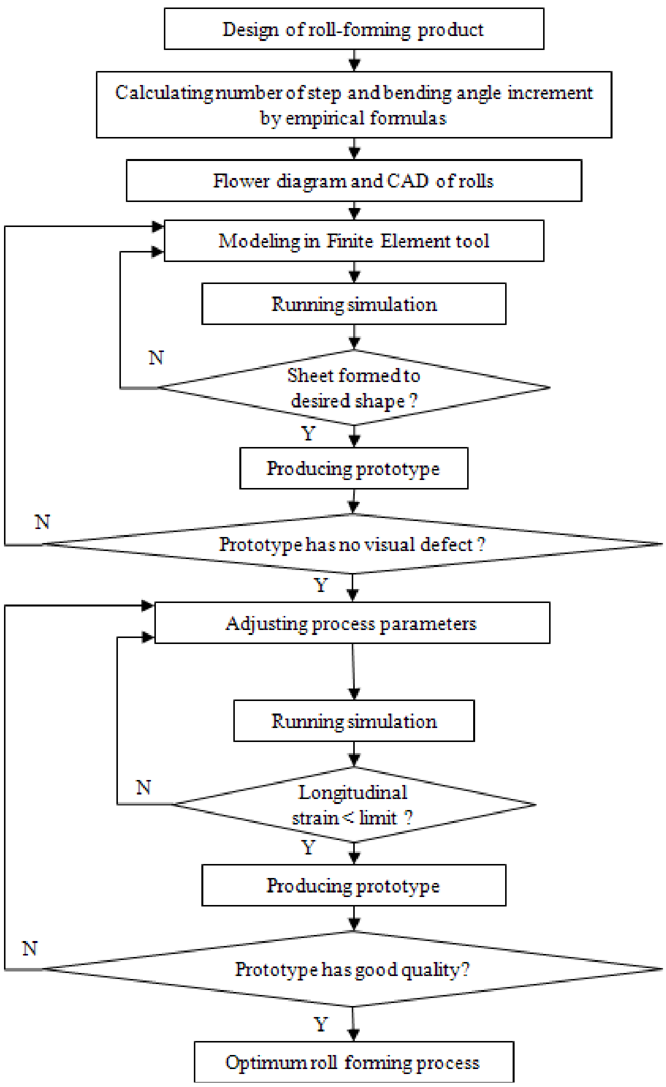

Fig. 18. Current analyzing and design procedure for RF process of car door-belt

In order to prove the efficiency of the design procedure using a combination of different analysis methods, an experiment with RF process of an automotive component is carried out. The component here is the car door-belt, which is manufactured by Roll Eng company, Korea. The flower diagram and forming line are shown in previous section. The profile is asymmetric and the number of pass is 16.

The current analyzing and design procedure for RF process of the car door-belt is shown in Fig. 18. The flower diagram and CAD data of rolls are created by the empirical formulas. The forming line is simulated analyzed by the specific RF software SHAPE-RF to check the deformed shape of the sheet. The simulation is done quickly but many important results such as the spring back angle, the existence of waviness or unusual movement of sheet cannot be obtained. The prototype has to be produced to check for defect and the forming line is adjusted gradually by experience. The parameters are optimized after the process passed the realistic evaluation. The initial parameters are taken from usual values in the factory. The simulation is done to check the excessive longitudinal strain. The prototype is produced and the parameters are adjusted to increase the quality of the prototype. The time for current procedure is about one week. It can be reduced by applying the procedure using different analysis methods.

With RF process of the car door-belt in this paper, the general analysis takes about 15 hours, and the specific analysis takes about six hours for each run. The general analysis normally is done three times for checking the applicability of the process. The specific analysis normally is done nine times in optimization of process parameters. The total time for design procedure is about 100 hours, less than conventional procedure 41%, while the cost for producing the prototype in the try-out process is cut. If the general analysis is carried out throughout the procedure, the total time is similar with the conventional procedure. The significant reduction of time is the benefit of the combination of general and specific analysis.

5. Conclusion

In this paper, many RF processes of different automotive components have been simulated and analyzed by the general and the specific analyses. The characteristics of each method and differences between them are clarified. It provided the foundation for applying both methods in analyzing and designing RF process of automotive component. With a realistic application in designing, the design procedure using a combination of different analysis methods obtained the optimum process with 41% less time for running, less cost for producing a prototype than the previous procedure. The further plan of this research is applying the combination of different analysis method to the design of flower diagram and optimization of the number of pass. It will provide the more reliable and optimum solution than empirical method at present.

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