# AUTOMATED HANDLING OF AUXILIARY MATERIALS FOR VACUUM BAGGING IN CFRP FUSELAGE PRODUCTION

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**Keywords:** vacuum infusion, vacuum bagging, robot-based automation, VAP, VARI

## Abstract

In order to match a predicted production ramp-up in aircraft production, state of the art manufacturing techniques have to be optimized regarding productivity and efficiency. Especially vacuum infusion techniques for large CFRP structures still involve a high amount of manual work. In detail, the vacuum bagging depends on manual lay-up processes of auxiliary materials. A first approach of automation concepts for robot-based vacuum bagging will be discussed in this paper.

In a research project at the Center for Leigtweight Production Technology in Augsburg, automated manufacturing of a single-curved CFRP fuselage demonstrator has been investigated. A rigid gripping system with needle grippers has been developed and validated for the application of auxiliary materials as peel ply, release film and airweave on the top of a dry fiber preform. Alongside the process chain, handling and positioning procedures have been analyzed both analytically and in experimental test series.

According to the rigidity of the gripping system, an adequate motion concept for the fuselage demonstrator has been found. The gripping system allows pick-up, transportation and positioning of auxiliary material packages on a single-curved preform with high accuracy. Based on these results conclusions for future vacuum bagging processes can be drawn.

## 1. Introduction

During the last decades, the amount of CFRP structures in aerospace has been increased continuously. For example, the aircraft A320 by Airbus Group, brought into service in the late 1980's, consists of fiber reinforced polymers of about 15 % per weight. The newest aircraft A350 by Airbus Group, entered into service in December 2014, has been manufactured with a high content of carbon fiber reinforced polymers (CFRP). The percentage per weight is at least 50 % [1]. In addition to the growing amount of CFRP components and structures in aircrafts, production rates increase rapidly. In detail, Airbus Group targets increasing production rates with up to ten A350 aircrafts per month by the end of 2018 [2]. This ramp-up requires a higher productivity and efficiency in airplane production technologies.

Excerpt from ISBN 978-3-00-053387-7

At the Center for Lightweight Production Technologies in Augsburg this challenge is addressed by investigations on solutions for process automation. In particular, state of the art manufacturing processes for out-of-autoclave part production are analyzed and optimized. Thus, automation concepts regarding textile preforming technologies, vacuum bagging, vacuum infusion and simultaneous quality assurance are developed. For example, in CFRP part manufacturing, automated lay-up and dry fiber preforming processes have been investigated in a wide range [3]. Nevertheless, the manufacturing of large CFRP structures in aerospace includes a high amount of manual process steps. Especially vacuum bagging for vacuum infusion processes is realized manually.

A research project has been launched with the DLR Stuttgart to investigate automated CFRP fuselage manufacturing processes. As demonstrator structure component, one half of a cylindric fuselage section has been chosen. Alongside the process chain, from preforming until curing in a convection ofen, automation potentials have been detected and analyzed. In the first part of the manufacturing study, a dry fiber preform has been produced. Therefore robot based gripping systems and handling strategies have been investigated [3]. The second part of the study dealt with automated vacuum bagging and resin infusion technologies. An approach for automated vacuum bagging for CFRP fuselage manufacturing will be discussed in this paper.

### 1.1 Vacuum bagging

For the impregnation of the dry fiber preform with resin serveral infiltration techniques exist. Especially for large structures, such as rotor blades or rear pressure bulkheads, vacuum assisted resin infusion (VARI) and vacuum assisted process (VAP) are commonly used. Both techniques base on a single-sided tooling which has to be sealed for evacuation. The applied vacuum results in a pressure difference between cavity and athomsphere, so that the pressure potential can be used for resin infusion. For sealing of the tooling, a vacuum bag has to be applied on top of the preform (Fig. 1). To ensure the impregnation of the entire dry fiber preform, the vacuum bag consists out of auxiliary materials as peel ply, release film and flow media [4].

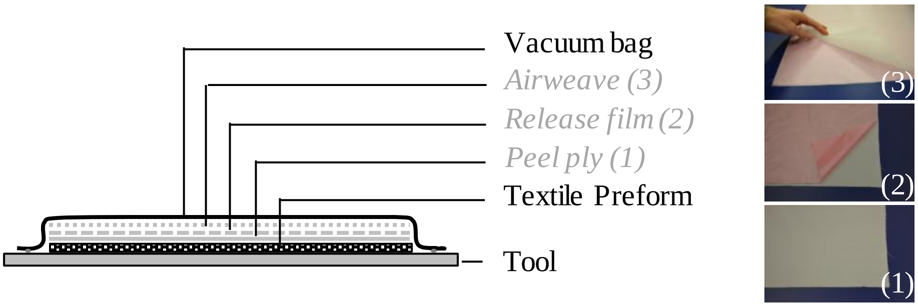

**Figure 1.** Vacuum bag for vacuum assisted resin infusion (VARI)

The peel ply affects an equally rough surface of the manufactured part which can be used for subsequent processes as painting or bonding. Because of its high porousity, airweave guarantees an appropriate resin impregnation of the preform. All those named auxiliary materials are disposables which have to be separated from the part after curing. An overview of auxiliary materials used in aircraft production is given in Tab. 1.

**Table 1.** Auxiliary materials for vacuum infusion processes in aircraft production

| Type | Product Name | Material | Manufacturer/ Supplyer |
|---|---|---|---|
| Airweave | VI5 | Polyester | Cytec Process Materials Ltd. |
| Release film | Vac-Pak A6200 | Fluropolymere ETFE | Cytec Process Materials Ltd. |
| Peel ply | Code 60001 | Polyester | Precision Fabrics Group, Inc. |

Nowadays, the manufacturing processes steps, cutting, positioning and lay-up of the vacuum bagging materials is commonly operated by workers in and on the tooling [5]. With an increasing geometric size of CFRP parts, handling and positioning become more difficult. As a result, the higher complexity causes a decrease in reachability and nevertheless precision and reproducibility. To match the

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requirements of higher productivity and reproducibility, manufacturing techniques for large CRFP parts have to be optimized. Automation concepts, as described in the following, address these challenges.

## 1.2. Manufacturing demonstrator

As fuselage manufacturing demonstrator, a half-cylindric section has been chosen. The demonstrator has a radius of 1977 mm with a total width of 2000 mm. The thickness varies between 2.4 and 2.8 mm depending on locally placed reinforcement layers. The structure is stiffened by six thermoplastic stringers. A first demonstrator (Fig. 2) has been manufactured manually to identify optimization potentials and therefore fundamentals for automation concepts.

**Figure 2.** Fuselage manufacturing demonstrator

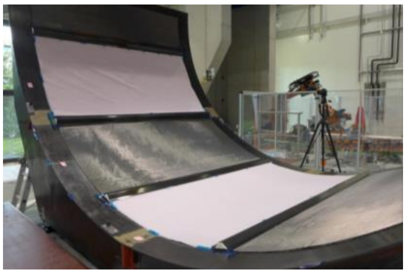

**Figure 3.** Manufacturing tool with preform and auxiliary materials

The dry fiber preform consists of biaxial carbon fiber non-crimp fabrics (Tenax HTS40 F13 12 K) manufactured by Saertex Ltd., Germany. For infusion, a high-temperatur epoxy resin (Cycom 977) by Cytec Industries Inc., Woodland Park, US is used. The infiltration concept and therefore the set-up of the vacuum bag has been selected due to the thermoplastic stringers (Carbon Fiber (CF)/ Polyetherimid (PEI)). The stringers remain dry and the preform has to be infiltrated. This can be realized using vacuum assited resin infusion (VARI). Regarding the dimensions of the demonstrator, rectangular cut-pieces of peel ply, release film and airweave have to be placed between the stringers (Fig. 3). Dimensions of the auxiliary materials are 1989 mm x 912 mm. For an adequate impregnation, one layer of peel ply and release film and two layers of airweave are stacked to packages.

According to in-flight fuselage structures, the current study addresses specific challenges. The carbon fiber fabrics and auxiliary materials have to be applied on a large surface. As shown in Fig. 2, the surface consists of leveled symmetric and unleveled unsymmetric sequences. Because of the wide dimensions, these sequeces are hardly accessible for manual handling by workers. Nevertheless, simplifications had to be set in contrast to in-flight structures. Width and number of stringers have been minimized. The number of differnet radii has been reduced from three to one.

## 3. Automation concept for vacuum bagging

Based on the geometry of the fuselage demonstrator and the infiltration concept, an automated handling and lay-up concept of auxiliary materials has been developed. The handling process will be discussed in the following (Fig. 4).

**Figure 4.** Handling procedure of auxiliary materials

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Alongside the handling process of auxiliary materials, first of all, cut-pieces have to be generated. Studies on automated cutting of auxiliary materials have been conducted besides this project. After cutting, the cut-pieces have to be arranged and prepositioned for handling devices. This handling devices could be used for grabbing, transportation, positioning and at least fixation of cut-pieces. The stated process chain describes both manual and automated solutions. An automated pick and place solution has been investigated.

Referring to the process chain in Figure 4, the described procedure has to be operated for each material layer by layer. Alternatively, single layers can be combined to packages in a prior manufacturing step. This approach causes two decisive advantages. On one hand, occupation time of the tooling can be reduced. In the case of the fuselage demonstrator, the number of pick and place procedures can be reduced by 75 % from 28 (layer by layer) to seven (packages). On the other hand, generation of packages can be extracted from the current vacuum bagging process. This allows parallelization of process steps and therefore another reduction in expensive occupation time of the tooling. Further advantages and consequences of such a strategie have been analyzed in a previous study [3].

### 3.1 Gripping system

In the following, a gripping system for handling and positioning of auxiliary material packages will be discussed. Based on the rectangular size of the packages, a set-up for the gripping system has been developed. According to the dimension of the sections between the stringers (Fig. 3), rectangular cut-pieces have been prepared. During the pick-up and placement process, these packages have to be positioned into a single-curved tooling. Due to the rectangular size of the packages and the low curvature of the tooling (radius: 1977 mm), a rigid framework has been selected for the gripping system. Furthermore, the single-curved shape of the tooling requires no draping of the material. The shape is mathematicaly developable. This characteristic also favors an rigid gripping system.

The rigidity of the gripping system is mounted by aluminum profiles of Witte Barskampf KG, Germany. The aluminum framework (900 mm x 2000 mm) shown in Fig. 5 covers the whole auxiliary material package.

In a first test series, adequate grippers for auxiliary material packages have been tested. Vacuum based grippers (Type SCG 1xE100 A MS**,** J. Schmalz Ltd., Germany) and needle grippers (Type SNG-R 16 1.2 V, J. Schmalz Ldt., Germany) have been compared. It was found, that both grippers can be used for porous and flexible textiles. Using vacuum grippers, grip forces have to be adjusted by varying the flow rate. Vacuum grippers have shown less accuracy when gripping loose packages. Fixation of each layer causes higher shear strength. In contrast, grip forces of needle grippers depend on the frictional connection between needles and textile material. All in all, 16 needles are arranged on two concentric circles on the bottom of the round gripper. Needles of the inner and outer circle are arranged with an angle of +45 degree and -45 degree. The needles have a diameter of 1.2 mm. Extension of the needles is realized by pressure impulses. After pressure equalization, needles are pulled inside the gripper by a return spring. The maximum needle rise of 4.5 mm can be adjusted manually by a hand wheel with a tolerance of ± 0.2 mm. When gripping loose packages, each layer has to be penetrated by needles, that is why needle grippers do not demand fixed packages. For vacuum bagging needle grippers can be used for those materials which do not have sealing functions.

As a result, needle grippers enable gripping both fixed and loose packages. Therefore, these grippers have been chosen for the gripping system. The adjustment of the round needle gripper on the aluminum framework is shown in Fig. 6.

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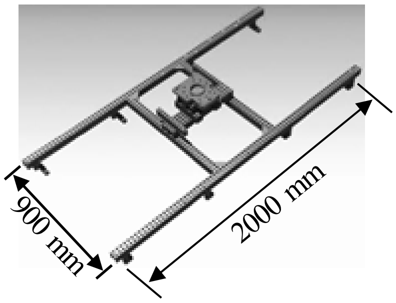

**Figure 5.** Aluminum framework

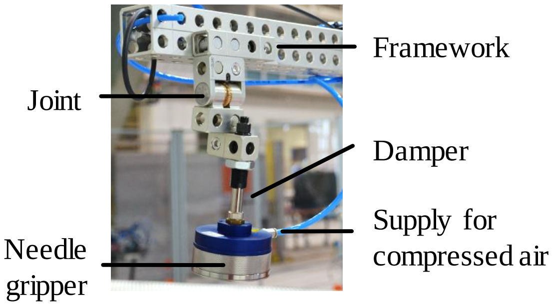

**Figure 6.** Gripping system with needle gripper

The gripper can be angled to the curved demonstrator tooling by a joint. Additionally, a damper prevents the system from causing damage on the preform or crashing the tool. Overall six round needle grippers have been adjusted equally on the long sides of the framework.

### 3.2 Mathematical description of the optimised gripping orientation

In case of the positioning of auxiliary materials into a single-curved fuselage manufacturing tool, the gripping system has to be adapted to an industrial robot. The robot has the function as a positioning system that moves and orientates the gripping system relatively to the tooling. Befor describing this automation set-up, the movement of robot and gripper will be discussed mathematically in order to achieve a damage free handling of the auxiliary materials.

For analyzing purposes, the gripping system will be examined two-dimensionally (Fig. 7). Displayed in the xy-plane the symmetric set-up with two needle grippers and single-curved tooling is easily described . As discussed in Chapter 3.1, the adaption of the needle grippers to the normal tool surface can be described by angle α. Furthermore, the rotation of the gripping system by the robot can be described by an angle β. Depending on the different lay-up positions in the tooling, angles α and β have to be varied.

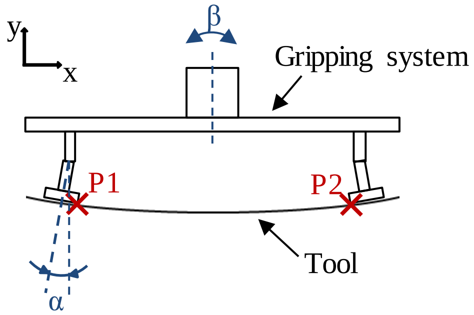

**Figure 7.** Two-dimensional sketch of the gripping system

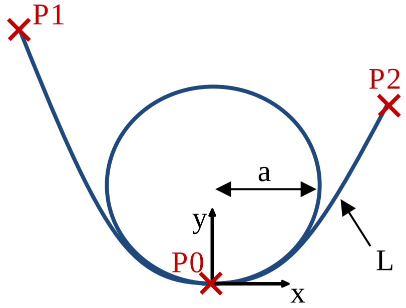

**Figure 8.** Principle of catenary

On the one hand, for depositing, the gripping system has to be adapted to the shape of the tooling. On the other hand, the position of the grippers depends on the shape of the gripped material. When the package of auxiliary materials is gripped by the needle gripper, the package sags between the gripp points *P1* and *P2*. This sagging effect can be described mathematically using the principle of the catenary. According to Fig. 8, the catenary between two points *P1* and *P2* depends on the length *L* of the sagging material. Furthermore, it depends on the radius *a* of the catenary at the minima *P0*. In case of the single-curved fuselage tool, two characteristic states can be extracted. In state 1 both points *P1* and *P2* have the same height ($\boldsymbol{y_1 = y_2}$). This state describes the centered section on the bottom of the tool. For all other sections (state 2) the heigt of *P1* and *P2* variies ($\boldsymbol{y_1 \neq y_2}$).

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Both states can be calculated using the following equations Eq. 1 and Eq. 2. As an additional condition Eq. 3 is given.

$$y(x) = a * \cosh(\frac{x - x_0}{a}) + y_0 \tag{1}$$

$$L = 2a * \sinh(\frac{x_2 - x_1}{2a}) * \cosh(\frac{x_2 + x_1 - 2x_0}{2a}) \tag{2}$$

$$\frac{\sinh \xi}{\xi} = \frac{\sqrt{L^2 - (y_2 - y_1)}}{x_2 - x_1} \qquad with\ \xi := \frac{x_2 - x_1}{a} \tag{3}$$

To solve the system of equations, Newtons approximation method was used. In addition to the shape of the catenary, the position of the grip point on the gripping system and the drop points on the tooling have been considered. Based on a MATLAB model, the angle α and β have been calculated for each section. For the centered position in the tooling (state 1), an optimum angle α of 10° has been calculated for the given cut-piece. As shown in Fig. 6, angle β is 0° for state 1. According to the rigidity of the framework, angle α should be set once before handling. Therefore, sections of state 2 have to be covered by only varying angle β. This can be realized for any single ply by the movement of the robot.

### 3.3 Description of the robot movement

Regarding the movement of gripper and robot, the process can be separated into three consecutive steps. First, the auxiliary material package has to be picked up from a supply station where it is stored after cutting and preparation. Second, the package is transferred from pick-up position to drop-off position. Third, the package has to be positioned and dropped off on the textile preform. In the following, pick-up and drop-off processes will be explained in detail.

#### 3.3.1 Pick-up process

Experiments have been conducted testing two specific pick-up procedures. These procedures base on the same preprocess. After cutting and preparation, the package is positioned horizontally on a flat pick-up table. The pick-up position on the table represents a given boundary condition. In a realistic process, this condition has to be defined previously. It is essential to consider, that deviations from the pick-up position will cause deviations at the target position on the preform.

In a first test series, the flat package has been picked up using a rolling moting of the gripping system. The package is picked firstly on the left and then on the right. Therefore, first the left-sided needle grippers are activated. After rotation to the right side, when the grippers are aligned to the surface of the auxiliary material package, the rigt-sided needle grippers are activated. For such motion, the tool center point (TCP) of the gripping system is essential. The TCP describes the center of the tooling (gripping system), where the point of origin for rotation and translation is located. For the rolling motion itself, two specific TCPs have been defined. For the rotation to the left side, point *P1* (Fig. 7) and Point *P2* (Fig. 7) for rotation to the right side. Using a combination of rotations and translations, the package has been picked up from the horizontal table. A sliding of the package to the right of up to 5 mm has been detected. The sliding effect refers to the robot motion. It could be minimized by fixing the package on the right side during the rotation of the gripping system.

In a second test series, the package has been picked up from a pick-up position with a single curved shape. For pick-up exclusively translational robot motion is needed. This procedure allows a centered pick-up of the package without sliding effects. Nevertheless, this method causes additional costs for the pick-up geometry which has to be considered.

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### 3.3.2 Drop-off process

The drop-off process is related to the mathematical analysis of Chapter 3.2. Two different states had been extracted. State 1 describes the centered position of the tooling and state 2 any other positions. Both states are shown exemplary in Fig. 3. According to these positions, two strategies for the drop-off process have been investigated.

In case of state 1, the shape of the package hanging on the grippers is symmetric. Referring to the effect of the catenary, the length of the material between the grip points is higher than the segment of a circle on the tooling. Thus the additional length results in wrinkles during the drop-off procedure. To avoid these wrinkles, the needle grippers should not touch the surface of the preform. Instead, the gripping system stops in a defined distance to the preform before wrinkles occure. Afterwards, the needle grippers are deactivated and the package drops down onto the preform. Based on the mathematical model (Chapter 3.2), the distance has been calculated to 46 mm for the given application.

In state 2, the shape of the package hanging on the grippers is unsymmetric. Same as in state 1, touching the surface of the preform during the drop-off process would cause wrinkles. In contrast to state 1, the gravity can be used for positioning. Therefore, the gripping sysem will be positioned to the preform on the upper side and slightly pushed against it. At this point, the needle grippers are deactivated. Afterwards, the needle grippers on the lower side are deactivated too. As an effect, the material drops onto the preform, still fixed by the pushing grippers on the upper side. Next, the package has to be fixed to preform and tooling. At least, the gripping system can be moved back to the pick-up position.

### 3.3 Concept validation and discussion

In addition to the previously described tests and anlaysis, a fuselage demonstrator has been manufactured. Alltogether, seven packages of auxiliary materials are needed. For testing purposes, a multifunctional robot cell has been set up at the DLR Augsburg. A KUKA robot system mounted to a linear axis above the cell is used as handling device. Thus, the gripping system can be positioned inside the fuselage tooling from above, which ensures reachability of large geometries. The test set-up as shown in Fig. 9 consists of a flat pick-up table, the fuselage tooling with dry fiber preform and a robot with gripping system. In the current study, fixation of the packages on the preform has not been addressed yet. Packages have been fixed manually with commonly used tapes.

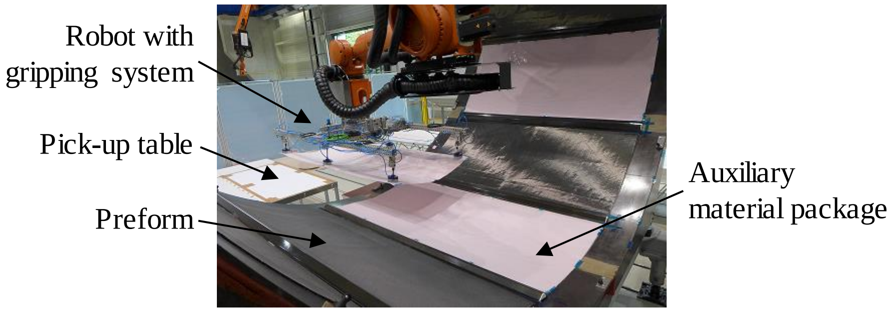

**Figure 9.** Automated pick-up and placement of auxiliary material packages on fuselage demonstrator

Pick-up and placement of the packages have been realized as described in Chapter 3.3.1 and 3.3.2. The drop-off motion of the state 1 package has been manipulated manually. Because of the sliding effect during pick-up, the drop-down position has been shifted out of the center line. As already stated about the accuracy of the lay-up, the drop-down process depends on the quality of the package and the pick-up position. In the present study, maximum overlaps of package and stringers of 25 mm have been

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detected. This refers to another influence on the drop-down accuracy. It was found that the alignment of the thermoplastic stringers was inexact. Therefore, varying distances with a difference of up to 14 mm between stringer edges have been detected. In comparison, during drop-off tests with lose packages and without stringers target positions have been reached with an accuracy of ± 4 mm. With fixed packages an accuracy of ± 3 mm could be realized.

## 6. Summary and conclusions

Concerning reachability, reproducibility and therefore efficiency, automated concepts for vacuum bagging could help optimizing infusion processes. Based on this background, an automation concept for handling and positioning of auxiliary materials has been developed. Materials as peel ply, release film and airweave allow a wide range of technical solutions because of their flexibility and stability.

A rigid gripping system equipped with needle grippers has been developed for handling and positioning of auxiliary materials. The main advantage of needle grippers is the handling of loose packages of flexible materials at once. Furthermore, needle penetration does not cause functional damage on the used auxiliary materials. In case of a single curved fuselage demonstrator, the handling process has been investigated intensively. According to several drop-off positions an adequate set-up was found using mathematical methods. Based on theses investigations, pick-up and drop-off processes have been analyzed. As a result, the gripping system has been operated successfully during a manufacturing study of a demonstrator structure.

As a conclusion the presented gripping system will be enhanced based on the gathered results. For example a fixation device shall be adapted to the framework. An investigation on process times indicated the manual fixation procedure as a time-consuming process. Furthermore, the drop-off procedure will be refined regarding vacuum bagging on even larger geometries than the manufacturing demonstrator. Concerning the whole process chain from cutting pieces until fixation, sources of defects have to be determined and analyzed. For example, cutting packages at once could minimize overlap of sinlge layers. This would affect the drop-off accuracy. Another question to be varfied is the prepositioning of packages before the pick-up process. Specific referencies for the robot system have to be defined. In addition to the material-based process optimization, the automation concept has to be refined. Currently the robot motion has been teached. For advanced path planning and teachless motion, drop points based on a CAD model are needed. Therefore, the mathematical model has to be compared to the real shape of the tooling.

## Acknowledgments

We would like to thank our colleagues at the Center for Lightweight Production Technologies for their support and helpfulness. In regard to our successful teamwork we would like to name A. Buchheim, F. Krebs, L. Larsen and Dr. A. Schuster.

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