A NEW DESIGN FOR FAN BLADE MANUFACTURING USING AERODYNAMIC PROFILES

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Abstract. *The necessity of adapting the standardized fan models to conditions of higher temperature has emerged due to the growth of concern referring to the consequences of the gas expelling after the Mont Blanc tunnel accident in Italy and France, where even though, with 100 fans in operation, 41 people died. However, since then, the defied solutions have pointed to aerodynamic disadvantages or have seemed non-appropriate in these conditions. The objective of this work is to present an alternative to the market standard fans considering a new technology in constructing blades.*

This new technology introduces the process of a deep drawing of metallic shells and posterior welding, in order to keep the ideal aerodynamic superficies for the fan ideal performance and the cast of a metallic base in which the shells will be assembled and will be connected to the fan hub. This process will result on an alternative to the usual market manufacturing processes with the advantage of lower weight, so lower stresses for the hub assembly systems and the electric fan start drives.

Keywords: *Aerodynamic profiles, Fan blades, Deep-drawing, Plastic instability, Sheet metal forming*

1. INTRODUCTION

With the cities growth, the available area per habitant has been decreasing leading to lack of area and the necessity of new means of transportation fast and safety. So, Engineering has developing new means to increase area by verticalyzing the cities. This could solve the people accommodation problem, but not their transportation.

This way, due to the increasing flow of people in big cities and the built of new traffic ways, it was necessary to create new alternatives of transportations, and the tunnel transportation. This application can be seen in subways and road tunnels, for some reasons as go through an obstacle, less ambient impact, or just to provide a fast access to a flow way.

It is also an economic side in opening tunnels for sub terrain exploitation, as used in mining, or safety, as inflammable gas exhaust, for example.

With the growth of tunnels utilization and the construction of even bigger ways, there was the necessity to develop safety systems of air ventilation allowing more number of people and harmful gas exhaust, in case of automotive exhausts. Due to that, it was created the ventilation systems.

The ventilation main purpose is to control the purity of air in a closed environment. Industrial ventilation is a mechanical operation to control temperature, air distribution, humidity, polluters as gas, flumes, dust, vapors, microorganisms, and smells design as "contaminants" or "polluters". Contaminants can be originated in industrial processes (welding, foundry), in superficial treatments (solvent cleaning, painting, sanding, polishing), particulate transfer processes (transfer belts, recipe filling), as emergency conditions (fuel combustion, fires, health harmful gases).

After the Mont Blanc Tunnel accident, with 12km length, with links France and Italy, when a truck caught fire leading 41 people to die by intoxication by smoke (Landroverclub, 2000), in a tunnel with more than 100 fans, the tunneling safety concepts were reviewed, mainly at emergency exits and hot gas exhaust systems in emergency. For the last one, it was created the European standard CEN: EN 12101-3 (2002), with specifies the classes and requirements for exhausting fans inside the tunnels.

By CEN: EN 12101-3, it was observed the necessity to adapt some existent technologies in fan market to the gas exhaust needs, to allow the operation of the ventilation system during a estimated time for tunnels evacuation and fire spots elimination. In a particular way, in this work, it is considered the condition of working a 100% capacity for 400ºC during two hours.

In a fan design, the blade is the most important element of a fan because it determinates fan performance, noise level, durability and appearance. Thus, an alternative process for fan manufacturing focused on its blades can be vital importance, because can limitate costs and technical aspects.

This work objectives to provide an alternative to the existent fan market by introducing a new blade technology, considering the state-of-art characteristics in a process of deep-drawing of plates and posterior welding to develop a fan with the ideal aerodynamic conditions and resistant to hot gases exhaust temperatures considered as 400ºC by two hours.

2. INDUSTRIAL VENTILATION: MARKET TENDENCY

The expression Industrial Ventilation is characterized by the use of fans in industrial processes as cooling, heat exchanger as renewing air in closed environments as schools, shows, industries, train and subway stations, road tunnels and others.

Industrial Ventilation Market is divided in two major groups, the cooling systems, usually for cooling towers and heat exchanger and air renovation, usually for harmful gas exhaust. (Fig. 1).

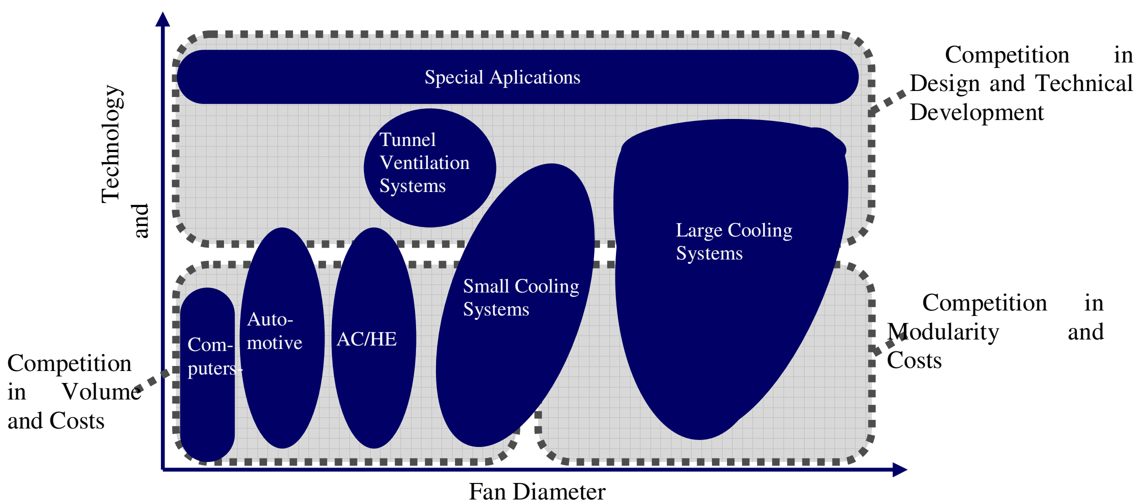

Figure 1 – Industrial Fan Market –Duty, Borbón et al (2003).

2.1 Air renovation process – subway / road tunnels

The ventilation market for subways and road tunnels application is characterized by the use of fans for primary and secondary ventilation in sub terrain tunnels. Tunnel primary ventilation provides fresh air and polluted air by different openings. Secondary ventilation is ramifications for excavation fronts. It is characterized by 0.6 to 2.5m diameter fans with low rate flow-pressure and a very high rate of blade area of the rotor.

It is important to add that efficiency is extremely important in this market, as much as ventilation needs constant energy supply. And any increase of 10% in flow consumes 33% more power. So, it is recommendable the use of aerodynamic profiles to increase the efficiency.

The industrial market is concentrated mainly in Europe, with 70% of market share. However, the biggest growing market is Asia with 20 of market share.

Considering the market of subway fans, the European market is very established, remaining the addiction of new lines. Beside that, there is the growth of lines in Asia and Latin America.

Statistics in 2003 shows 123 subway systems in operation, with 22 in construction and 16 in design with a market projection of 900/year concentrated in only four major manufacturers.

As the manufacturers had to renew its product families in five years, the market cannot be considered mature. There's also safety parameters to be defines. A new parameter recently defined is the necessity to operate in a temperature of 400ºC during 2 hours, to simulate the hot gas exhaustion in a tunnel fire according to CEN:EN12101-3.

2.2. Types of fans and technologies- blades

Blades are considered the most important element of a fan, being the interface between the rotative movement made by the motor and the air flow generated by aerodynamic concepts. By them, it is the defined the fan operation point, efficiency, noise level, durability and appearance. The next items will show some design elements focusing on axial fans and connecting them with projects applications and requirements.

2.2.1. Aerodynamic profiles

It is commonly found in operation blades with several aerodynamic profiles even the simplest one, found the the domestic fans, with a plate bent to aerodynamic profiles considering the laminar or turbulent flowage.

The plate bent fans usually in operation have domestic applications, with secondary efficiency importance or old fashioned equipments. They have low production costs when compared to other technologies, but low efficiency.

In oppositions, for the aerodynamic profile fans, there are some concerns about efficiency, noise level which make them the most used for industrial ventilation systems. However, its cost is very higher that the previous technology. Differentiating factor for each manufacturer is the adoption of a proper aerodynamic profile in terms of performance, behavior with the increase of pressure drop, stall curves, among others.

2.2.2. Materials

The materials used vary, mostly, with the manufacturing process, the duty than any government requirement of specification. The majority of manufacturers supplies fans in plastic, carbon steel, aluminum and fiber-reinforced plastic (FRP). A disadvantage of the metallic materials is that they are not so elastic and more susceptible to vibration forces. The carbon steel has high specific mass, which will be converted in centrifugal force, aluminum has low admissible stress comparing to carbon steel and FRP have maximum operation temperature up to 100ºC, high cost as compared to metallic materials and complicated manufacturing process.

For this work, it will be admitted an exception by defining materials for fan blades working in a 400ºC temperature during 2 hours. Or this, it will be used the stainless steel AISI 409, due to its exceptional nature of this application.

2.2.3. Manufacturing processes

The manufacturing process of a blade provokes limitations in cost and technical aspects. These processes affect mainly the technology of blade twist and chords.

For aerodynamic profiles, there are three processes usually used: massive blade casting, profile extrusion and confection by two shells with posterior pasting.

Blade casting is the simplest manufacturing process and the most used for small blades. Its problem is the excessive blade weight, which makes critical its loads stresses at the hub. Besides that, the inertia momentum of the rotor is very high, which difficulties the fan electric start up.

Extrusion process is the confection of a profile by pressing a material by some matrix. It is a cheap process, but it does not allow the differentiation of the blade with its radius. With this, twist and chord are kept constant, which limitates the maximum efficiency for the utilized aerodynamic profile (Fig 2).

The two shells process is more expensive, but allows blade differentiation. It is made by the confection of shells in two moulds and posterior pasting in a basic structure. The shells are identified as pressure side shell and vacuum side shell. This way, it is possible to twist the blade and vary the chords to keep the maximum efficiency of the adopted aerodynamic profile.

Figure 2. Extruded blade fan, Foroni (2005).

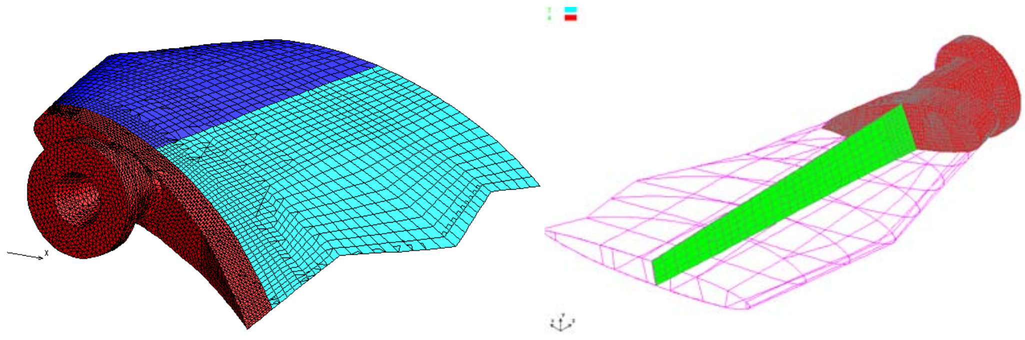

Figure 3. Proposed blade fan, Foroni et al (2007).

This work presents the use of metallic fans with two shells conformed by deep-drawing and welded and structured by a cast structure for the fixing root, a metallic nest with the first aerodynamic profile and a internal longarine as show in Fig. 3.

3. EXPERIMENTAL TESTS

The experimental validation of the proposed blade panels can be divides according to the involved processes, besides the validation of the final product in prototype tests. To simplify the work, on this work, the prototype experimental tests, welding and high temperature material performance will be omitted, as soon as, some mechanical properties were obtained by literature.

The blade manufacturing process can be divided in two sub processes: welding and deep-drawing. On next, we will be describing mostly the deep-drawing process.

3.1. Welding process

The welding process is made by a TIG welding due to its lower head transfer, high penetration and a process with thin and uniform welding cordon, which leads to a good union among the shells and the massive blade root. Besides that, it is important to minimize deviations in the aerodynamic profiles to maximize the blade performance. The blade thickness considered was two millimeters, with is perfectly weld able with low risk of making holes in he conformed shell.

3.2. Deep-drawing process

Even considering the selection of stainless steel AISI 409 due to its conformability, the difficult to discover the maximum localized stresses during the blade conformation obliged to perform conformability tests. Thus, it was made real scale tests to control and discover any problems. It was considered the pressure side of the aerodynamic profile the most critical conformation, due to its drawing depth. If the pressure side conformation would be viable, the vacuum side would be viable too.

The major problems in a deep-drawing process are: wrinkles on the conformed areas, plate breaking, excessive localized estriction, number of steps for full conformation and, finally, the force needed for drawing to select a press machine. To avoid some of these problems, it was used some cares as: deep-drawing with stretching , with a pressed blank-holder to avoid wrinkles, the use of a two-millimeter plate, a slow process to avoid plate breaking and excessive localized estriction and, finally, the adoption of a pressing machine with 50% extra capacity.

3.2.1. Initial test with SAE 1020 steel

For the first test, it was considered as material the carbon steel SAE 1020 to minimize the development costs. Thus, it allowed the comparison among the tests with carbon steel and stainless steel AISI 409.

A two millimeter carbon steel plate was conformed using the maximum friction area between the blank-holder and the matrix base. So, it was performed a more conservative test considering the plate slide between the blank-holder and the base. It was also used a square mesh of 50 x50 mm to verify the most affected areas by estriction. The plate with the referred mesh prepared for deep-drawing can be seen on Fig. 4a.

At this test, it is described the steps in order to detail the entire procedure. At subsequent tests, steps were omitted, focusing mainly on tests results.

As shown on Fig.1, the matrix is not a plain surface for plate lay down. Due to that, to lower the blank-holder, some load is add to provoke an initial deformation on plate. This load is exerted by approximately 20 M12 bolts to oblige touch the entire surface of the matrix base except the punch-related area. This previous deformation can be seen at Fig. 4b.

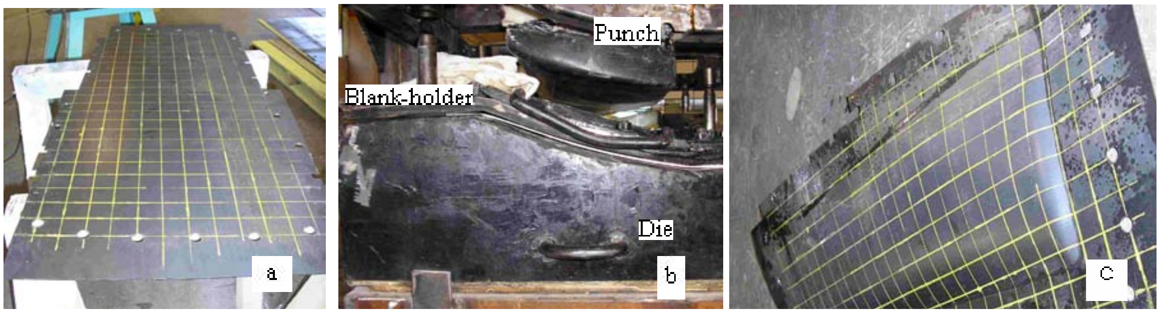

Figure 4. Conformation of Sheet 1 by blank-holder load. (a) Prepared Sheet; (b) During Process; (c)Conformed sheet Foroni (2005).

After the initial conformation by the blank-holder, it can be guaranteed the existence of a pre stress at Sheet 1. The next step is using the punch with a pressing machine.

After the initial conformation, the punch were lift up and a hole were made on sheet t verify is the conformation was complete. It was discovered the load force was not enough. However, it was already some sheet conformation.

Figure 4c indicates the conformed sheet, even at its critical region, with bigger conformation, did not present wrinkle, which shows the friction among the matrix base, sheet and blank-holder were enough to guarantee the estriction of the plate. In addition, no excessive localized deformation was noticed. This way, it was concluded that part of the contact surface blank-holder-sheet-base could be eliminated in order to facilitate the experimental preparation.

3.2.2. Load increased and lower friction

For the second test, according to the conclusions of the fist test, it was used a lower friction área, in order to facilitate the set up process, and increased the load up to the press limit, i. e., 75 tons, which is 50% higher the calculated load for stainless steel plate.

To verify if the conformation was complete, it was made a hole at the step shown on Fig. 4b which showed that the system with steel SAE 1020 could not be completely conformed even to the maximum press machine load. However, the conformation was deeper that the first test, as shown at Fig. 4.

For dimensional measure of the conformed plates, the plate was cut at the conformation edge to keep only the useful part of the final product plate. Fig. 5 shows this cut which gives us a very close view of the final shape of the blade.

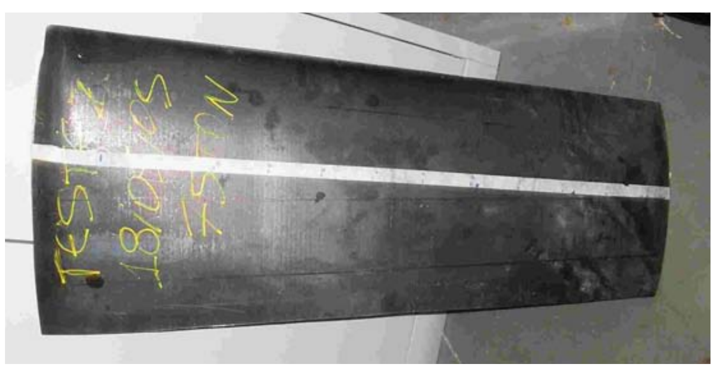

Figure 5. Sheet 2 final cut for dimensional measurement. Foroni (2005).

3.2.3. Material changes

As the second test reached the press machine load limit, it was necessary to finalize the carbon steel tests. And start testing a more ductile material, stainless steel AISI 409. Thus, the 3.2.2 procedure was made with the new material. The results can be seen at Fig. 6.

Figure 6. Sheet 3 after conformation. Foroni (2005).

Figure 6 leads to some conclusions. It was used the same punch load as item 3.2.2. However, the material was fully conformed except by one bubble at the lower part of the matrix. Due to that, it was noticed that was some lubricating oil accumulation, from punch, forming a pool at that area.

Like item 3.2.2., the sheet was cut and dimensional measured.

Due to the pool formation verified, it was necessary a better control of oil leakage from the pressing machine, as much as lubricating cares, in order to avoid these interferences at system (oil pool formation).

3.2.4. Bubble Ellimination

As described at item 3.2.3, it was observed the punch loads were enough for a single-stage deep-drawing production. The pre-load made by the blank-holder avoided any wrinkles at the estriction surfaces (necking). There was no plate breaking, as soon as there was no excessive estriction. Even this, a forth test was made in order to verify and eliminate the bubble happened at item 3.2.3 and the obtaining of a final dimensional measurement of the plate according to the design. This way, a new test was performed including a hole at the bottom part of the plate to avoid oil or even air pool formation during conformation. The result can be seen at Fig. 7.

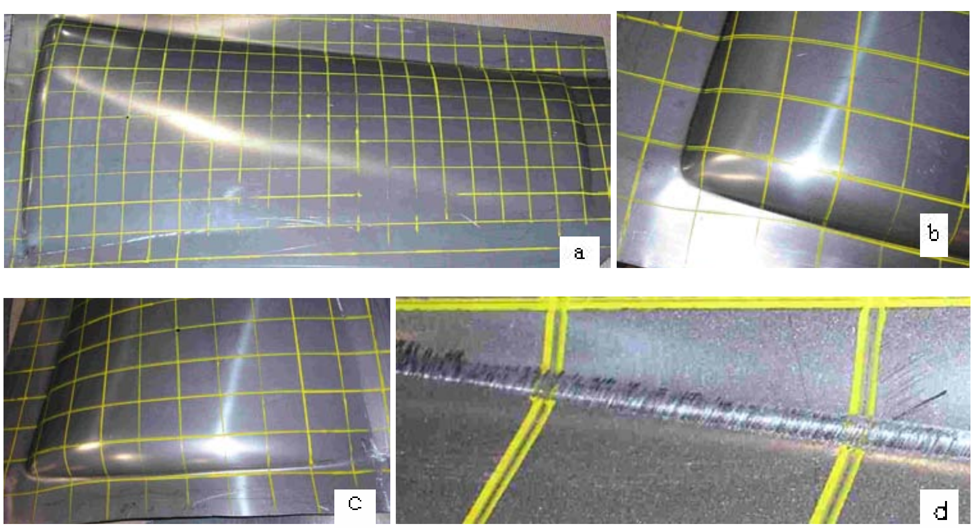

Figure 7. Sheet 4 after conformation.(a) General view; (b) Critical Section (no wrinkles); (c) Blade Root (no bubbles) and (d) Localized Estriction. Foroni (2005).

3.2.5- Forming limiting curves

The process done up to this point measuring the limit deformation on the sheet plane was not reliable. Due to this, a new kind of grid, more refined, and with circles much lower than the previous grid squares, was used in order to show the strain gradients on the sheet plane. The refined limit strain measurement made us able to verify the reliability of the deep-drawing process of the pressure side of the blade because makes possible to verify the reliability of the process comparing the strains measured with the limit strains calculated by using the theories of Dorn (1948), Hill

(1948), Swift-Hill (1952) and TPAE (Menezes,1999). These theories indicate, with dependability, if there is or not failure during the deep-drawing process by observing if the measured strains are lower that the calculated theoretically by them. These theories also allow the definition of the limit strains on AISI 409 stainless steel by plastic properties such as strain-hardening index, *n,* normal plastic anisotropy coefficient, *R* and initial strain-hardening, ε_o. This way, the plate was marked using an electrolytic process with circle printings forming a circular grid to measure strains on the entire blade area and show the strain gradients, mainly at the most deformed areas. The circles were printed with initial diameter 8mm followed by posterior deep-drawing according to previous tests procedure.

Strains are calculated by dividing the final ellipse and the initial circle diameters, in log scale. This way, the localized deformations were measured in positions where the deformations were bigger (mainly at blade root). These were compared with the calculated limit strains theories on a forming limit curve, as shown on Fig. 5, considered the material anisotropic, with (*R*=1,2); and anisotropic with behavior similar to isotropic with (*R*=1,0), initial strain ε_o = 0 and the strain-hardening index of sheet materials, *n*=0,22.

Therefore, it is verified by Fig.7 that the deformations on the most drawn regions, at the blade root did not reached the limit strains for the AISI 409 stainless steel, which lead to an inexistence of failure of these sheets during the deep-drawing process. Thus, the deep-drawing process was considered reliable, and the experimental tests could stainless be concluded.

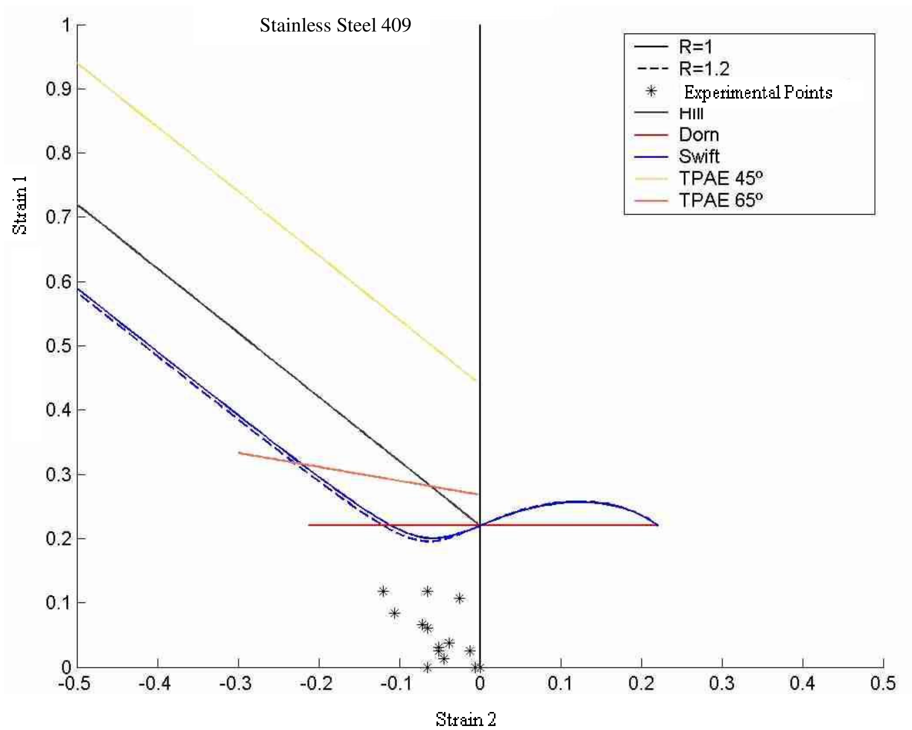

Figure. 8. Limit strain theories applied with experimental points measured. Foroni (2005)

4- CONCLUSIONS

It was verified by the experimental tests that the deep-drawing process was feasible and controlled as the most deformed areas, at the blade root where the plate is thinner, did not reach the limit strains for the stainless steel AISI409. This confirms the inexistence of failure during the deep-drawing process. Besides that, at these most deformed regions, the sheet will be cut for posterior edge welding, what will naturally reinforce these areas according to the blade panel design. The critical region of the shell is where it is not supported by the metallic root, as indicated in Figure 9, which does not have excessive deformation.

It can also be observed, at Figure 8, the effect of plastic anisotropy on diffuse and localized necking at the sheet plane. It was verified that, for a material with initial strain (ε_o=0), the influence of normal plastic anisotropy is only significant for the limit strains calculated by the theory of Swift (diffuse necking), and that is more expressive for the deep-drawing region of the forming limit curve.

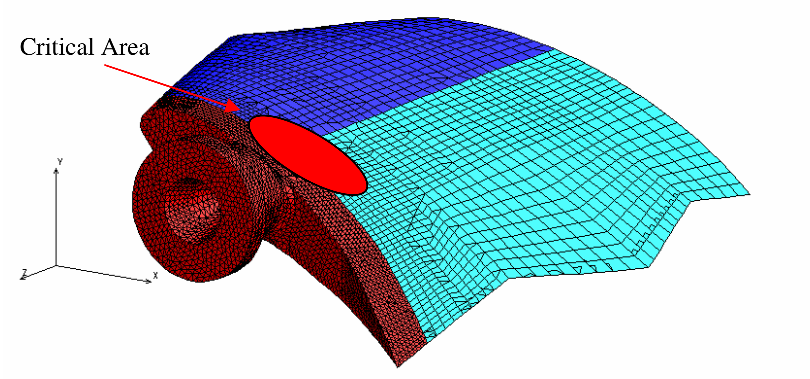

Figure 9. Critical area in operation.

The new developed fan provides a new solution for fan blade manufacturing, using the stainless steel AISI 409. This solution consisted by adapting technologies used in the fan market as aerodynamic profiles, materials and manufacturing processes to provide a market solution which is a blade to work in operation temperatures for fire gases exhaust in emergency conditions.

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