Evaluate the influence of temperature and humidity on the cure process of aeronautic sealants

Nuno Miguel da Silva Rodrigues

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Abstract

In a growing competitive market, the continuous search for production efficiency became the main goal of any production cycle in the aeronautics industry. The optimization of manufacturing processes and the reduction of delivery times are imperative to increase both market share and turnover. This work results from the cooperation between Instituto Superior Técnico and OGMA - Indústria Aeronáutica de Portugal, with the primary goal of reducing the manufacturing time of a certain aircraft wings. The primary structure of the wings is wet assembled, involving sealant application between faying surfaces and fillet and overcoat sealant along the overlapping joints for sealing the integral fuel tanks. This is the most time consuming step of the wings' production cycle, not only because of the thoroughness of the sealant application process, but mainly due to sealants' curing times. Laboratory tests were performed at Instituto Superior Técnico facilities in order to evaluate the influence of temperature and humidity conditions on the behavior of the sealants used in the wings' assembly process. In addition, the assembly operations on the assembly line of the wings were monitored and tests were carried out using structural specimens. It was concluded that an increase of temperature and/or humidity accelerates the curing reaction of sealants, reducing the respective curing times. Equipments that accelerate the cure reaction of sealants were tested in order to reduce the dependence on environmental conditions. In the end, it was proved that waiting times between sealant applications can be significantly reduced, decreasing the wings' manufacturing time.

Keywords: cure, integral fuel tanks, sealant, tack-free, wet assembly, work life

1 Introduction

The aeronautics industry is well known for its competitiveness and OEMs have as their primary goal the optimization of manufacturing processes without compromising final product quality. Keeping this in mind, efforts are made to continuously increase production cycle efficiency in order to reduce the delivery times and increase both market share and turnover.

This work results from the close cooperation between Instituto Superior Técnico (IST) and OGMA-Indústria Aeronáutica de Portugal. OGMA is specialized in providing MRO services and manufacturing aircraft components, some of them are the wings, fuselage and vertical stabilizer. The wings' assembly process is the spotlight of this work, focusing the study on the sealing process of wings' integral fuel tanks.

1.1 Motivation

The matter of interest to this work is the wings' assembly process. The sealing process of integral fuel tanks is the most time consuming operation when assembling the wings because it involves several phases of sealant application. Between each one of these steps it is required to wait until the sealant is cured before proceding to the next operation. It is well known that sealants' behavior is highly dependent on temperature and humidity, so it becomes extremely important analysing the influence of these conditions on sealants' tack-free and cure times, explained forward in this work. The main goal of this research is to reduce the waiting times between sealant applications during the sealing process of the wings' fuel tanks.

1.2 Polysulfide Sealants

Liquid polysulfide sealants are the *state of the art* of high performance sealants and have been widely used in the aircraft industry in the past 50 years. These are elastomeric materials consisting in polymer backbones containing formaldehyde groups (-CH2-O-) and sulfur atoms, which are responsible for polysulfides' unique properties: high flexibility and excellent chemical resistance. The cure of polysulfides consists in a condensation reaction between the terminal thiol groups (R-SH, where R is an alkyl and -SH is the thiol group) in the presence of an oxidising agent. This reaction causes the polymer chains to extend and crosslink during cure, giving the final elastomer [1].

Two-part polysulfide sealants are the most typicall sealants in aircraft applications. These are prepared and packaged as two components. One component is the base compound that contains the base resin and the other component is the curing agent or accelerator, usually manganese-dioxide. Mixing the two components, the cure reaction begins immediately. The mixture ratio between the two components is formulated so the sealant can meet the required specifications of its intended performance [2].

1.3 Sealant Properties

Sealants are formulated depending on the function it is desired them to perform and the substrate where they are intended to be applied. All sealants must be able to fill the space between two or more surfaces and conform to their irregularities; form an impervious barrier to fluid flow and maintain its sealing property during the expected lifetime, under service and environment conditions.

1.3.1 Identification

In the commercial market, sealants are identified as follows: Commercial Reference - Class - Application Time. The commercial reference depends on the product supplier. Typically there are three major classes of sealants. **Class A** sealants are suitable for brush application. **Class B** sealants are suitable for extrusion gun or spatula application. **Class C** sealants are suitable for extrusion gun, spatula, brush or roller application. After the class identification there is a dash number indicating the minimum application time, in hours [3].

1.3.2 Sealant Types

There are three main sealant types: overcoat, fillet and interfay sealants. **Overcoat** sealants, typically Class A sealants, are intended for overcoating fasteners and joints. **Fillet** sealants, usually Class B sealants, are used where thick layers of sealant have to be applied, for instance, along joints and filling cavities. **Interfay** sealants (Class C sealants) are used for wet assembly. This process requires sealant application within an overlapping joint, between the matting surfaces [3]. Figure 1 shows the different sealant types.

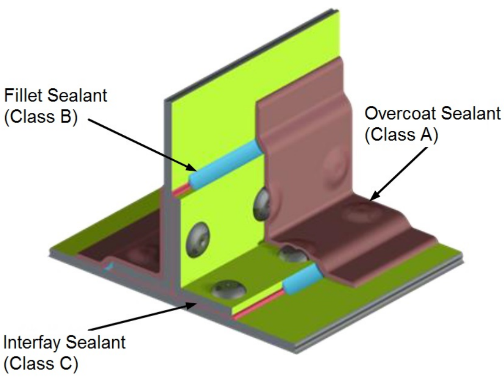

Figure 1: Sealant Types [3]

1.3.3 Uncured Properties

To correctly perform their function, sealants have to be able to “wet” the substrate where they have been applied, i.e., the liquid spreading of the sealant over the surface results in intimate contact between them and sealant is able to fill all surface irregularities. This allows the sealant to properly adhere to substrates and avoid the formation of air pockets [2].

Application time is the allowable usage time of the sealant after mixture. When this time is expired, the selant can no longer be applied. Within the **work life** (or assembly time) the final fasteners have to be installed in the structure where interfay sealant has been applied. This time is only specified for Class C sealants. **Tack-free time** defines the period, after mixture, when the sealant is dry to touch. This is only applicable to Class A and B sealants. **Cure time** is the time span, after mixture, required for sealant to reach a specific hardness. For sealants Shore A indentors are used [4]. These times are always specified for each sealant in the respective technical data sheet (TDS) for standard conditions (23°C, 50% R.H.). For conditions other than these, the times specified on sealant’s TDS are no longer valid.

1.3.4 Cured Properties

Sealants are formulated to meet specific properties in its final cured state. Typically, polysulfide sealants’ hardness is determined by the amount of penetration of a Shore A durometer in its cured state. While curing hardness increases until it reaches its maximum value that sealant has been formulated for. Although, a change in sealant’s hardness during service gives an indication that degradation might be occuring.

Almost every single joint where sealant has been applied experiences some movement during service life. Sealants with lower modulus of elasticity can accomodate much greater joint movement without compromising structural stability, i.e., without putting large stresses in the substrates and in the sealant itself.

During the operating lifetime of an aircraft sealants can be exposed to severe conditions. For instance, sealants used for aerodynamic smoothing and sealing the exterior skin panels of the fuselage experience very low temperatures during flight and are exposed to environmental effects. Sealants used in engine areas are exposed to high temperatures and inside the fuel tanks subjected to chemical attack. For these reasons, sealants need to be able to resist a wide range of temperatures while in continuous service operation without suffering degradation. Sealants should also be resistant to chemicals and fluid exposure to protect the surfaces where they have been applied, for example, to prevent fuel leaks and moisture penetration inside joints [1, 2].

1.3.5 Applications

Sealants are used in several aircraft areas. These are applied in fuel tanks to prevent fuel leaks and aircraft cabin areas to maintain pressurization. Sealants are also used for window sealing and aerodynamic smoothing, acid-resistant sealing in battery compartments, high temperature sealing in engine areas and weather sealing to protect aircraft skins and structural joints against moisture and fluids.

1.4 Cure Properties

The final properties of a sealant in its cured state will strongly depend upon the cure profile. Knowing that the cure process of polysulfide based sealants is highly influenced by temperature and humidity conditions, it is easy to conclude that parameters and conditions during cure have to be rigorously controled in order to obtain the desired properties of the sealant in its cured state.

The rate of cure is the speed at which the sealant develops strength until final cure state is achieved. This is a very important parameter when selecting a sealant. Slow curing can lead to increased production cycle times, although, it is important that sealant does not cure faster than it can be handle during the application process.

Depth of cure is related to the sealant cure mechanism. It is very important to achieve deep section curing in order to garantee that sealant behaves as expected. This is critical when using one-component sealants since these depend on moisture diffusion through the sealant to cure. If the skin of the sealant sets first it may inhibit the transmission of moisture to the interior section.

Shrinkage during cure is another important characteristic. If a sealant suffers excessive shrinkage it can cause voids in the sealant joint and uneven distribution of stress. Joints that are not completely filled with sealant are susceptible to contaminations such as dirt and moisture, that can lead to sealant failure and affect joint durability [1].

2 Sealing Process

Sealing a structure is a very thorough process and has specific requirements that must be fulfilled in order to ensure the correct application of the sealant. It requires qualified materials and equipment and performing personnel receives specif training in order to be skilled to deal with sealants. The sealing process follows a certificated protocol to meet customers quality requirements. The general steps of sealant application process are indicated in figure 2. In this work, only two-part polysulfide based sealants with a manganese dioxide curing agent were used, the same that are currently applied on the wings' assembly process. Further on, every mention to "sealant" is regarding two-part polysulfide systems.

2.1 Storage

Sealants must be stored under the conditions specified by the manufacturer in their respective TDS. Typically, these are stored under a temperature between 5°C and 25°C and have a shelf life about 6 to 9 months. Storage at higher temperatures will shorten the shelf life of a sealant.

2.2 Surface Preparation

The proper adhesion of the sealant to the substrate where it is going to be applied is significantly dependent on the surface condition. It must be free from grease, oil, metal swarfs and dirt. Usually the surface is cleaned wiping it with a proper solvent. After cleaning and degreased, a certain time must passed for the evaporation of solvent before applying the sealant.

Primers can also be used to improve adhesion and protect the substrates. Depending on the sealant material, if a primer is required, it should be choosen in accordance with sealant manufacturer recommendation. In some cases, it is required the application of an adhesion promotor on primer surfaces if good adhesion of the sealant cannot be ensured.

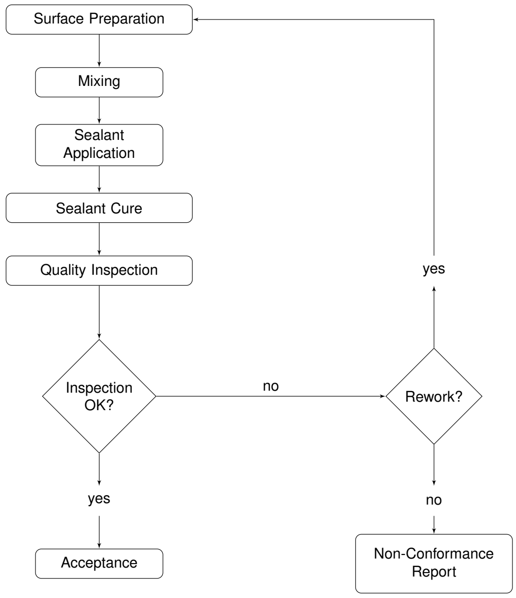

Figure 2: General Sealant Application Process

2.3 Mixing

Mixture is one of the most critical steps of the sealing process. The proper weighning and mixing of components is essential to ensure proper curing and adhesion of sealants [5].

The sealants used in this work are supplied in can kits and these are mixed by hand. The mixing process must be slow enough so that no air pockets are formed inside the mixed sealant. The mixing area is maintained at standard conditions

To ensure the quality of the mixture, mixed sealant should have no lumps or coarse particles and no skin. Periodically, specimens are made from samples of the mixture and inspected after standard cure regarding hardness, texture, color and porosity.

2.4 Sealant Application

Ideally, sealant application shall take place at standard conditions. Although, due to the difficulties in controlling the environmental conditions on the assembly line, customers define an authorized temperature and humidity envelope under which the sealant can be applied. It must be kept in mind that increasing temperature and/or humidity leads to a reduction in sealant's application, tack-free and cure times. The opposite is also true.

Interfay sealant is applied on the smaller face of the assembly and spread evenly using a roller or a brush. The matting surfaces shall then be assembled within the sealant application life and fixed with tacking fasteners. Riveting has to be completed within the sealant work life. An uniform squeeze-out must be formed during the assembly to ensure that sufficient amount of sealant has been applied to fill the gap between the faces.

Fillet sealant is usually applied with an air gun along joints. The air gun shall be guided in a way that prevents the inclusion of trapped air in the sealant layer. After application, the fillet seal is smoothed with a brush or a spatula. When filling cavities, fillet sealant is injected through the opening until sealant is squeezed out to ensure the gap is completely filled. In the case of joints on the aircraft skin, the edge of the seal is masked with masking tape and filled with fillet sealant according to aerodynamic and aesthetic requirements. The sealant is then smoothed using a spatula (butt joints) or a brush (lap joins). The masking tape shall be removed before a tack-free condition has been reached.

Overcoat sealant is applied with an air gun or a brush and then spreaded evenly. It is used in the sealing of fasteners and in some applications (sealing of fuel tanks) is also used to overcoat other sealant layers.

2.5 Quality Inspection

The steps described in 2.4 must be performed in accordance with customer requirements. Sealant layer dimensions are specified for each type of application and if one or more quality requirements are not met, it can be allowed to performe rework. This includes situations when has not been applied enough (or too much) sealant or when the sealant layer contains porosity. If rework cannot be performed, a non-conformance report has to be issued.

3 Sealing Fuel Tanks

An integral fuel tank is defined as primary wing structure (figure 3) that is sealed to contain fuel. This is the most efficient way to carry it. During manufacture, great care must be taken to protect fuel tanks against future corrosion and the possibility of fuel leaks [6].

Figure 3: Wing Primary Structure

The sealing process of the wings' fuel tanks is shown in figure 4. When the wing is ready for assembly, the matting surfaces of the wings' structure are sealed with Class C-12 interfay sealant to prevent the channeling of fuel along the joints from an internal leak source. After Class C-12 interfay sealant has been applied, the parts are assembled and the installation of fasteners must be concluded within the work life of the sealant, assuring an uniform sealant squeeze-out during the process. The fastening of the matting parts is made from the centre outwards to avoid air entrapment. After cleaning and degreasing, Class B-2 fillet sealant is applied along the joints of the fuel tank (edges of the matting surfaces). To garantee proper adhesion, adhesion promoter is applied to the areas that will be fillet sealed. The fillet sealant is then allowed to cure until it reaches a tack-free condition. After fillets have been applied, all fasteners and the fillet seals themselves are sealed with two layers of Class C-2 overcoat sealant. The first coat is allowed to cure to a tack-free condition, while the second coat is allowed to cure until it reaches a total cure condition. All these steps are performed twice: in the first place when the lower skins are incorporated on the wing structure and when the upper skins are installed.

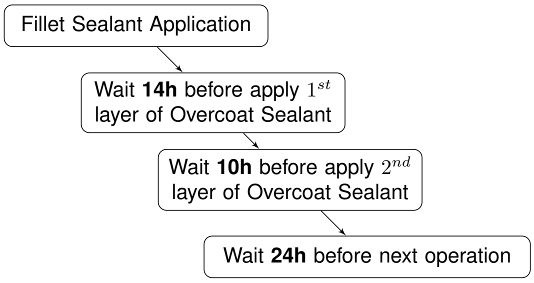

Figure 4: Current Fuel Tank Sealing Process [7]

From figure 4 it can be seen that the sealing of the wings' fuel tanks is a very time consuming operation during the assembly process. This is mainly due to tack-free and cure times of the sealant employed that are required to wait when applying several layers of sealant (96 hours total per wing!). The goal of this work is to reduce these waiting times.

Figure 5: Sealed Fuel Tank

4 Laboratory Research

The cure reaction of a sealant is highly dependent on temperature and humidity. After mixing the two components, sealant's application, tack-free and cure times will be shorter or longer depending on higher or lower temperature and/or humidity conditions, respectively. Knowing this, it becomes of extreme importance determining quantitatively the influence of environmental conditions on sealant's tack-free and cure times.

4.1 Experimental Procedure

In order to analyse the influence of temperature and humidity on sealant's behavior, laboratory tests were performed using the sealants applied in the sealing process of the fuel tanks. These took place at IST facilities in a chamber of controlled temperature and humidity. Sealants' tack-free and cure times were determined in function of these conditions using specimens 6 mm thick and 35 mm in diameter, similar to the ones shown in figure 6.

Figure 6: Sealant specimens used during laboratory tests

4.1.1 Tack-Free Test

Sealants' tack-free time was determined in accordance with [8]. Tack-free time is defined as the period required for the mixed sealant to be dry at the surface. A strip of polyethylene film 0.10 $\pm$ 0.05 mm thick was applied to the sealing compound and held in place using little pressure for 2 min $\pm$ 10 s. The strip was then slowly and evenly peeled back at right angles to the sealant surface. When the polyethylene came away clean and free of sealing compound it means that the sealant has reached a tack-free condition. This procedure is shown in figure 7.

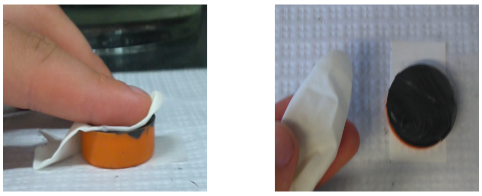

Figure 7: Tack-Free Test

4.1.2 Hardness Test

Fillet and overcoat sealant cure time is defined as the period required to the mixed sealant reach a hardness value of 35 and 30 Shore A, respectively. Sealant's hardness was determined in accordance with [9] using a hand held durometer. The sealant specimen was placed in a flat, hard, horizontal surface. The durometer presser foot was applied parallel to the specimen surface in a smooth downward action. After a firm contact between the presser foot and the specimen surface, the hardness readings were recorded within 1 $\pm$ 0.1 s. This procedure is shown in figure 8.

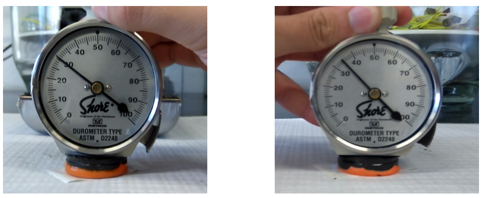

Figure 8: Hardness Test

4.2 Data Validation

There is almost no information available about sealants' tack free and cure times outside standard conditions. Although, the manufacturer of the sealants used in the wings' assembly process gave access to data containing Class C-2 overcoat sealant cure time for different temperature and relative air humidity conditions. This data was used to validate the experimental method described in 4.1 and the results obtained. Figure 9 compares Class C-2 overcoat sealant cure curves from the manufacturer (dashed lines) with the results obtained from laboratory tests using the same sealant (solid lines). Comparing the cure data for 50% relative air humidity, it can be seen that there is a very good agreement between manufacturer and laboratory results. For this reason, the experimental method and the results from laboratory tests were validated with success.

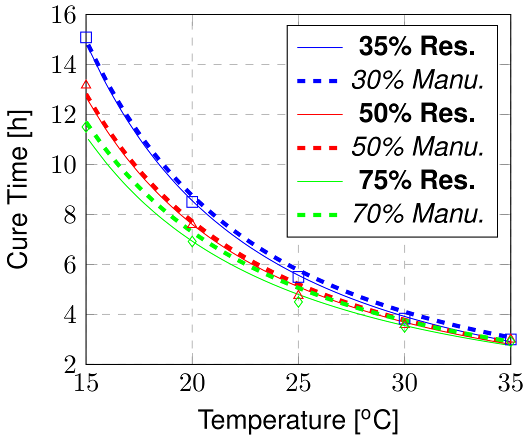

Figure 9: Data Validation

4.3 Results

In this section, the results obtained with laboratory tests are presented and further analysed.

4.3.1 Fillet and Overcoat Sealants

Table 1 shows Class B-2 fillet sealant and Class C-2 overcoat sealant tack-free and cure times obtained from the laboratory tests in function of different temperature and relative air humidity conditions. From the results indicated in table 1, tack-free and cure times for each sealant were plotted in function of temperature, under constant relative air humidity values.

Table 1: Class B-2 fillet sealant and Class C-2 overcoat sealant Tack-Free and Cure Times in Dependence of Temperature & Relavite Air Humidity

Temperature [°C]	Rel. Air. Hum. [%]	Class B-2 Sealant Tack-Free	Class B-2 Sealant Cure (35 Shore A)	Class C-2 Sealant Tack-Free	Class C-2 Sealant Cure (30 Shore A)
15	20	27h05	31h15	—	—
	35	24h15	26h00	14h20	15h05
	50	18h25	23h15	10h40	13h10
	60	16h25	20h50	—	—
	75	13h45	18h15	8h45	11h30
20	20	17h10	20h35	—	—
	35	13h20	15h30	7h05	8h30
	50	11h50	13h45	6h00	7h35
	60	10h20	12h30	—	—
	75	7h40	11h30	5h00	6h55
25	20	10h20	12h15	—	—
	35	8h30	9h55	4h10	5h30
	50	6h35	7h50	3h30	4h45
	60	5h30	7h10	—	—
	75	3h50	6h40	2h50	4h30
30	20	6h10*	6h25*	—	—
	35	4h00	5h15	2h30	3h50
	50	3h15	5h00	2h25	3h35
	60	3h10	5h00	—	—
	75	2h55	5h00	2h15	3h30
35	20	3h35*	4h05*	—	—
	35	2h50	3h50	1h50	3h00
	50	2h30	3h40	1h30	3h00
	60	2h10	3h40	—	—
	75	2h05	3h40	1h25	2h55

Class C-2 overcoat sealant tack-free and cure behavior in function of temperature and relative humidity are shown in figures 10 and 11, respectively.

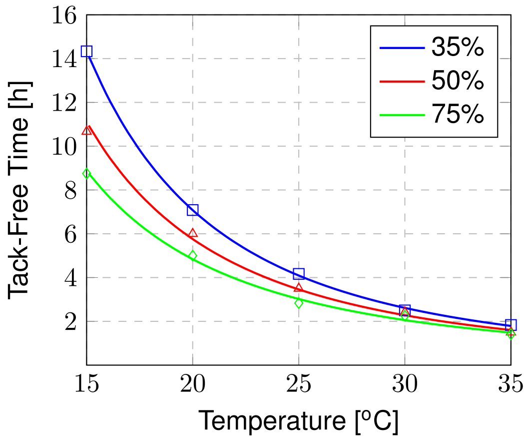

Figure 10: Class C-2 overcoat sealant Tack-Free Time in Dependence of Temperature & Relavite Air Humidity

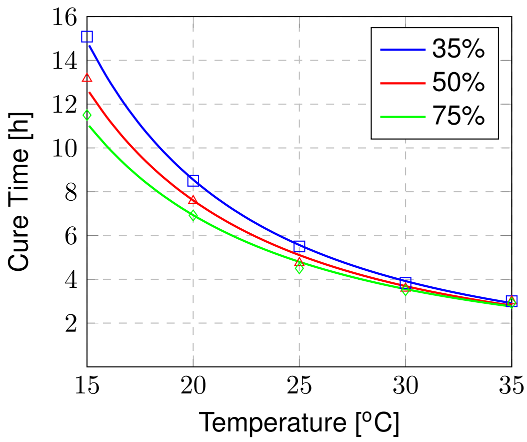

Figure 11: Class C-2 overcoat sealant Cure Time to 30 Shore A in Dependence of Temperature & Relavite Air Humidity

Class B-2 fillet sealant tack-free and cure behavior in function of temperature and relative humidity are shown in figures 12 and 13, respectively.

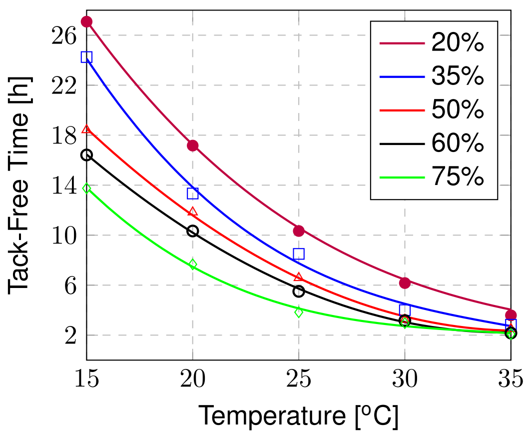

Figure 12: Class B-2 fillet sealant Tack-Free Time in Dependence of Temperature & Relavite Air Humidity

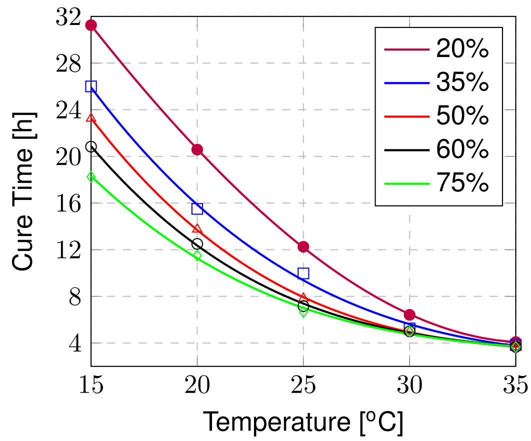

Figure 13: Class B-2 fillet sealant Cure Time to 35 Shore A in Dependence of Temperature & Relavite Air Humidity

Fitting the experimental points using Microsoft Excel, it was found that both Class C-2 overcoat sealant tack-free and cure curves are described by (1)

$$t = KT^{n} \tag{1}$$

Where *t* is tack-free or cure time, in hours, and *T* is the temperature (°C). The fitting parameters of Eq.(1) for Class C-2 overcoat sealant tack-free and cure curves are indicated in tables 2 and 3, respectively.

Table 2: Class C-2 overcoat sealant Tack-Free Curves Parameters

Temp. [°C]	**Rel. Air. Hum.** [%]	$K\ \left(\frac{h}{{}^{o}C^{n}}\right)$	*n*	R^2
$[15, 35]$	35	11097	-2.456	0.9989
	50	5408.6	-2.285	0.9952
	75	2682.2	-2.109	0.9922

Table 3: Class C-2 overcoat sealant Cure Curves Parameters

Temp. [°C]	**Rel. Air. Hum.** [%]	$K\ \left(\frac{h}{{}^{o}C^{n}}\right)$	*n*	R^2
$[15, 35]$	35	2723.8	-1.924	0.9990
	50	1592.4	-1.784	0.9916
	75	962.83	-1.647	0.9930

Fitting the experimental points using Microsoft Excel, it was found that both Class B-2 fillet sealant tack-free and cure curves are described by (2)

$$t = A_1T^3 + A_2T^2 + A_3T + A_4 \tag{2}$$

Where *t* is tack-free or cure time, in hours, and *T* is the temperature (°C). The fitting parameters of Eq.(2) for Class B-2 fillet sealant tack-free and cure curves are indicated in tables 4 and 5, respectively.

Table 4: Class B-2 fillet sealant Tack-Free Curves Parameters

Temp. [ºC]	**Rel. Air. Hum.** [%]	A_1 $\left(\frac{h}{{}^{o}C^3}\right)$	A_2 $\left(\frac{h}{{}^{o}C^2}\right)$	A_3 $\left(\frac{h}{{}^{o}C}\right)$	A_4 (h)	R^2
	20	-0.0010	0.1245	-5.4262	83.843	0.9999
	35	-0.0018	0.1942	-7.1583	94.000	0.9964
$[15, 35]$	50	0	0.0388	-2.7488	51.040	0.9991
	60	$5.560 \cdot 10^{-5}$	0.0320	-2.4234	45.410	0.9994
	75	-0.0014	0.1467	-5.0639	61.633	0.9981

Table 5: Class B-2 fillet sealant Cure Curves Parameters

Temp. [ºC]	**Rel. Air. Hum.** [%]	A_1 $\left(\frac{h}{{}^{o}C^3}\right)$	A_2 $\left(\frac{h}{{}^{o}C^2}\right)$	A_3 $\left(\frac{h}{{}^{o}C}\right)$	A_4 (h)	R^2
	20	$7.780 \cdot 10^{-4}$	-0.0036	-2.7159	70.155	0.9999
	35	-0.0011	0.1379	-5.8067	85.743	0.9982
$[15, 35]$	50	-0.0014	0.1596	-6.2183	85.307	0.9999
	60	-0.0014	0.1574	-5.8746	78.452	0.9995
	75	-0.0011	0.1192	-4.6028	64.100	0.9983

4.3.2 Interfay Sealant

Table 6 shows Class C-12 interfay sealant cure time obtained from the laboratory tests in function of different temperature and relative air humidity conditions. From the results indicated in table 6, cure times were plotted in function of relative air humidity, under constant temperature values.

Table 6: Class C-12 interfay sealant Cure Time to 30 Shore A in Dependence of Relavite Air Humidity & Temperature

	Rel. Air. Hum. [%]				
Temp. [ºC]	10	15	20	30	50
40	—	20h10	—	16h50	15h20*
50	12h40*	—	10h55	9h10	—
60	7h10	—	6h10	5h40	—

Class C-12 interfay sealant cure behavior in function of temperature and relative air humidity is shown in figure 14.

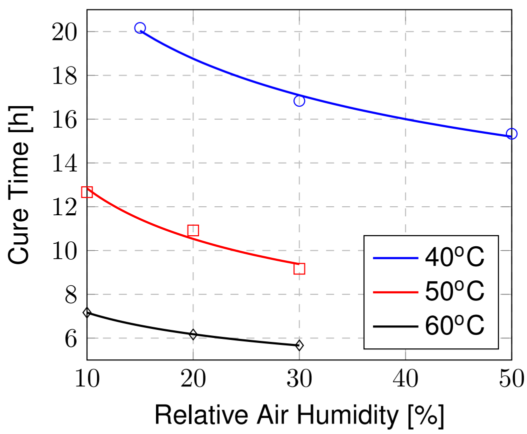

Figure 14: Class C-12 interfay sealant Cure Time to 30 Shore A in Dependence of Temperature & Relavite Air Humidity

Fitting the experimental points using Microsoft Excel, it was found that Class C-12 interfay sealant cure curves are described by (3)

$$t = BH^m \tag{3}$$

Where t is cure time, in hours, and H is the relative air humidity (%). The fitting parameters of Eq.(3) for Class C-12 interfay sealant cure curves are indicated in table 7.

Table 7: Class C-12 interfay sealant Cure Curves Parameters

Rel. Air. Hum. [%]	**Temp.** [ºC]	B (h)	m	R^2
$[15, 50]$	40	37.302	-0.229	0.9910
$[10, 30]$	50	24.787	-0.286	0.9619
	60	11.727	-0.214	0.9999

4.3.3 Discussion

The results obtained in the laboratory tests prove clearly the high dependence of sealants' behavior upon temperature and humidity conditions. It was concluded that an increase in temperature and/or humidity reduce both tack-free and cure times. On the other hand, a reduction in temperature and/or humidity leads to longer tack-free and cure times.

It is important to note that during the fuel tank sealing process, Class C sealants are used for overcoating, while its primary application is interfay sealing. For Class C sealants, manufacturers only specify work life instead of tack-free time. The laboratory research allowed to fulfill this lack of information regarding Class C-2 overcoat sealant tack-free time.

From the fitting curves, it can be easily established a correlation between the environmental conditions verified in the assembly line and the tack-free and cure times of Class B-2 fillet and Class C-2 overcoat sealants. For the majority of conditions, except for low values of temperature and relative humidity, the waiting times between sealant applications indicated in figure 4 can be significantly reduced.

Class C-12 interfay sealant was forced-cured at slightly higher temperatures outside the allowed temperature envelope for sealant application. It was not exceeded the maximum temperature the sealant can be exposed during cure, as specified by the manufacturer (60ºC). In standard conditions, Class C-12 interfay sealant takes several days to cure. The results obtained indicate that curing the sealant at high temperatures can significantly reduce its cure time.

5 Wings' Assembly Line

During the laboratory research, tests were carried out under constant temperature and humidity values. Although, environmental conditions in the assembly line suffer flutuations. For this reason, tests were performed in the assembly line to evaluate the sealants' behavior when applied on the wing structure and compare it with the results obtained from laboratory testing. Structural specimens were made from skins and stringer parts used in the assembly of the wings.

5.1 Work Life Test

After the application of interfay sealant, once a wing has been assembled, the matting surfaces seals are not acessible unless the basic structure is disassembled. For this reason, the application of interfay sealant must be controlled very carefully and the assembly process has to been performed properly. This requires the assembling of the structure within the sealant application time and riveting within the sealant work life. Previous to the installation of fasteners, during assembly, the structures are fixed with tacking fasteners. These are then removed one by one and the rivets are installed.

Figure 15 shows the structural specimens used in this test. After Class C-12 interfay sealant has been applied between the faying surfaces, these were fixed with tacking fasteners. The specimens were disassembled after the sealant's work life. The result is shown in figure 16. The positions of the tacking fasteners are indicated by red circles.

Figure 15: Structural specimens

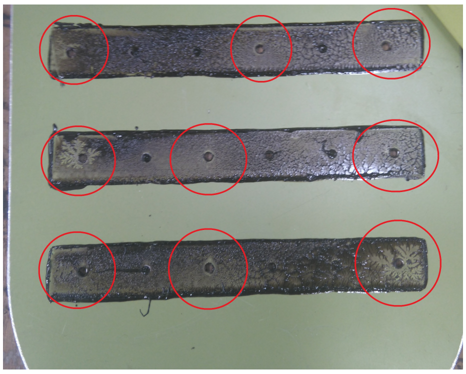

Figure 16: Interfay Sealant after disassembling the specimen

5.2 Fuel Tank Sealing Process

The fuel sealing process described in 3 was reproduced using the specimens shown in figure 17. The waiting times between the several sealant applications were determined using the laboratory curves, according to the conditions in the assembly line at the time when sealant application took place.

After applying Class C-12 interfay sealant between the skin and stringer parts and proper fastening (figure 17, upper left image), Class B-2 sealant was applied as a fillet seal around the stringers, after application of AMS3100 adhesion promoter (figure 17, upper right image). At this time, the conditions in the assembly line were 23°C, 60% R.H. When fillet sealant reached a tack-free condition, the fillet seal and the fasteners where overcoated with a layer of Class C-2 overcoat sealant (figure 17, bottom image). At this time, the conditions in the assembly line were 30°C, 45% R.H. The required waiting times between the application of fillet and overcoat seals obtained from the experimental results are indicated in figure 18.

Figure 17: Reproduction of the fuel tank sealing process

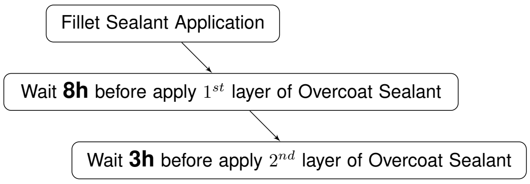

Figure 18: Reducing Fuel Tank Sealing Process

5.3 Discussion

The objective of reproducing the steps of the fuel tanks sealing process was to compare the sealants' behavior in the production environment with the expected tack-free times obtained from the laboratory curves. Despite of the flutuations verified in the temperature and humidity conditions during testing, it was concluded that both Class B-2 fillet and Class C-2 overcoat sealants have reached a tack-free condition within the expected times indicated in figure 18. This sustains the accuracy of the laboratory results.

The procedure described in 5.1 simulates the wet assembly process of structures. When the specimens shown in figure 15 where disassembled right after the assembly time, it was verified that Class C-12 interfay sealant was still tacky and "humid" enough to allow the proper installation of fasteners. The result obtained clears up the importance of tacking fasteners and installing rivets within the work life of the interfay sealant. In figure 16 it can be seen that where tacking fasteners have not been applied, there is an excessive amount of sealant (darker areas). Near the holes with tacking fasteners the sealant is "spread" outwards the joint. Tacking fasteners are essential when assembling structures in order to avoid chips entering the faying surfaces. These provide a strong clamping that causes the interfay sealant to squeeze-out. The proper sealant squeeze-out ensures that enough sealant has been applied in the interfay seal, allowing the excess of sealant to be removed. After the work life has expired, the sealant begins the final transition from liquid to solid polymer and can no longer be readily squeezed-out from joints. Due to this, if the installation of fasteners cannot be accomplished within the assembly time, it can only be performed after full interfay sealant cure time.

6 Process Optimization

The sealing process of wings' fuel tanks is divided in two major phases. After the basic structure of the wings is assembled (spars, ribs and stringers), the lower skin panels are installed and the sealant application steps indicated in figure 4 are performed. Then the upper skin panels of the wing are installed and the same sealant application steps are executed again.

The current sealing process requires a total of 96 hours of waiting times between the different sealant applications. Take into account the tack-free and cure curves obtained during laboratory testing can be an important step to optimize the production cycle time, adjusting the required waiting times in function of the real time conditions on the assembly line. Figure 19 indicates the required waiting times considering standard conditions on the assembly line, based on the laboratory curves. In this case, the sealing process only requires a total of 38 hours of waiting times, reducing 58 hours per wing when compared with the actual production cycle.

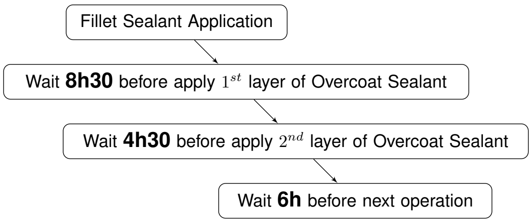

Figure 19: Fuel Tank Sealing Process at 23°C, 50% R.H.

To streamline the process, was developed a program using Microsoft Excel to be incorporated in the assembly line. This program receives as an input the temperature and relative air humidity conditions verified in the assembly line. Then, the program indicates the tack-free and cure times of Class B-2 fillet and Class C-2 overcoat sealants with a safety margin coefficient to cover flutuations in the assembly line conditions. Figure 20 shows the program template. At the time of conclusion of this work, the implementation of this program was still pending on customer's approval.

REQUIRED WAITING TIMES DEPENDING ON WINGS ASSEMBLY LINE CONDITIONS			
OPERATION CONDITIONS		Class B-2 Fillet Sealant	
Temperature (ºC)	23	Tack-Free (h)	Cure (h)
Rel. Air Hum. (%)	50	10 h	12 h
AUTHORIZED CONDITIONS		Class C-2 Overcoat Sealant	
Temperature: 18 - 30 ºC		Tack-Free (h)	Cure (h)
Rel. Air Hum. < 75 %		5 h	7 h
TACK-FREE AND CURE TIMES INDICATED WITH A SAFETY MARGIN OF 30%			

Figure 20: Program Template

6.1 Possible Improvements

The fuel tanks sealing process is significantly dependent on the behavior of sealants. On the other hand, sealants' behavior is highly influenced by temperature and humidity. In order to reduce the dependence on environmental conditions, some equipments are available in the market that can accelerate the cure reaction of sealants without degrading them.

6.1.1 IR Curing Device

The IR Curing Device permits the reduction of tack-free and cure times by emitting an infrared signal to the sealants. The infrared beam adjusts the emission spectrum with the absorption spectrum of the sealant to maximize energy absorption. This allows an homogeneous polymerization of the sealant and reduces the risk of micro-bubbling inside the sealant layer. This type of equipment is widely used in the aircraft industry during maintenance operations, for instance, when repairing sealants inside fuel tanks or replacing cockpit windows. Figure 21 exemplifies the application of this equipment.

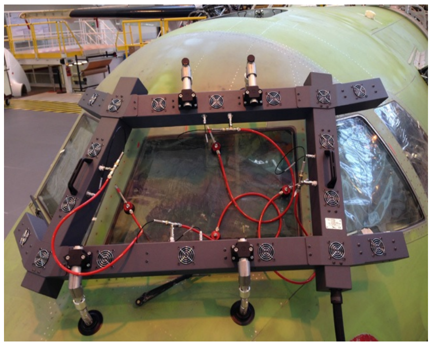

Figure 21: IR Curing Device, *Courtesy of the Manufacturer*

Contacts have been established with a supplier of IR Curing Devices to find a solution to accelerate the cure reaction of sealants after these have been applied on the wings. This equipment can reduce Class B-2 fillet sealant tack-free time to 30 minutes, around 95% less when compared with the actual 14h required. At the time of conclusion of this work, the design of the equipment to be applied on the fuel tanks sealing process could not be finished.

6.1.2 Heating Blankets

Heating blankets are specially designed to heat structural elements to a specific temperature. These act as heatspreaders to ensure approximately an uniform temperature distribution on the surface of the material. The heating blanket temperature is controllable using a thermostat box. During its operation, the heating blanket must make a good contact with the heated material, in order to ensure a good energy transfer between the structure and the heating blanket.

Figure 22: Heating Blanket Testing

This technology is not currently applied to accelerate sealants' cure, so tests were performed using frames and a panel of the same material of the wing (figure 22) in order to evaluate the applicability of heating blankets. The thermostat was adjusted to 50°C and the heating blanket was turned on 30 minutes after sealant application, to reduce the risk of creating air bubbles in the sealant layer. During the functioning of the heating blanket, the temperature of Class B-2 Class C-2 sealants were monitored and registed to obtain the respective cure profiles. The results are shown in figures 23 and 24 for Class B-2 fillet and Class C-2 overcoat sealants, respectively. Class B-2 fillet and Class C-2 overcoat sealants' tack-free and cure times using the heating blanket are shown in table 8.

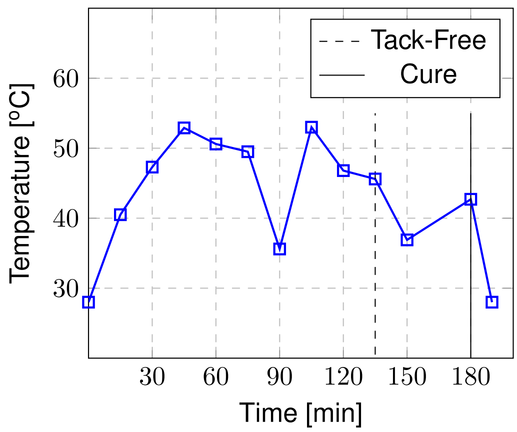

Figure 23: Class B-2 Fillet Sealant Cure Profile

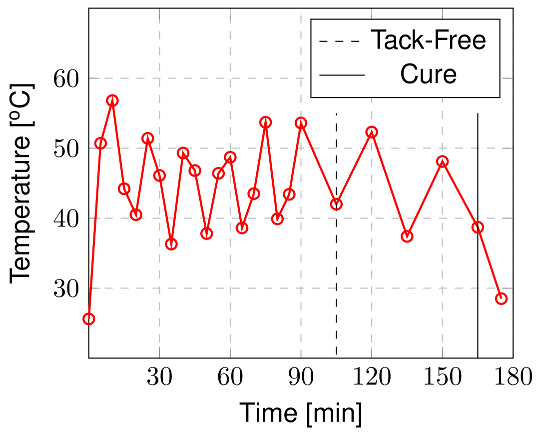

Figure 24: Class C-2 Overcoat Sealant Cure Profile

Table 8: Class B-2 fillet and Class C-2 overcoat sealants' tack-free and cure times using the heating blanket

	Class B-2 Sealant	**Class C-2 Sealant**
Tack-Free	2h15	1h45
Cure	3h	2h45

7 Conclusions

Throughout this work, the focus was on the study of sealants' behavior under different temperature and humidity conditions. Apart from chemistry variations of each type of sealant, these are the essential parameters that have significant influence on the cure reaction of sealants. Laboratory results shown clearly the high dependence of sealants' behavior upon temperature and humidity. It was observed that an increase in temperature or humidity leads to a reduction in tack-free and cure times of sealants. The opposite is also true. Tests were performed on the assembly line in order to compare the sealants' behavior when applied on the wing structure with the experimental results. Is was verified that laboratory curves can successfully determine sealants' tack-free and cure times, depending on the environmental conditions in the assembly line. In the end, sugestions were made in order to optimize the sealing process of the fuel tanks. Laboratory curves can be used to estimate the waiting times between sealant's applications in function of the conditions in the assembly line. Equipments that can accelerate the cure reaction of sealants were tested. It was concluded that waiting times can be significantly reduced without damaging sealants.

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