Engine test Experience of Ceramic Composites for the F100 Application

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Abstract

Building on past material efforts, Ceramic Matrix Composites based on either carbon fiber or a SiC fiber with a sequenced self-sealing matrix have been developed in order to bring durability improvements in hot section parts of gas turbine engines. The specific application being pursued on this effort is an F100-PW-229 nozzle seal. Full design life ground engine testing has been accomplished with both material systems. These ground testing has demonstrated a significant durability improvement from the baseline metal design. Furthermore, residual properties are being determined, for both ceramic matrix composite seals, by measuring tensile properties. The results showed no significant tensile debit for both composite, in accordance with basically no degradation of the bulk materials.

1. Introduction

For military aircraft, one of the key issues faced by manufacturers and end-users of gas turbine engines is durability. Particularly, conditions in the afterburning section is so severe that the design life of an engine nozzle is often half that for the rest of the turbine engine hardware. Current nozzles are based on axi-symmetric variable nozzle made of seals and flaps. These components must withstand extreme temperature, typically superior to 1000°C, as well as rapid thermal cycles, corresponding to the afterburner lights. In addition, afterburning sections are often characterised by non-uniform combustion functioning that create hot streaks on some nozzle petals. As the result, these parts are submitted to heterogeneous thermal flow, pronounced by the overlapping design of the flaps and seals, which generated high thermal stresses across the width.

Nickel-based alloys are commonly used for the divergent flap and seal components. The severe thermomechanical environment produces extensive cracking in the Ni-based components, combining with creep deformation resulting from the high temperature[1]. The result is an increasing components removal with a direct impact on operability, maintenance and cost.

The quest for longer service life of hot section components and higher thrust-to-weight, in military engines, has opened the door to ceramic materials. Ceramic Matrix Composites (CMCs) are targeted for use in the afterburning section which are exposed to high temperature (up to 1000°C), including high thermal gradients. So, there is continuing interest in developing, testing and deploying CMCs into military gas turbines engines and some developments have ended in success. This the case of the introduction of SiC/C CMC for F414 engine nozzle powering the F/A-18 E/F Super Hornet[2] fighter, and the introduction of C/SiC CMC for M88 engine nozzle outer flaps, powering the Rafale[3] fighter.

CMCs that are considered for gas turbine components, cover a wide range of fibers and matrices fabricated by Chemical Vapor Infiltration (CVI), sol gel route, polymer Inflitration and Pyrolysis (PIP) and Melt Infiltration (MI)[4]. The resulting materials are capable to withstand exhaust nozzle high temperature and thermal fatigue. However, the durability of CMC components is directly linked to their oxidation resistance which can affect their thermomechanical potential and led to parts ruptures.

In the last few years, advanced SiC/SiC and C/SiC materials, including multilayer woven coupled with sel-sealing matrix, have been developed by Snecma Propulsion Solide (SPS). These materials are being considered by Pratt & Whitney and Air Force Research Laboratory for the F100-PW-229 engine nozzle divergent seals, that powers F16 and F15 fighters. Several CMC seals have been ground tested and mechanical properties have been measured after a representative full ground engine life.

This paper presents results of engine experience and post-test characterisation. The suitability of the material system for gas turbine nozzle applications will be discussed.

2. Materials, design and seals manufacturing

2.1 CMC Materials under consideration

CMC using 2D weave suffer from insufficient characteristics in the third direction, which can generate delamination risks during the manufacturing step or in service. To minimize these risks, multilayer reinforcement, named GUIPEX® has been developed. The considered technology is applicable to carbon and ceramic fibers. GUIPEX® preforms are made of layers linked together. The number of layers is adjustable to obtain composite thickness, 4 mm composite thickness for the considered application. Furthermore, these multilayers reinforcements have been optimized to obtain orthotropic CMC, with in-plane characteristics close to a 2D material.

A self-sealing route has been selected for the matrix in order to eliminate finishing treatment. The principles of the self-sealing approach are to consume part of the incoming oxygen and to prevent access of residual oxygen to the weak carbon interface on the fibers through microcracks. A novel matrix technology, combining carbides deposited by CVI process with specific sequences of Si-C-B ternary ceramic has been developed[5].Self-sealing mechanism and characteristics of the resulting materials has been already described elsewhere[6].

These technologies can be applied to both carbon and Hi- Nicalon™ fibers. The first one, using carbon fibers, in named the SEPCARBINOX®A500, and the second one using Hi- Nicalon™ fibers is named CERASEP®A410. Main characteristics, ruling their thermomechanical behaviour are presented in table 1. SEPCARBINOX®A500 and CERASEP®A410 exhibit a significant difference of in-plane thermal expansion and elastic modulus. These two combined characteristics are favourable for SEPCARBINOX®A500 to lowering thermal stresses, in the case of components submitted to heterogeneous thermal flow, like nozzle flaps.

Table 1: Main mechanical and thermal characteristics of SEPCARBINOX®A5 00 and CERASEP®A410

Ref	Tensile at RT, dir. 1			α_1 [10^{-6}/K]	Thermal conductivity at 1000°C	
	σ_1 [MPa]	ε_1 [%]	E_1 [GPa]		λ_1 [W/m.K]	λ_3 [W/m.K]
SEPCARBINOX®A500	230	0.80	65	2.5	13	4
CERASEP®A410	315	0.50	220	4.5	7	2

The materials performances, in term of life duration in aggressive environments, has been determined by Pratt & Whitney, before to engage more investigations to install these both materials on F100 engine ground test. Detailed results have been reported previously[7,8].

CERASEP®A410 was submitted to fatigue tests in tension, at stress levels of 115 and 155 MPa, for a temperature of 1204°C. Most of this testing was done in air. Testing was also performed in a 90% steam and 90% steam with an overload applied (20% increase in load at the start of the first fatigue cycle). The time to failure, at 155 MPa, was between 70 to 120 hours, which is consistent with reported values for CERASEP®A410. The most interesting aspect of this testing is that there was no debit in life for the steam testing environment as reported for other material systems[9]. However, the steam environment affects the failure mode, with clearly attacks of the surface of the sample and cracks evident in the seal-coat.

SEPCARBINOX®A500 was characterised in tensile and flexural creep at 600 and 1000°C, for a stress range of 90 to 170 MPa, in air. All sample tests that latest 500 hours were stopped due to time constraints. At 1000°C, there were no failures at stress levels of 90 and 130 MPa. At 130 MPa, the tests at 600°C failed before 500 hrs with scatter in the failure times. Test at 600°C and 90 MPa achieved full test duration. At stress levels above 130 MPa, shorter lives have been measured for both temperatures, but 1000°C remains slightly more favourable than 600°C.

In summary, All of the testing show that the materials perform consistently as expected from the database[6]. The fatigue and creep testing have highlighted that the sequence matrix protects the material at the design stresses being considered. This protection is the same regardless of the environment as shown for the CERASEP®A410. The SEPCARBINOX®A500 has also shown that C fiber based systems can show lifetimes 2 orders of magnitude greater than other systems without a sequence matrix[10]. This is key information that supports going into ground and flight-testing.

2.2 Design and thermomechanical analysis

Design of the divergent seal has been performed in order to insure that its design is comparable to or better than the existing metallic seals. Two different cross section of seals for the F100-PW-229 were developed : constant and variable thickness as shown in fig.1. These were initial attempts to manufacture both the SEPCARBINOX®A500 and CERASEP®A410 as nozzle seals. The following seals were made: of CERASEP®A410, 2 of constant cross section and 2 of variable cross section, of SEPCARBINOX®A500, 2 of constant cross section were made. After the last CVI cycle, metallic hardware was assembled on the seals. This hardware was required for the integration of the seal into the divergent nozzle.

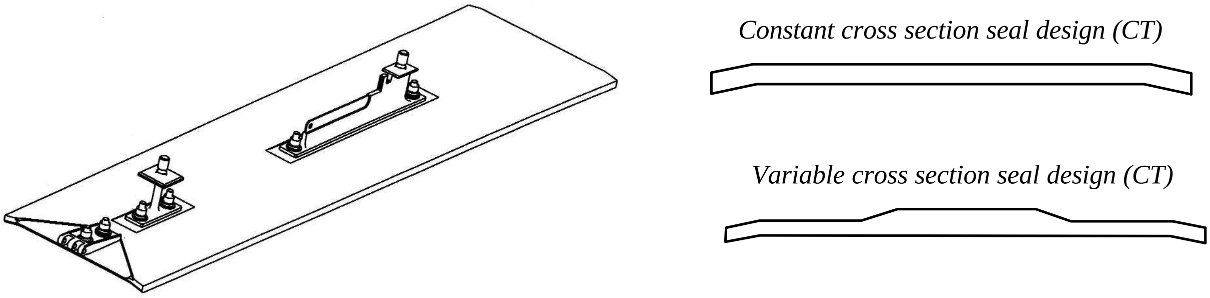

Figure 1: F100-PW-229 CMC seal schematics

As part of the process to introduce experimental hardware on the engine, design analysis and reviews were carried out in order to ensure that the expected stresses that would be seen in the CMC component were consistent with the material database and material capability. The thermal and mechanical analysis has been carried out taking into account the worst case flight point corresponding to maximum afterburner conditions. Results have been reported previously[7,8]. All of the analysis has shown that the material capability would be greater than the stresses imposed during engine testing.

However, as presented in fig.2, the calculated max. in-plane stresses, in the case of SEPCARBINOX®A500 are significantly lower than the calculated max. in-plane stresses in the case of CERASEP®A410. As already mentioned, the intrinsic characteristics of the SEPCARBINOX®A500 are favourable to lowering thermal stresses.

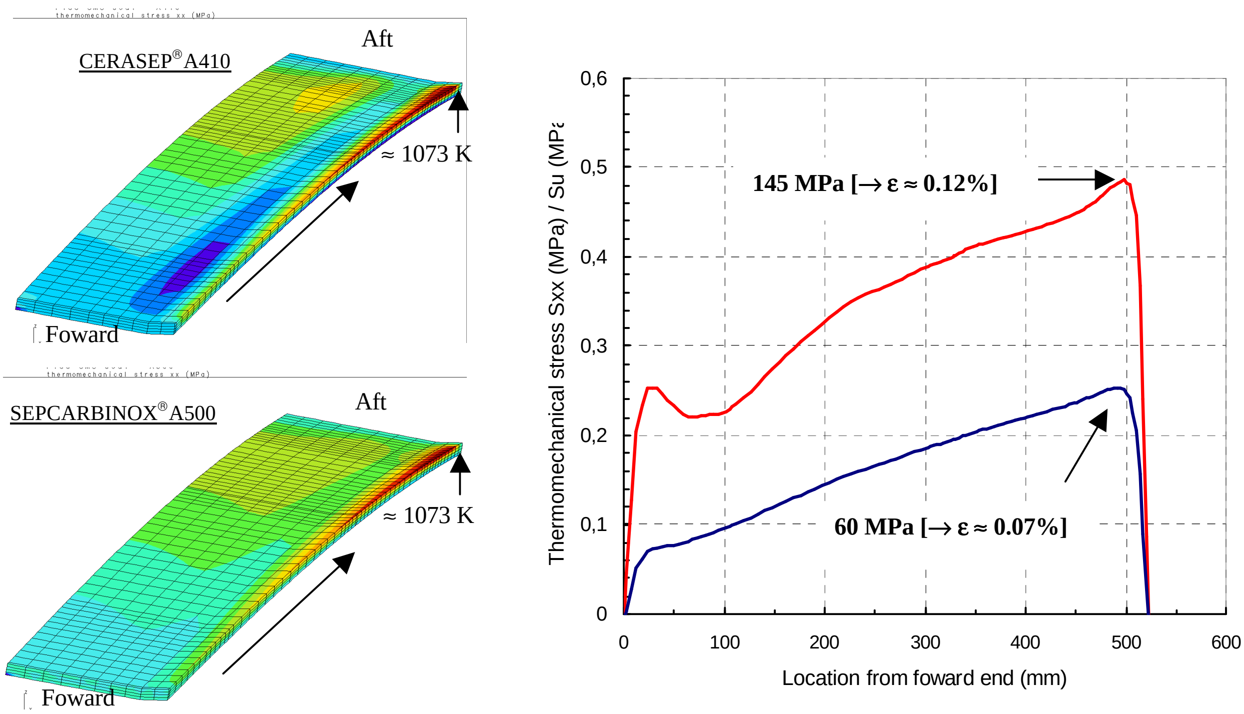

Figure 2: Calculated longitudinal stress

2.3 Seals manufacturing

The seal preforms were woven as an 8HS weave with a multilayer reinforcement. The number of layers was determined to obtain a composite thickness of 4 mm, without seal-coat thickness . A CVI (Chemical Vapor Inflitration) hardening cycle is performed to obtain the desired shape, while a mold, ensures the perform shape and appropriate fiber volume fraction. The next and final phase after de-molding, consists in performing CVI cycles for densification and sealing protection. If any machining is to be done, it will occur between these CVI cycles. A total of six seals were made for ground endurance engine testing : 4 CERASEP®A410 seals (2 constant thickness and 2 variable thickness) and 2 SEPCARBINOX®A500 constant thickness seals. The physical properties of the CMC materials after manufacturing are described in table 2. The seal porosity is higher than the usual plates porosity because this was the first engine hardware fabricated from these materials for this application.

For both components, a witness seal has been cut out of the as-processed seal (fig.3) and characterised in tension , at room temperature. The results, reported in table 2, are consistent with both CMCs database.

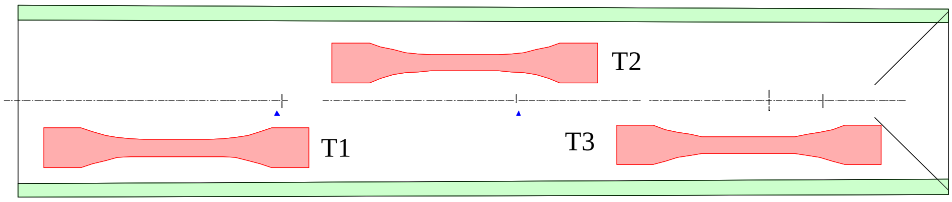

Figure 3: Cutting diagram of CERASEP®A410 and SEPCARBINOX®A500 witness seals

Table 2: Tensile properties, at RT, of witness seals.

Witness seal	# Coupon	σ [MPa]	ε [%]	E [GPa]
CERASEP®A410	T1	314	0.39	197
	T2	277	0.32	197
	T3	370	0.57	204
	Average	**320**	**0.43**	**200**
SEPCARBINOX®A500	T1	210	0.78	82
	T2	201	0.79	82
	T3	202	0.85	81
	Average	**204**	**0.81**	**82**

3. Ground test experience

3.1 Engine Endurance

testing of CMC seals

The six CMC divergent seals were tested on an F100-PW-229 engine at two different test locations. When that engine was not available, testing was moved to an F100-PW-220 engine. About half of the testing was done at sea level test stands located at Pratt & Whitney in West Palm Beach, Florida. The other half of the engine testing was done at the Arnold Engineering Development Center (AEDC) located at Arnold Air Force Base, Tennessee that performs sea level and altitude testing. The engine was tested through a Robust Accelerated Mission Test (AMT). This testing consisted of various throttle movements to change the thrust produced by the engine. The seals were installed in the engine as shown in fig. 4. Since multiple engine tests were covered by the test, the location varied throughout the test. The various engine nozzle locations

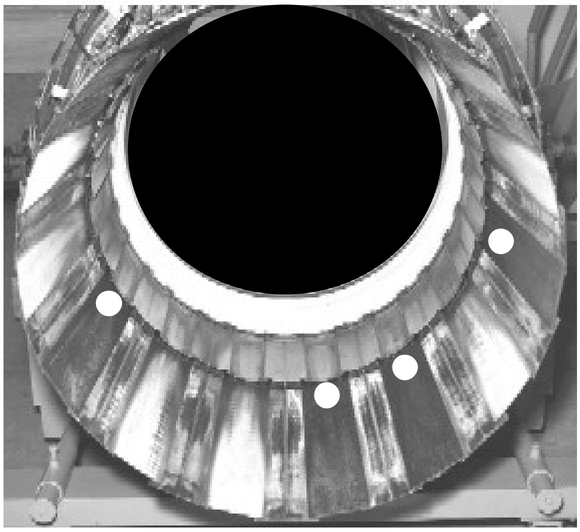

Figure 4 : CMC seals installed as direct replacement for metallic seals in F100-PW-229 engine (multiple locations).

used during the test were chosen to always have an A410CT and an A500 seal in a hot streak location.

Since the seals were not all installed at the same time, the engine time per part varies. Table 3 summarizes the engine tests experience achieved per seal. F100 Parts are tracked based on the Total Accumulated Cycles (TAC) as well as engine time (hours). The A/B hours (afterburner) are a subset of the total engine hours.

Table 3: Engine summary

Seal type	CT / VT	TACs	Engine hours	A/B hours
CERASEP®A410	**A410-CT1**	**4851**	**1294.9**	**97.6**
	A410-CT2	6580	1748.8	117.4
	A410-VT1	4623	1341.8	94.8
	A410-VT2	4623	1341.8	94.8
SEPCARBINOX®A500	**A500-CT1**	**4609**	**1307.2**	**94.4**
	A500-CT2	6799	1485.0	124.0

For the A410-CT1 seal, there has been seal coat loss, as previously reported[7]. This was a seal that had an upstream component failure that caused localized vortexes that locally increased the temperature in creasing the thermal strains resulting in seal-coat cracking and liberation during the first 250 hours of engine test. Additional engine testing has resulted in additional loss but at a greatly reduced rate (fig.5).

The CERASEP®A410 CT seals saw respectively 4851 TACs and 6580 TACs and the SEPCARBINOX®A500 saw respectively 4609 TACs (fig.6) and 6799 TACs. This greatly exceeds the life of the metal hardware, currently used in engines, particularly for the metallic seals in hot streak position.

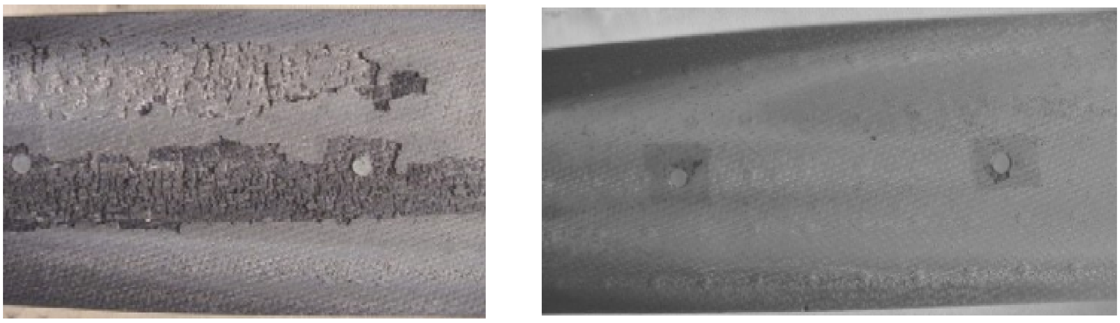

Figure 5: CERASEP®A410 seals, A410-CT1 showing seal-coat loss and A410-VT1 without any degradation

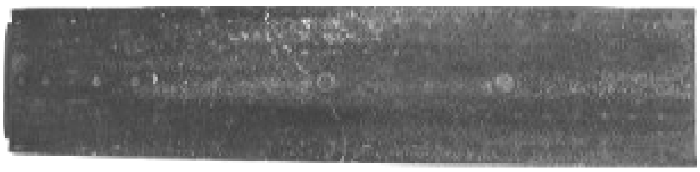

Figure 6: SEPCARBINOX®A500 seals, A500-CT1 showing a very satisfying aspect

3.2 Post-engine test mechanical result

The intent of some of the engine test exposure was to perform residual tensile property testing on the seals to note if property degradation was occurring. Both CERASEP®A410 seal and SEPCARBINOX®A500 seal were pulled for this effort. Assuming that the initial objective was to demonstrate a minimum of 4600 TACs in ground testing, A410-CT1 with 4851 TACs and A500-CT1 with 4609 TACs have been machined per the cutting diagram shown in fig.7. The sample length was decreased form the standard length of 150 mm to 120 mm. The gage width for A410 Seal coupons 1,2,3,4,6 and 7 were 16 mm and the gage width for A410 Seal coupons 5,8,9,10 and 11 were 10 mm. The gage width for A500 Seal coupons were 10 mm.

The results of this testing, for the A410-CT1 seal, are shown in table 4. Samples 1,2,3,4,6 & 7 had grip or radius failures (fig.8) due to the relatively wide gage section used for this sample geometry. Hence, the strain to failure and ultimate tensile strength are minimum values. The modulus measured for these samples are valid. These values are consistent with the data of the witness seal properties that is reported as 200GPa. Samples 5,8,9,10 & 11 had gage failures (fig.8) and the values UTS reported is in agreement with the value of 320 MPa of the witness seal. For all cases, the ruptures are non-brittle (fig.8).

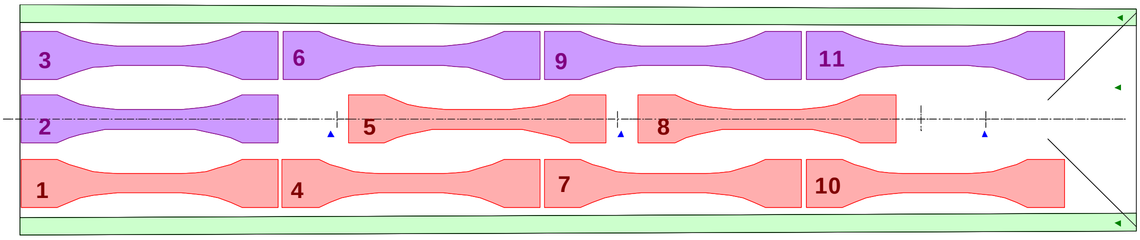

Figure 7: A500-CT1 and A410-CT1 cutting diagram

Table 4: A410-CT1 – Post engine test mechanical properties

Seal	**# Coupon**	Tensile test at RT			
		σ [MPa]	**ε [%]**	**E [GPa]**	**Failure**
A410-CT1	1	>210	>0.17	230	Grip section
	2	>240	>0.20	240	
	3	>290	>0.29	230	
	4	>180	>0.16	200	
	6	>180	>0.12	190	
	7	>230	>0.24	190	
	5	320	0.57	170	Gage section
	8	332	0.47	200	
	9	320	0.52	-	
	10	350	0.61	200	
	11	360	0.55	200	
	Average [5,8,9,10,11]	**337**	**0.54**	**193**	
Witness seal	**Average**	**320**	**0.43**	**200**	

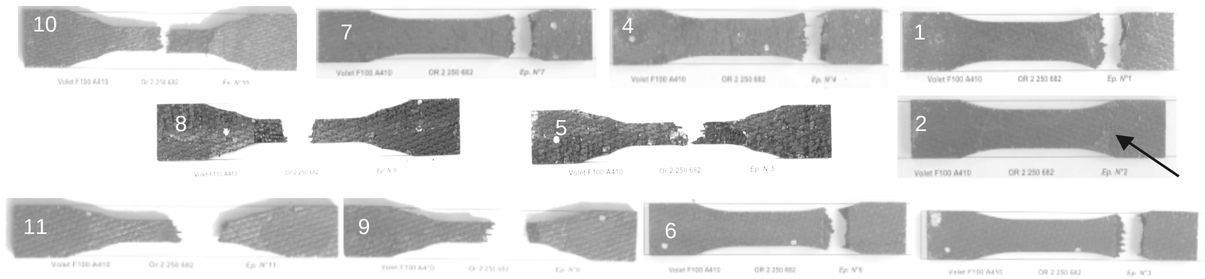

Figure 8: A410-CT1 – Valid and non Valid failure

The A500-CT1 seal results are shown, in table 5. In this case, the gage width has been limited to 10 mm, for all coupons, taking into account the A410-CT1 seal experience. So, all ruptures are valid (gage failures), leading to ultimate stresses rupture very closed to witness seal average tensile stress that is reported as 204 MPa. The modulus and the elongations are also consistent with the witness seal data. At last, for all samples, the ruptures are non-brittle (fig.9).

Considering the promising results obtain in ground engine test with CERASEP®A410 and SEPCARBINOX®A500 seals, efforts are underway to provide the technology for a Field Service Evaluation. However, the SEPCARBINOX®A500 presenting the best compromise performance / cost, is the preferred option. This evaluation is planned to test SEPCARBINOX®A500 seals in an F-16 fighter with F100-PW-229 engines. This will be done at 2 different bases to gain the most experience of the material in flight environment. A working team with United States Air Force personnel has been set up to work this program.

Table 5: A500-CT1 – Post engine test mechanical properties

Seal	# Coupon	Tensile test at RT			
		σ [MPa]	**ε [%]**	**E [GPa]**	**Failure**
A500-CT1	1	181	0.69	66	Gage section
	2	183	0.59	78	
	3	178	0.77	68	
	4	189	0.89	61	
	6	192	0.74	65	
	7	197	0.95	62	
	8	198	0.68	69	
	9	197	0.89	73	
	10	205	0.68	82	
	11	198	0.71	85	
	Average	**192**	**0.76**	**71**	
Witness seal	**Average**	**204**	**0.81**	**82**	

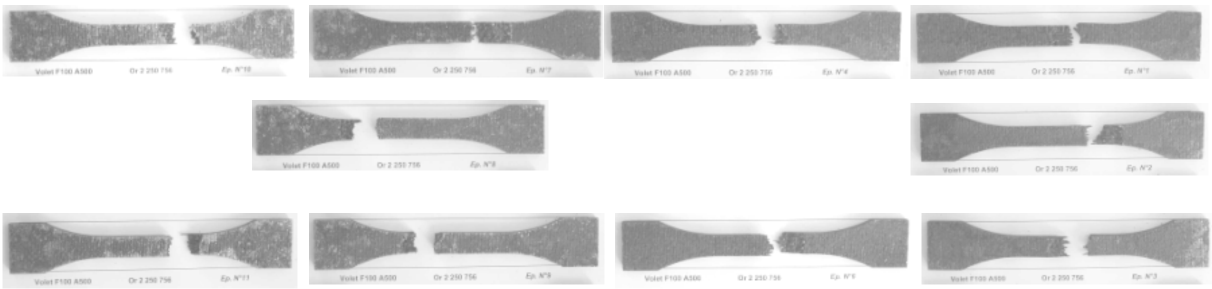

Figure 9: A500-CT1 – Coupons failure mode

Furthermore, SPS has engaged for 2 years, a significant industrialization and cost reduction program on SEPCARBINOX®A500 to match an attractive technology with readiness criteria. A first step was to adjust the CVI parameters in order to meet the constraints of the large size industrial furnaces. This effort has been finalised by the production of a first batch in an industrial one-meter diameter furnace. A second step was an optimisation of the furnace loading ratio, with a first batch in lab furnace and the production of a batch manufactured in a 600 mm diameter pilot furnace. Witness panels were included with each of the production runs for characterization of the microstructure and strength measurements using room temperature tension tests. Fig. 10 shows average tensile stress values versus CVI furnace run and qualitative loading ratio. All specimens exhibited excellent strength values that were considerably higher than the minimum "-3 sigma" value of 170 MPa at room temperature of the database. It is also important to highlight that the average results appear to be steadily rising, as knowledge is gained from each production batch. The ability to produce quality material in different furnaces, over two years, with no issues, is also very encouraging.

4. Conclusion

The accelerated mission testing of nozzle seals made out of CERASEP®A410 and SEPCARBINOX®A500 have shown the ability to survive the full ground test duration of 4600 TACS. Two seals have greatly exceeded this objective. This endurance demonstration is a significant durability improvement over metal seals which need to be replaced several times during such a test program. This is especially true when looking at hot streak locations in the nozzle. Post-test engine experience has shown no debit of the material properties after endurance ground test exceeding 1,000 hours. The tensile testing documented above has shown that the modulus has shown no degradation and that the material capability is retained. The strain to failure and ultimate tensile strength at room temperature is similar to the database of the as-processed material. This, again, demonstrates that the sequenced matrix is protecting the material. This also shows that the stresses and temperatures seen during engine test are within the material capability and confirms the design stress analysis. Field service evaluation of SEPCARBINOX®A500 Seals on F-16 fighters is planned.

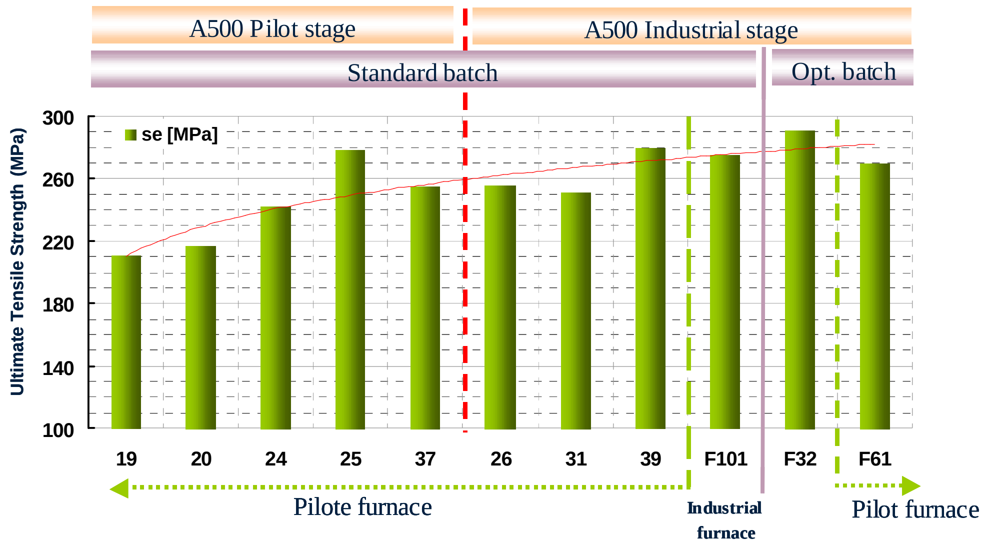

Figure 10: Plot of average tensile strength values measured on witness panels versus individual CVI furnace runs.

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