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Flow Forming of Aircraft Engine Components

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ABSTRACT

Aircraft engine components are often an assembly of several parts that are manufactured using various processes: deep drawing, machining, among others. Sheet metal forming requires expensive tooling and is performed in numerous steps, increasing lead-time. Furthermore, with the ever increasing costs of raw material, machining parts out of forged or cast rings is becoming less cost effective as up to 90% of the material can be wasted.

For these reasons, the use of near net shape manufacturing methods is becoming inevitable. An alternative forming process is here investigated: flow-forming, process well adapted to axisymmetric parts. The amount of forming steps, welding and machining could be significantly reduced, hence reducing lead-time and manufacturing costs.

Metallurgical and mechanical properties of a flowformed case will be presented and compared with material characteristics of cases manufactured by machining of forged rings. It will be shown that both forming processes yield to equivalent results.

1.0 INTRODUCTION

Aircraft engine components are often an assembly of several parts (e.g. combustion chamber) that are manufactured using various processes (e.g. stamping, machining). A significant number of these parts are formed using sheet metal forming (e.g. deep drawing). Deep drawing requires expensive tooling and is generally performed in numerous steps, often including intermediate annealing. All these steps are time consuming and therefore increase lead-time. Furthermore, if the assembly involves welding of different parts, lead-time is further increased and more distortion is likely in the final assembly.

Additionally, with the ever-increasing costs of raw material, especially of super-alloys and titanium alloys, machining of axisymmetric parts out of forged rings is becoming less and less cost effective as up to 90% of the material can be wasted. Reducing the use of raw material is therefore inevitable.

For these reasons, near net shape manufacturing methods are appealing. An alternative forming process is here investigated: flowforming, process well adapted to axisymmetric parts. The number of forming steps, welding and machining can be significantly reduced, hence reducing lead-time and manufacturing costs. It should be noted that alloys suitable for sheet metal forming are also suitable for flowforming.

Savoie, J. (2006) Flow Forming of Aircraft Engine Components. In *Cost Effective Manufacture via Net-Shape Processing* (pp. 22-1 – 22-14). Meeting Proceedings RTO-MP-AVT-139, Paper 22. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Gas-generator cases belong to components well suited for this forming process. They hold the pressurized air from the compressor and force it to flow inside the combustion chamber (Figure 1). It is thus a pressure vessel subjected to cyclic stresses and relatively high temperatures. The metallurgical integrity and mechanical properties of the flowformed parts are thus crucial.

In this paper we will compare the metallurgical and mechanical properties of parts produced by both processes (flowforming and the more traditional machining), keeping in mind that the flowformed components must be at least as good as the machined ones to avoid significant design changes and hence qualification costs.

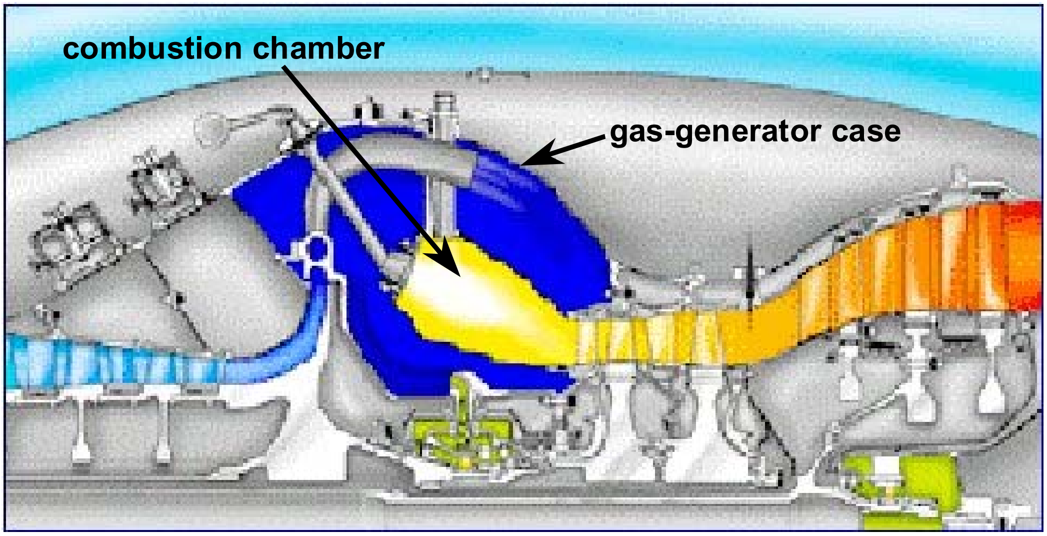

Figure 1: Cross-section of part of a turbo-fan

2.0 FLOWFORMING PROCESS

Flowforming is a process used to form rotationally symmetrical hollow parts. It involves applying a compressive force to the outside diameter of a preform mounted on a rotating mandrel. The preform is forced to flow along the mandrel by a set of two to four rollers that move along the length of the rotating preform, forcing it to match the shape of the mandrel (Figure 2).

Flowforming can produce parts of varying wall thicknesses as well as varying internal diameters. In some cases the design of the components must be adapted to the new forming processes to facilitate the manufacturing (for example, smooth transitions are more adapted to flow forming).

All of these parts require tight tolerances that can be achieved with the modern flowforming machines. However, containment parts and especially structural parts produced in a new way must be re-certified for both metallurgical and mechanical characteristics.

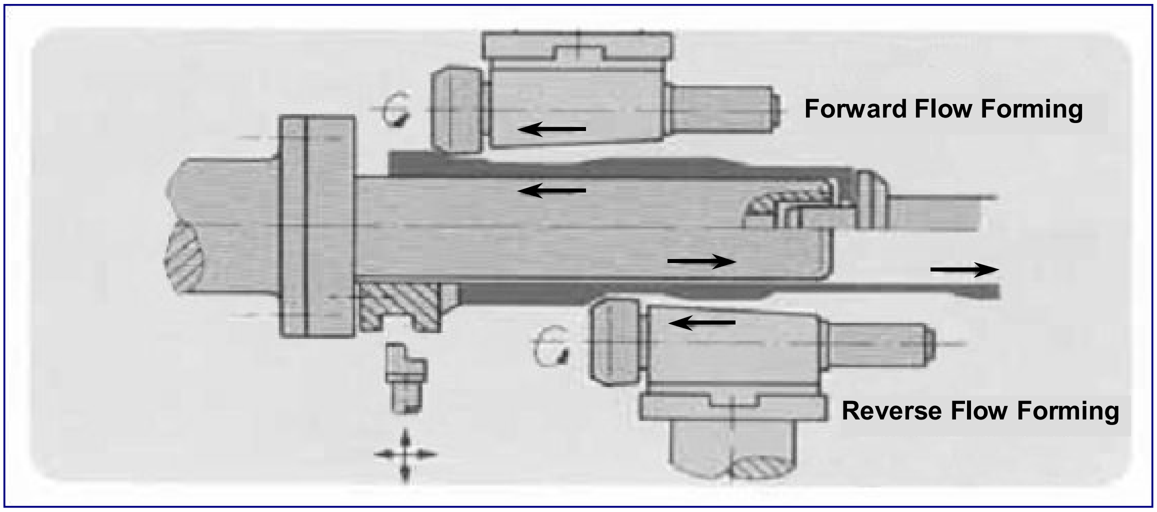

Figure 2: Principles of Flowforming

As an example, we consider here the case-gas generator of one of our engine (Figure 3). The thickness decreases from 1.168mm to 1.041mm, from the smallest (335.28mm) to the largest (388.42mm) outside diameters, respectively. The material is a ferritic/martensitic stainless steel SS410 (12.5%Cr, <0.75%Ni, <0.15%C). After machining/forming and final assembly, the cases are hardened and tempered to obtain the wished microstructure and hardness.

The traditional way would be to machine the case out of two or three forged rings to meet the thickness tolerances. The use of flowforming reduces the costs significantly by at least 30% (use of raw material and machining time) while respecting the drawing specifications.

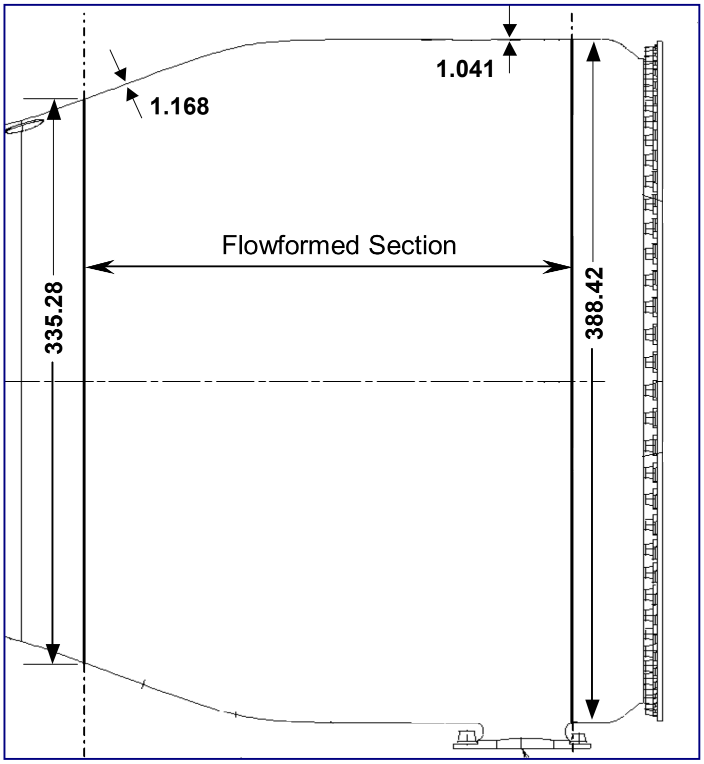

Figure 3: Case gas generator cross-section showing the flowformed section. The two extremities (flange and conical cylinder) are machined (due to complex internal features) and welded to the flowformed case - Dimensions in mm

Figure 4 shows the preform shape together with the mandrel geometry. The preform is obtained from deep drawing using a cold rolled and annealed sheet 2.795mm thick. The case is then flowformed in one pass using a two-roller flowforming machine, leading to a maximum reduction of about 63%. A full anneal then follows to recrystallise the microstructure (30 minutes at 745ºC, then gas cooled).

To compare microstructure and properties of the flowformed part with those of traditional machined components, specimens were extracted from a SS410 forged ring machined into a cylinder.

3.0 RESULTS AND DISCUSSION

In this section we will discuss four main topics: microstructure, tensile properties, crystallographic texture and low-cycle fatigue (LCF) life. Samples were extracted at various locations on the flowformed case (Figure 5). The microstructure of the flowformed and annealed material (Figure 6) exhibits very fine equiaxed ferritic grains with a grain size of about ASTM-11 (9µm) and hardness of 84 Rockwell B. No defects were detected. The presence of very fine grains is with no doubt the consequence of the work hardening experienced by the material during flowforming. The microstructures and hardnesses are very homogeneous along both the axial and circumferential directions.

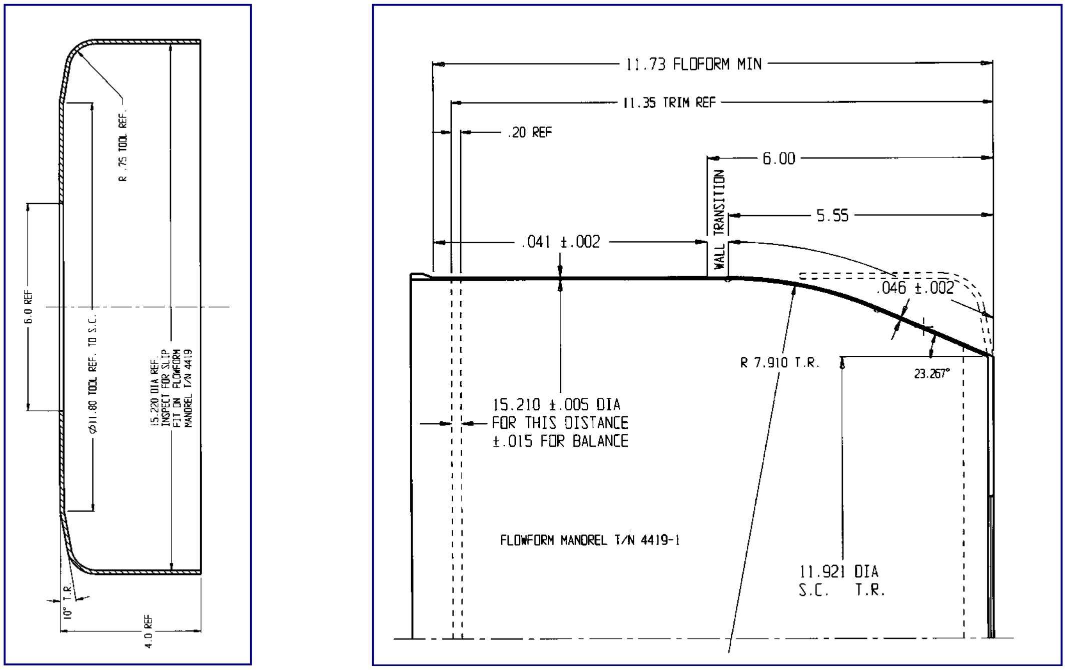

Figure 4: Preform shape and mandrel geometry (Courtesy of PMF-Industries) - Dimensions in inches

Mechanical properties were measured from small samples cut along the axial (L) and circumferential (T) directions at various positions (Figure 7 and Table 1). Tensile tests were performed at constant displacement (0.0212 mm/sec) at Ecole de Technologie Supérieure (Montréal, Canada) with a Messphysik video extensometer using a point measurement module. The positions (X and Y) of 3 points were recorded together with the force at 60Hz. The deformation was calculated from the average deformation of the 3 pairs of points.

The tensile data exceed by far the requirements of the aerospace specification AMS5504 for annealed SS410 sheet: a minimum of 207Mpa and 450-650Mpa for the yield and tensile strengths respectively, as well as a minimum of 15% elongation. These results are consistent with the very fine grain structure: the AMS standard specifies a grain size of ASTM-5 (72µm) or smaller. Additionally, it is clear from the results that the tensile properties are homogeneous throughout the part and that the effect of sample orientation can be neglected. Such conclusion, however, is postulated in the limit of resolution of the method: the sample size and curvature, as well as the small number of reference marks limit the accuracy of the results.

Tensile results hence suggest that the anisotropy of the material is weak. This conclusion is rather surprising as the flowforming process introduces relatively large deformations in the case. Unfortunately, the as-deformed material is currently unavailable. However, we can assume that the recrystallisation mechanism is such that it favours the occurrence and growth of a large spectrum of nuclei that randomise the texture.

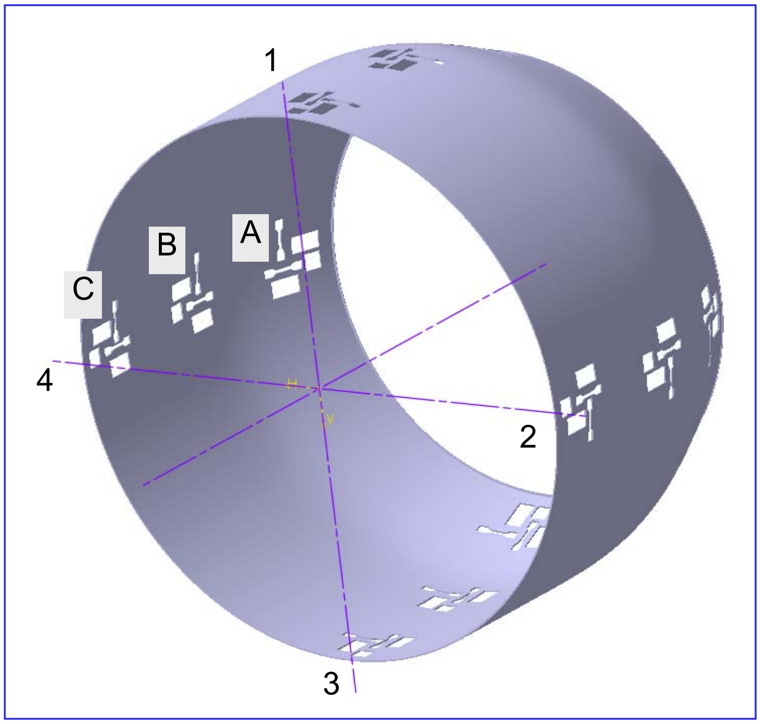

Figure 5: Sample extraction (1=initial rolling direction). Rectangular samples are cut for metallographic and crystallographic texture investigations. Gauge geometry of small tensile samples: 2.5mmx10mmxthickness. Samples are identified using numbers and letters, along circumferential and axial directions, respectively.

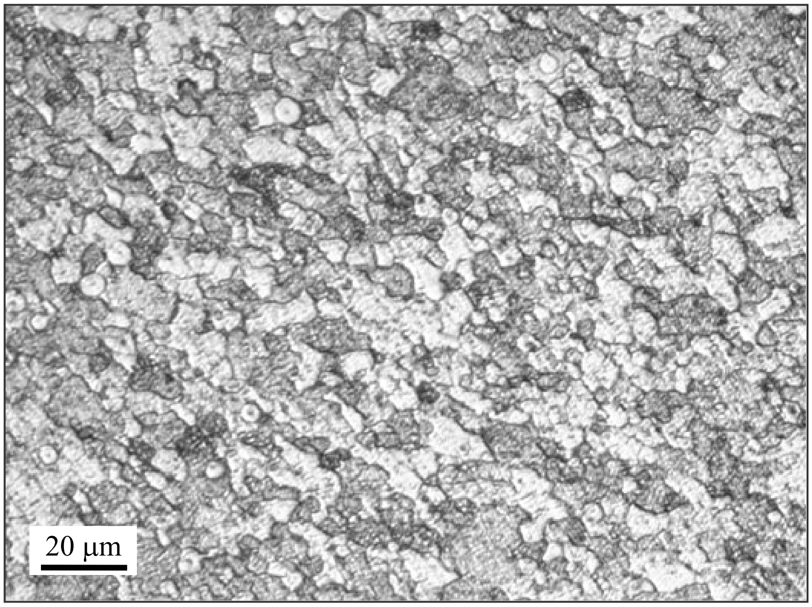

Figure 6: Microstructure of flowformed and annealed case (Sample B1)

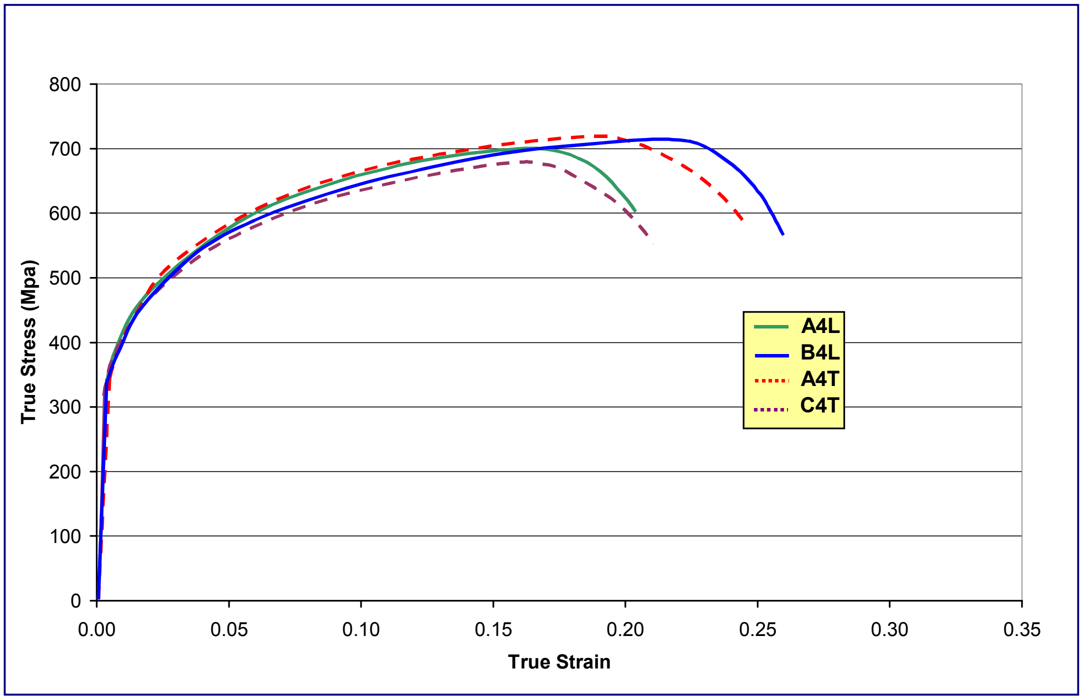

Figure 7: Tensile results from samples taken along the axial direction 4 of flowformed case (L=axial direction, T=circumferential direction)

Sample	A1L	A1T	A3L	A3T	A2L	A2T	A4L	A4T
Yield (Mpa)	350	365	330	330	360	360	350	350
UTS (Mpa)	727	696	717	706	714	702	703	721
strain at UTS	0.21	0.14	0.18	0.16	0.19	0.18	0.16	0.19
Sample	**B1L**	**B1T**	**B3L**	**B3T**	**B2L**	**B2T**	**B4L**	**B4T**
Yield (Mpa)	350	360	370	330	350	-	340	-
UTS (Mpa)	662	684	681	718	693	702	719	752
strain at UTS	0.14	0.13	0.14	0.21	0.13	0.15	0.21	0.22
Sample	**C1L**	**C1T**	**C3L**	**C3T**	**C2L**	**C2T**	**C4L**	**C4T**
Yield (Mpa)	345	340	360	-	-	355	365	340
UTS (Mpa)	716	703	688	-	697	706	697	682
strain at UTS	0.23	0.21	0.17	-	0.19	0.18	0.17	0.16

Table 1: Tensile test data of all samples of the flowformed case (L=axial direction, T=circumferential direction). Results of samples 1/3 and 2/4 are presented together as they correspond to symmetrical positions on the case: 0º/180º and 90º/270º, respectively

To confirm this, crystallographic textures were determined from pole figures measured at McGill University (Montréal, Canada). The orientation distribution functions (ODF's) were calculated from three incomplete pole figures, (110), (200), (211), using the series expansion method [1] and ghost corrected using the exponential method [2]. The ODF sections at φ2=45º show that the textures are effectively weak and do not vary significantly along the circumferential direction but only slightly along the axial direction (Figure 8). It consists of a dominant gamma fibre (all orientations whose (111) plane normals are parallel to the radial direction), with the Goss- (011)<100> and cube- (001)<100> texture components. These ODF's are similar to the ones obtained after rolling (at intermediate reductions) and recrystallisation of alpha steels [3]. Before drawing more conclusions, the as-deformed textures and orientation imaging mapping (OIM) investigations will have to be performed.

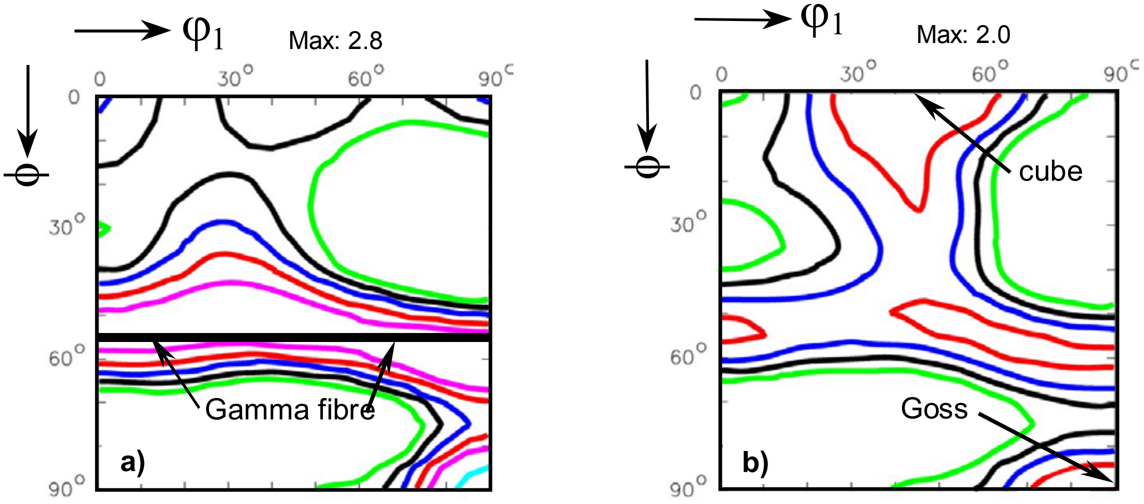

Figure 8: φ2=45° ODF-sections of a) A1 sample and b) C1 sample, showing the gamma-fibre, cube and Goss texture components (flowformed case). Intensity levels: 1-1.2-1.5-1.7-2.0-2.5

The resulting properties can only be close to isotropic. It should be noted that the presence of a uniform gamma-fibre (independently of its intensity) does not induce planar anisotropy [4]. The fact that flowforming and rolling textures share similar features, at least after recrystallisation, adds more conviction to the affirmation that both flowforming and rolling are plane-strain processes (the rolling and transverse directions being replaced by the axial and circumferential directions, respectively) [5].

In the engine program under consideration, we decided not to take into account LCF tests on specimens extracted from the flowformed case, due to concerns related to the curvature in the specimens. Attempt to "flatten" these specimens would have altered the process and made the test data interpretation problematic. We therefore decided to complete the LCF test with a complete flowformed case subjected to the maximum possible pressure. The test assembly completed 120,000 cycles with no crack initiated, substantiating 30,000-mission life with a scatter factor of 4.

3.1 Comparison with machined case

The microstructure of the forged SS410 ring consists of a mixture of ferritic and tempered martensitic grains (Figure 9). The microstructure exhibits more or less equiaxed grains with a grain size of ASTM-8 (25µm) and hardness of 84.5 Rockwell B. The fact that the forged microstructure (ferrite and martensite) is not harder than the flowformed one (only ferrite) could be explained by its coarser grain size.

The yield stresses are comparable for the machined and flowformed parts. The ultimate stresses, however, are higher by about 40Mpa in the machined part, probably due to the presence of martensite in the forged material (Figure 10 and Table 2). Finally, as expected, the crystallographic texture is nearly random with a maximum orientation density or probability f(g)=1.6 (Figure 11). The material is nearly perfectly isotropic.

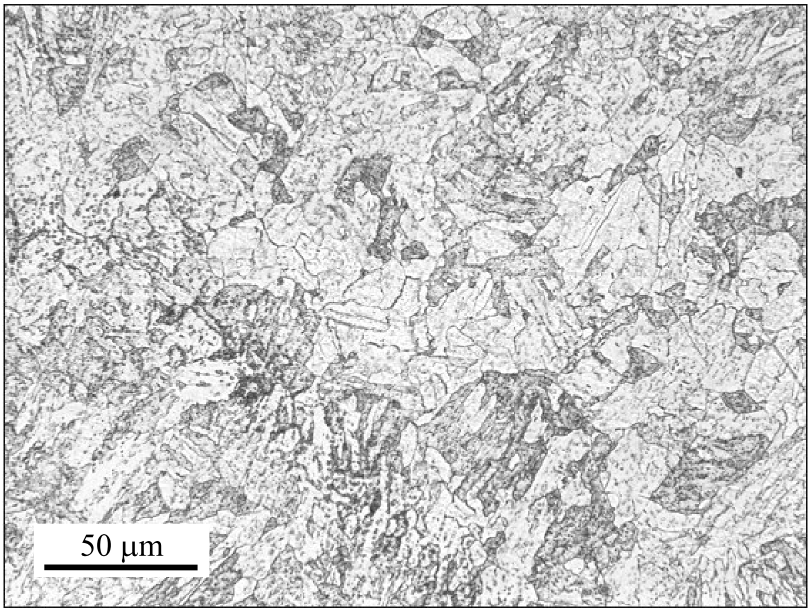

Figure 9: Microstructure of forged ring

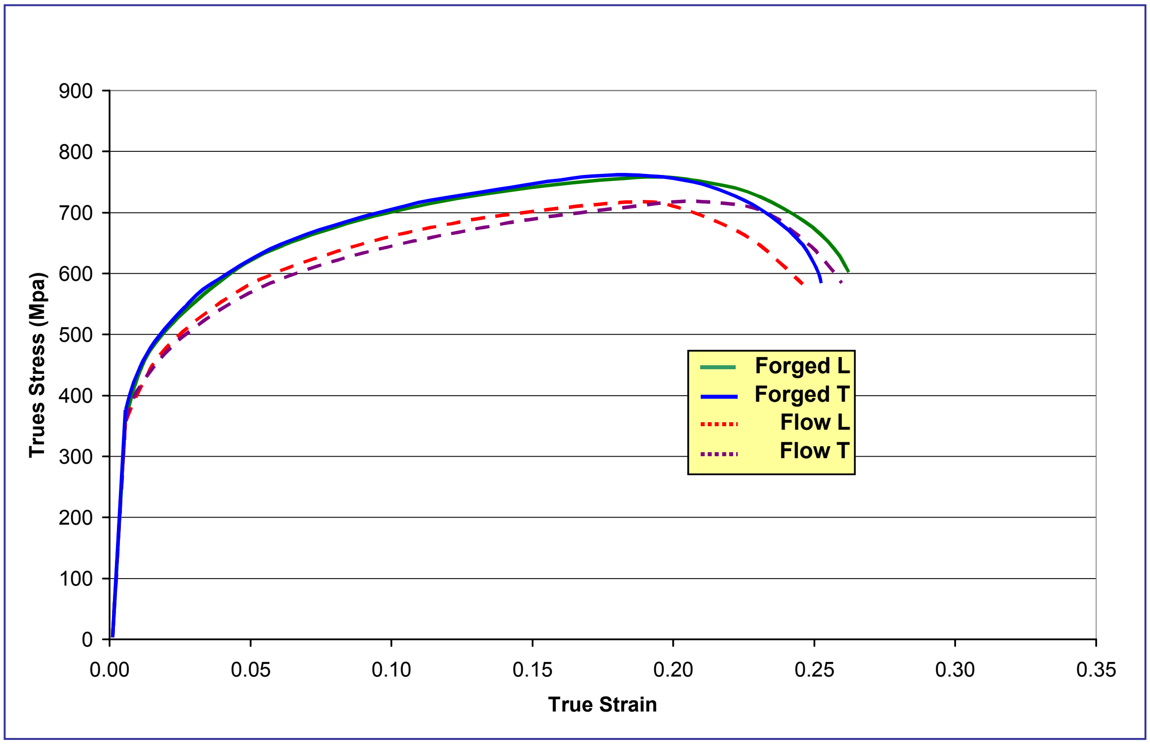

Figure 10: Tensile test results of samples taken in the flowformed case and forged ring (L=axial direction, T=circumferential direction)

Sample	Flowformed L	Forged L
Yield (Mpa)	340	365
UTS (Mpa)	719	758
strain at UTS	0.21	0.20
Sample	**Flowformed T**	**Forged T**
Yield (Mpa)	350	340
UTS (Mpa)	721	763
strain at UTS	0.19	0.20

Table 2: Tensile test data of flowformed and machined samples (L=axial direction, T=circumferential direction)

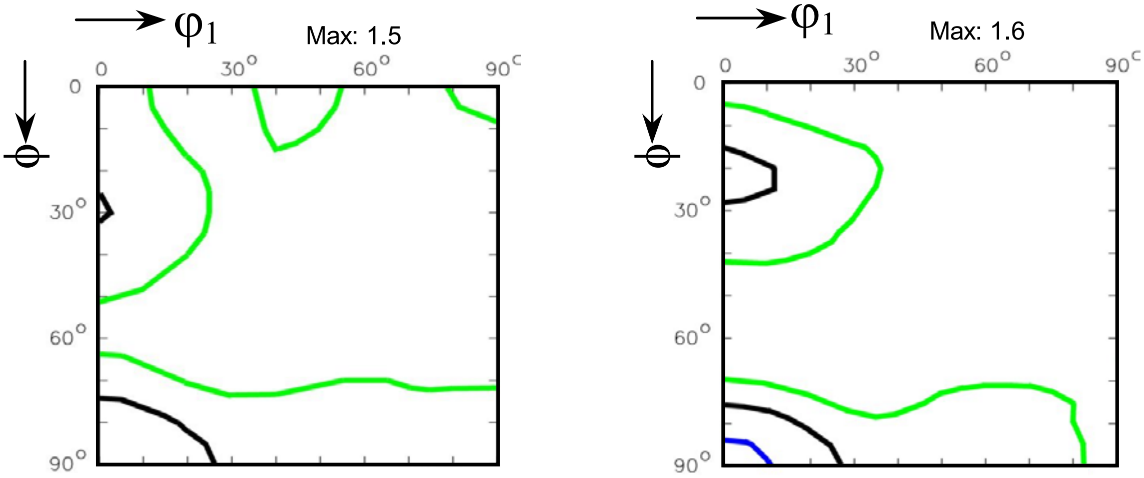

Figure 11: φ2=45° ODF-sections samples taken at two locations on a forged ring. Intensity levels: 1-1.2-1.5

3.2 Hardened Condition

After forming/machining and assembly, the case-gas generator is hardened-tempered to give the material its final properties. The case is first held in the austenite range at 980°C for an hour and forced gas cooled, followed by a treatment to temper the martensite (580°C for two hours). The material hardness target ranges from 26 to 32 Rockwell C.

The microstructures of flowformed and machined samples are close in terms of phase distribution and “grain size” with a somewhat finer structure for the forged part (Figure 12). The hardnesses reach 31 and 30 Rockwell C for the flowformed and machined samples, respectively.

The yield stresses are comparable for the machined and flowformed parts. The ultimate stresses, however, are slightly higher by about 15-20Mpa in the machined part, reflecting the finer microstructure in the forged material (Figure 13 and Table 3). Crystallographic textures were not measured. However, as the textures were already weak (before harden and temper treatment), they should be even closer to random after experiencing two phase-transformations (ferrite to austenite to martensite).

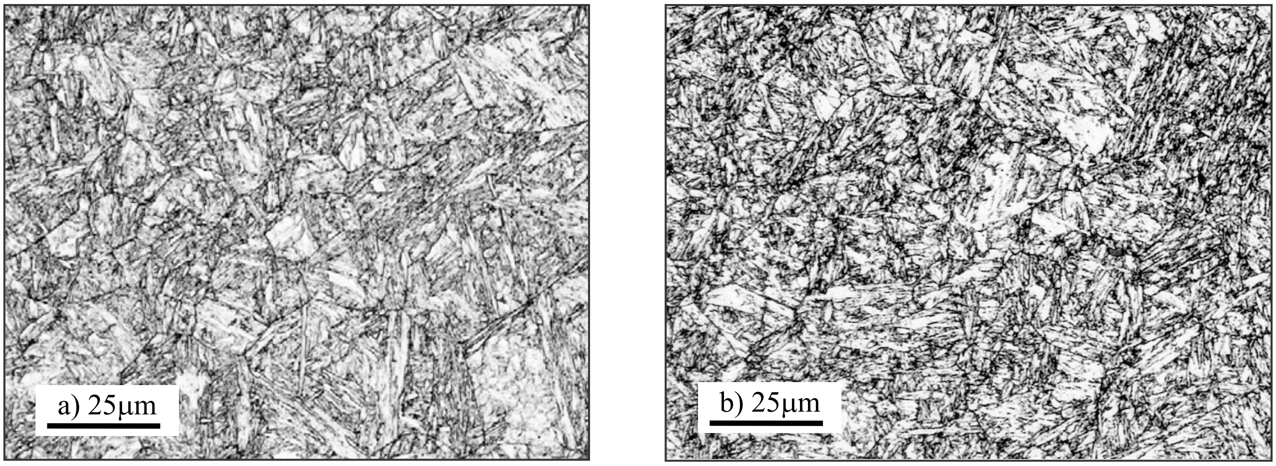

Figure 12: Microstructure in the hardened condition of a) flowformed part and b) machined part

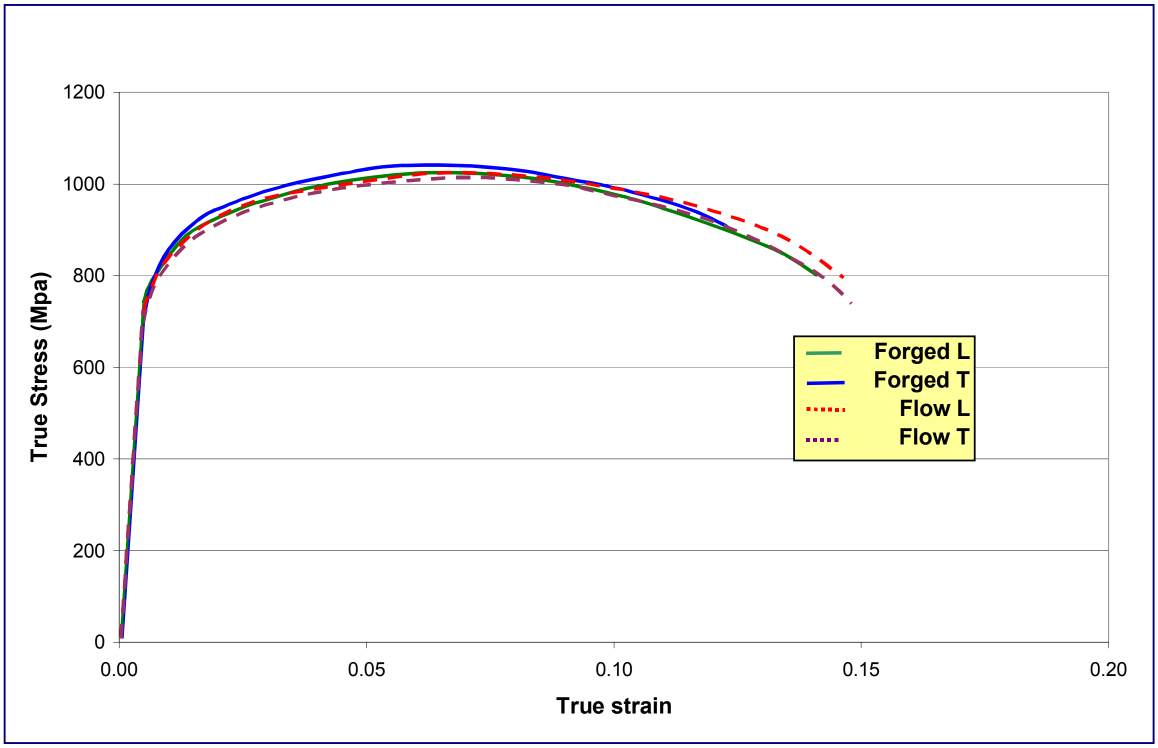

Figure 13: Tensile test results of samples taken in the flowformed case and forged ring in the hardened condition (L=axial direction, T=circumferential direction)

Sample	Flow C3 L	Flow C2 L	Forged 1 L	Forged 2 L
Yield (Mpa)	720	730	720	730
UTS (Mpa)	1030	1016	1058	1031
strain at UTS	0.07	0.09	0.09	0.07
Sample	**Flow C3 T**	**Flow C1 T**	**Forged 1 T**	**Forged 2 T**
Yield (Mpa)	730	720	730	720
UTS (Mpa)	1018	1023	1041	1042
strain at UTS	0.08	0.08	0.07	0.09

Table 3: Tensile test data of flowformed and machined samples in the hardened condition (L=axial direction, T=circumferential direction)

4. CONCLUSIONS

Flowforming is an alternative forming method to produce axisymmetric parts at lower costs than the traditional machining of forged rings. Because of the work hardening that the flowformed part experiences, the microstructure is finer and mechanical properties are better (higher yield and ductility). However, after martensitic phase transformation, the resulting microstructure and properties are equivalent.

Flowforming of pressure vessels in SS410 is therefore a safe forming process as long as the forming parameters and the initial sheet properties are controlled (locked process) once the process has been qualified to ensure reproducibility.

ACKNOWLEDGEMENTS

The author wish to thank Mark Beauregard and Mélissa Després of Pratt & Whitney Canada for the numerous discussions and results used in this paper as well as to Kenneth Healy from PMF-Industries who provided us flowformed cases for this investigation.

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MEETING DISCUSSION – PAPER NO: 22

Author: J. Savoie

Discusser: C. Bampton

Question: 1. What are ID and OD surface finishes? 2. Can you join flanges by inertia welding?

Response: 1. ID surface finish is comparable to the one of deep drawn parts. OD finish is rougher - roller lines. 2. Could be a possibility for thick parts. However, case-gas-generators walls can be thin (1-1.5 mm). In that case, inertia welding might be difficult.