Flow Forming of Aircraft Engine Components

Jean Savoie
Pratt & Whitney Canada
1000 Marie Victorin, Longueuil
Québec J4G 1A1
CANADA

jean.Savoie@pwc.ca

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.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
MAY 2006	**N/A**	**-**

4. TITLE AND SUBTITLE	
Flow Forming of Aircraft Engine Components	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Pratt & Whitney Canada 1000 Marie Victorin, Longueuil Québec J4G 1A1 CANADA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202748. Cost Effective Manufacture via Net Shape Processing (Rentabilite de fabrication par un traitement de finition immediate), The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**65**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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.

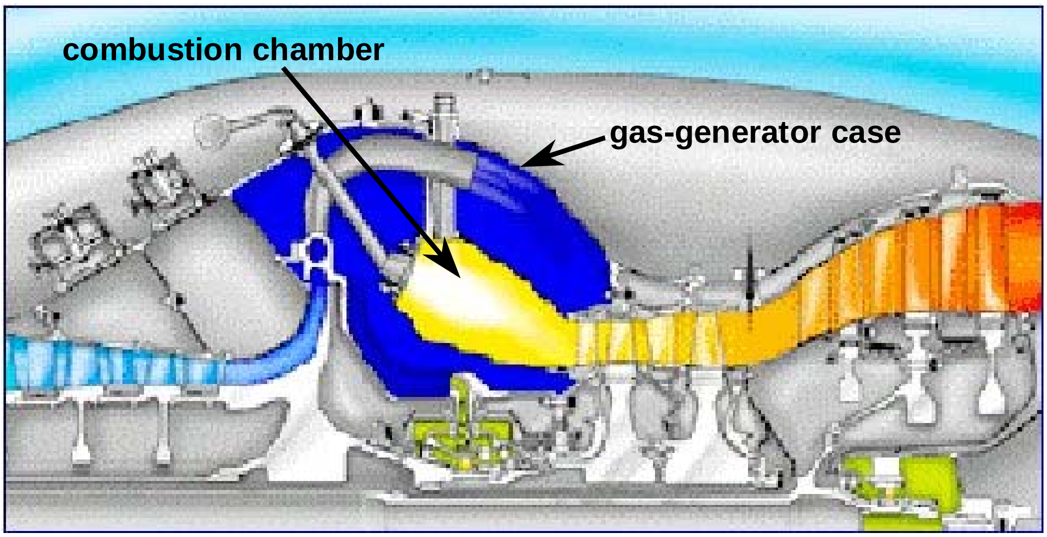


Figure 1: Cross-section of part of a turbo-fan

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.

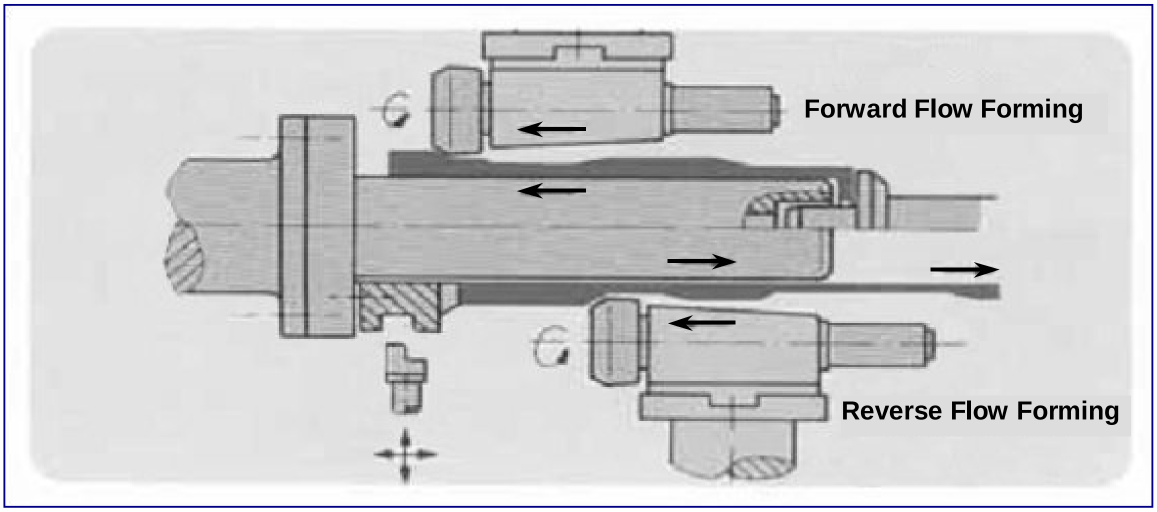


Figure 2: Principles of Flowforming

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.

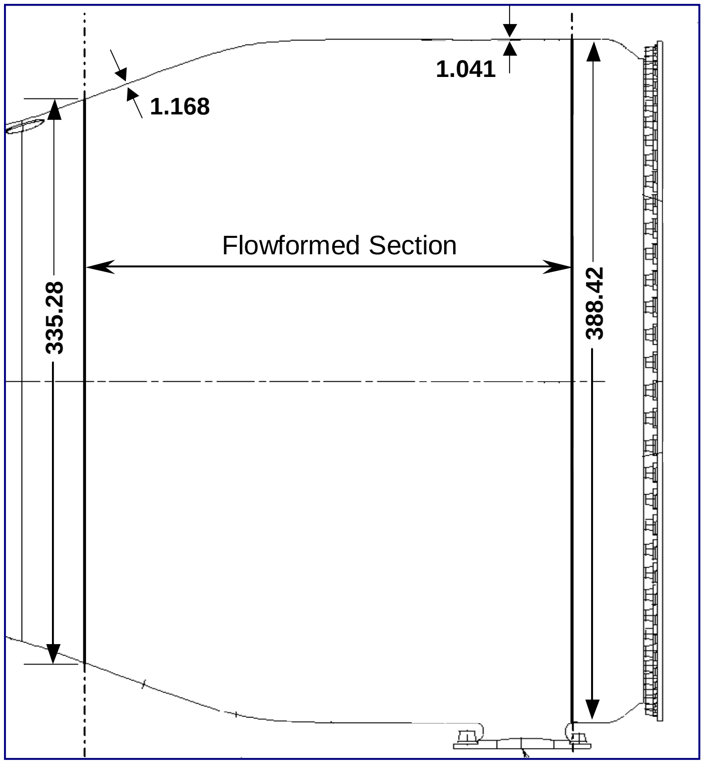


Figure 3: Case gas generator cross-section showing the flowformed section. The two extremities (flange and conical cylinder) are machined (due to complex internal features) and welded to the flowformed case - Dimensions in mm

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.

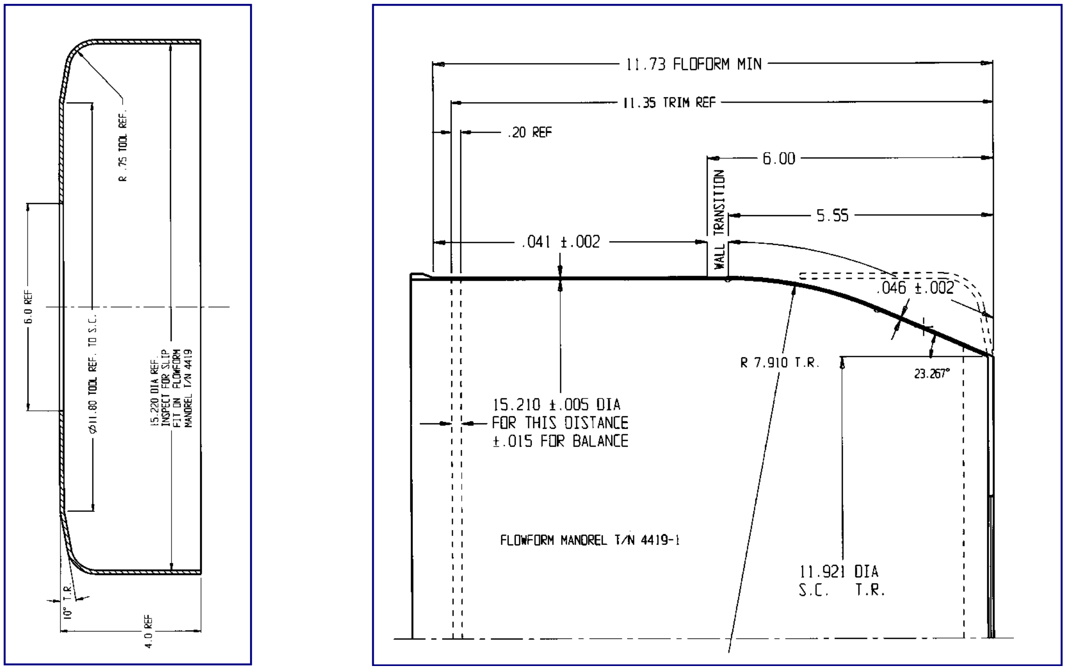


Figure 4: Preform shape and mandrel geometry (Courtesy of PMF-Industries) - Dimensions in inches

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.

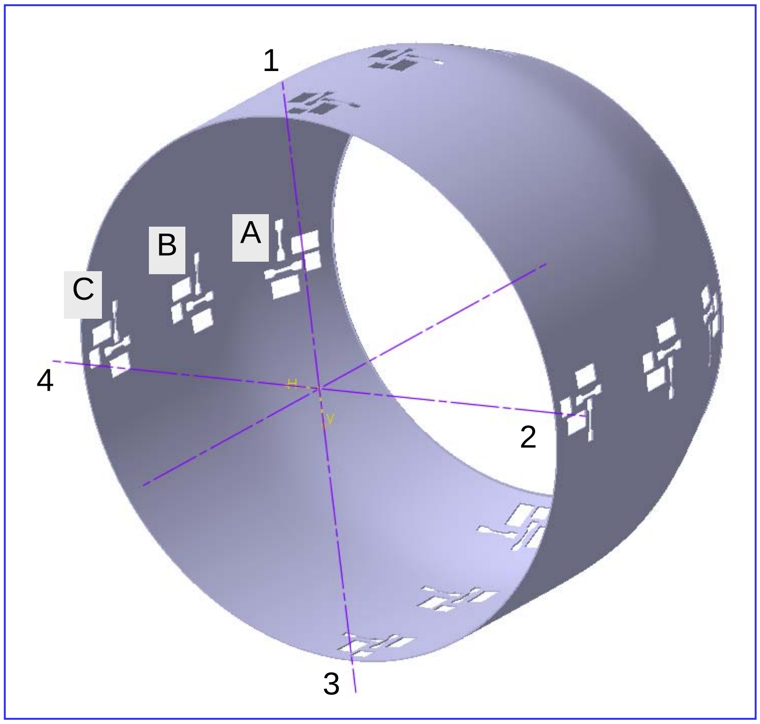


Figure 5: Sample extraction (1=initial rolling direction). Rectangular samples are cut for metallographic and crystallographic texture investigations. Gauge geometry of small tensile samples: 2.5mmx10mmxthickness. Samples are identified using numbers and letters, along circumferential and axial directions,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

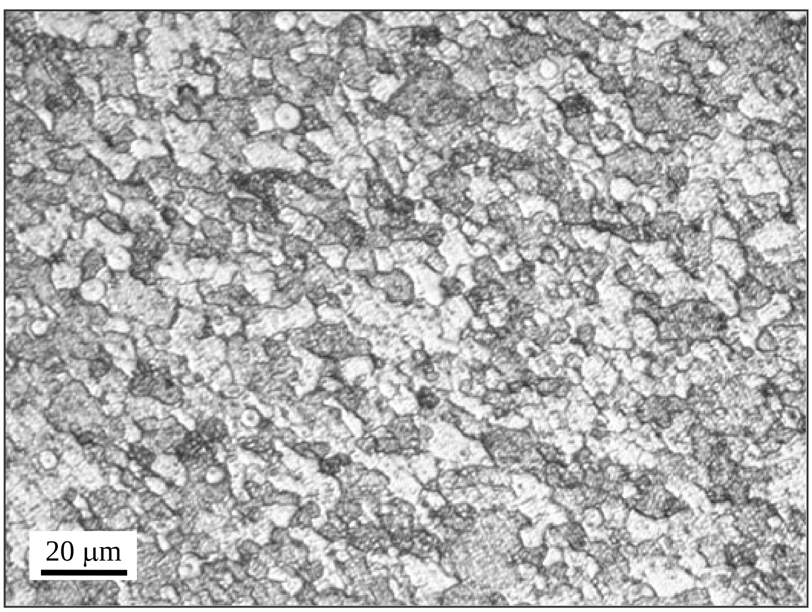


Figure 6: Microstructure of flowformed and annealed case (Sample B1)

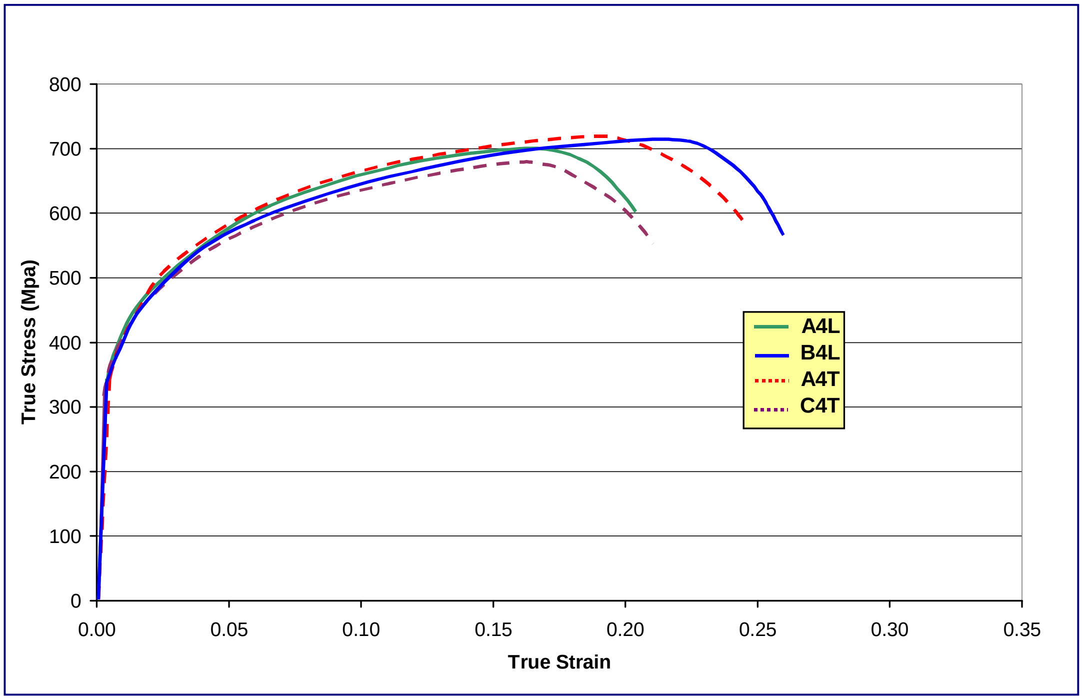


Figure 7: Tensile results from samples taken along the axial direction
4 of flowformed case (L=axial direction, T=circumferential direction)

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.

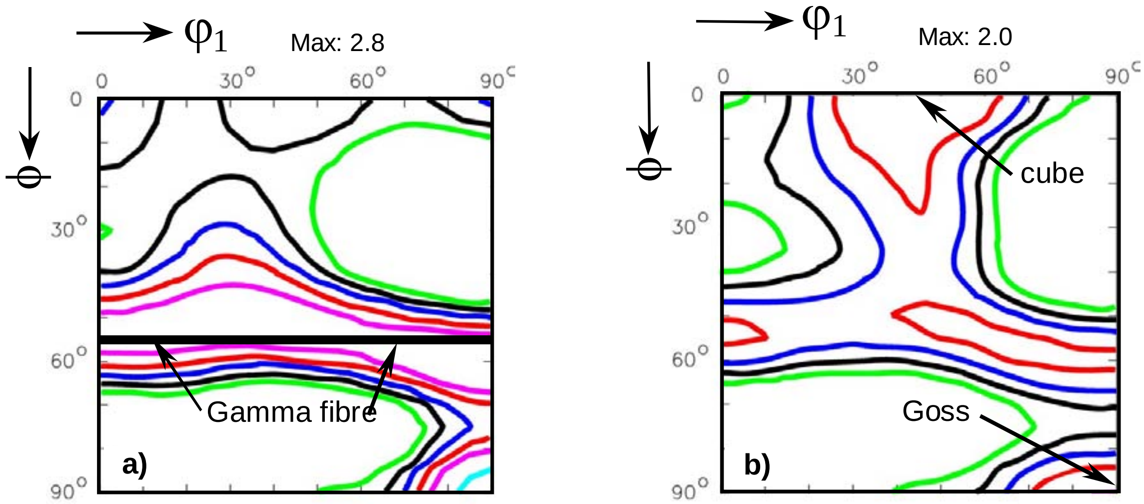


Figure 8: φ2=45º ODF-sections of a) A1 sample and b) C1 sample, showing the gamma-fibre, cube and Goss texture components (flowformed case). Intensity levels: 1-1.2-1.5-1.7-2.0-2.5

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.

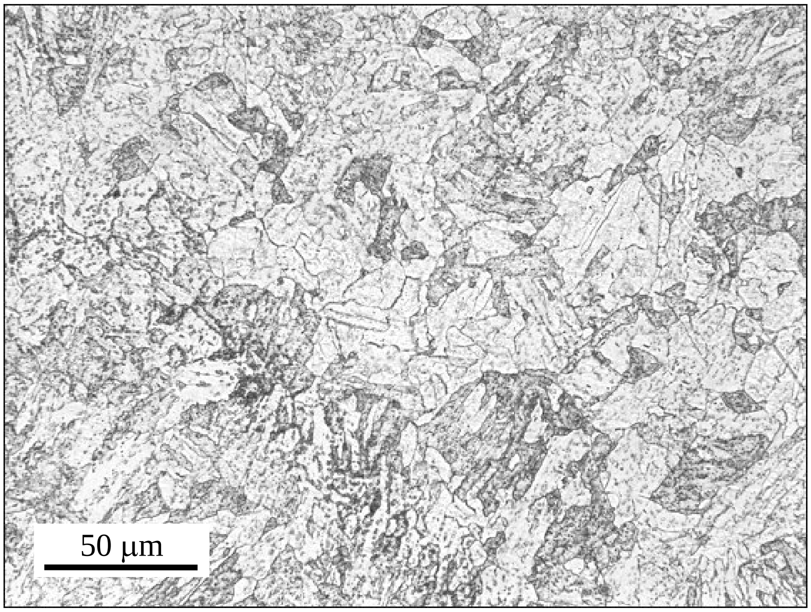


Figure 9: Microstructure of forged ring

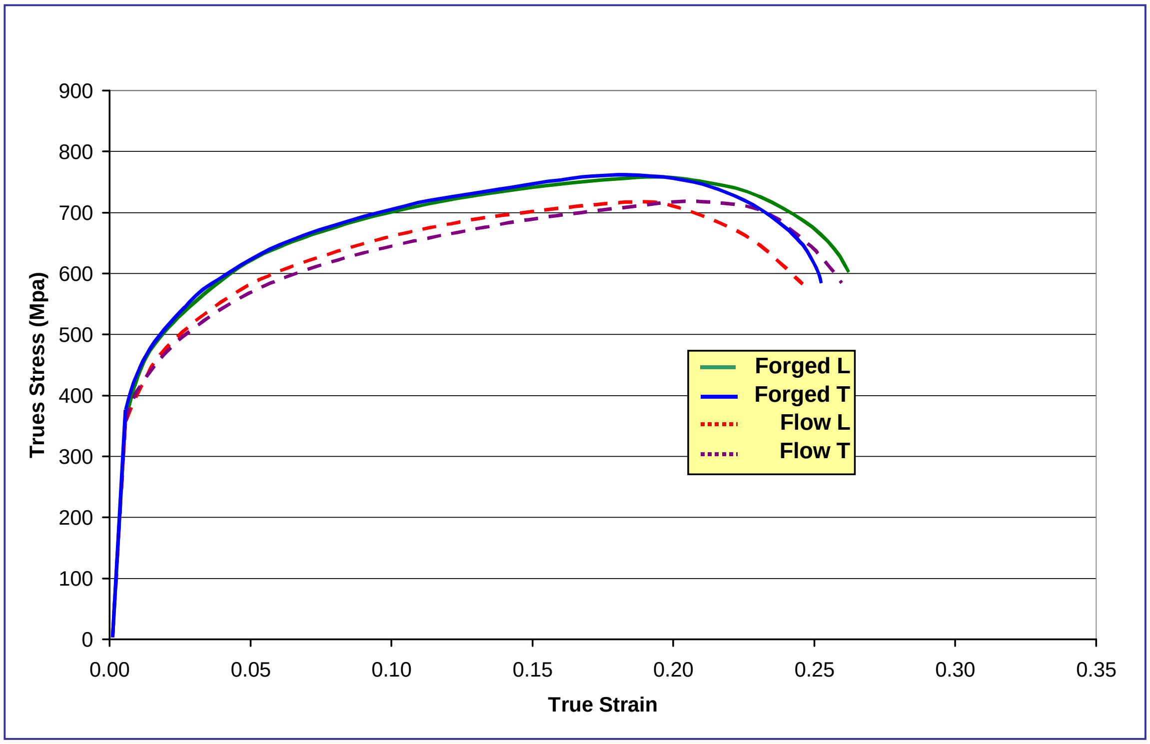


Figure 10: Tensile test results of samples taken in the flowformed case and forged ring (L=axial direction, T=circumferential direction)

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)

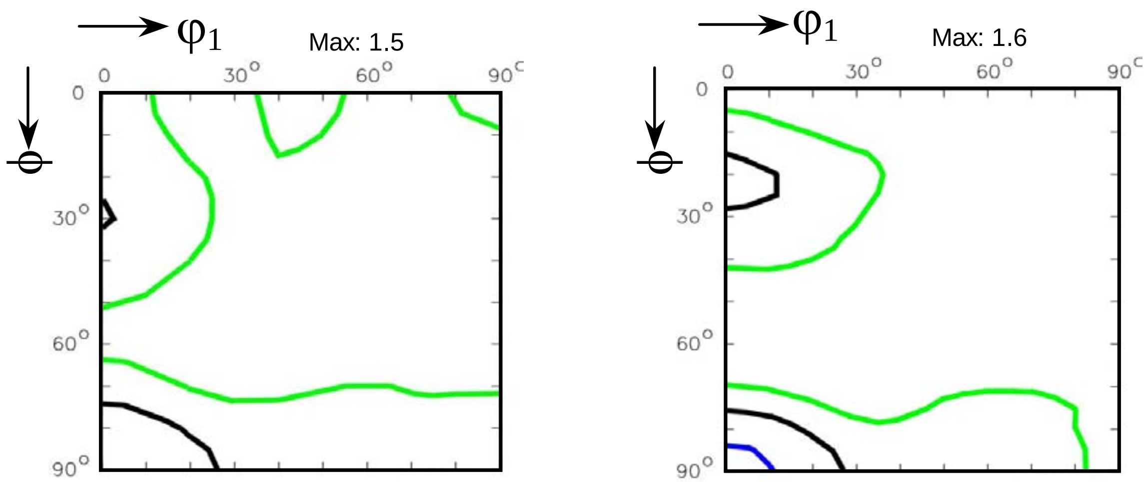


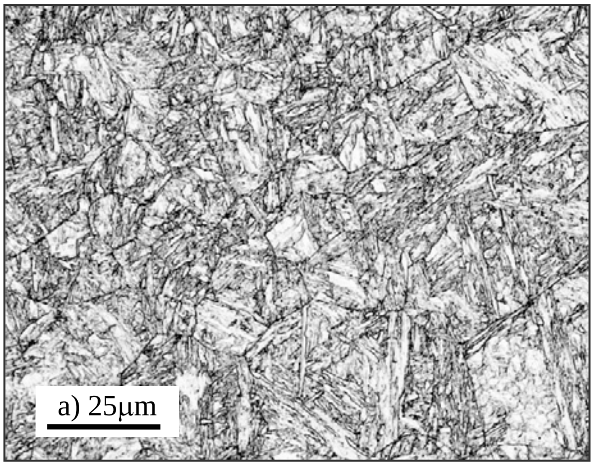
Figure 11: φ2=45º ODF-sections samples taken at two locations on a forged ring. Intensity levels: 1-1.2-1.5

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).



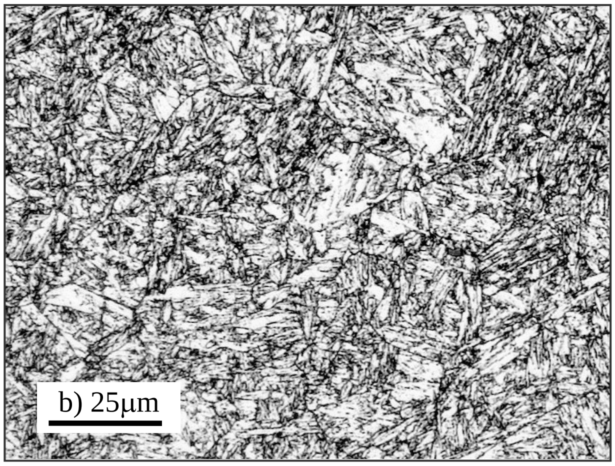


Figure 12: Microstructure in the hardened condition of a) flowformed part and b) machined part

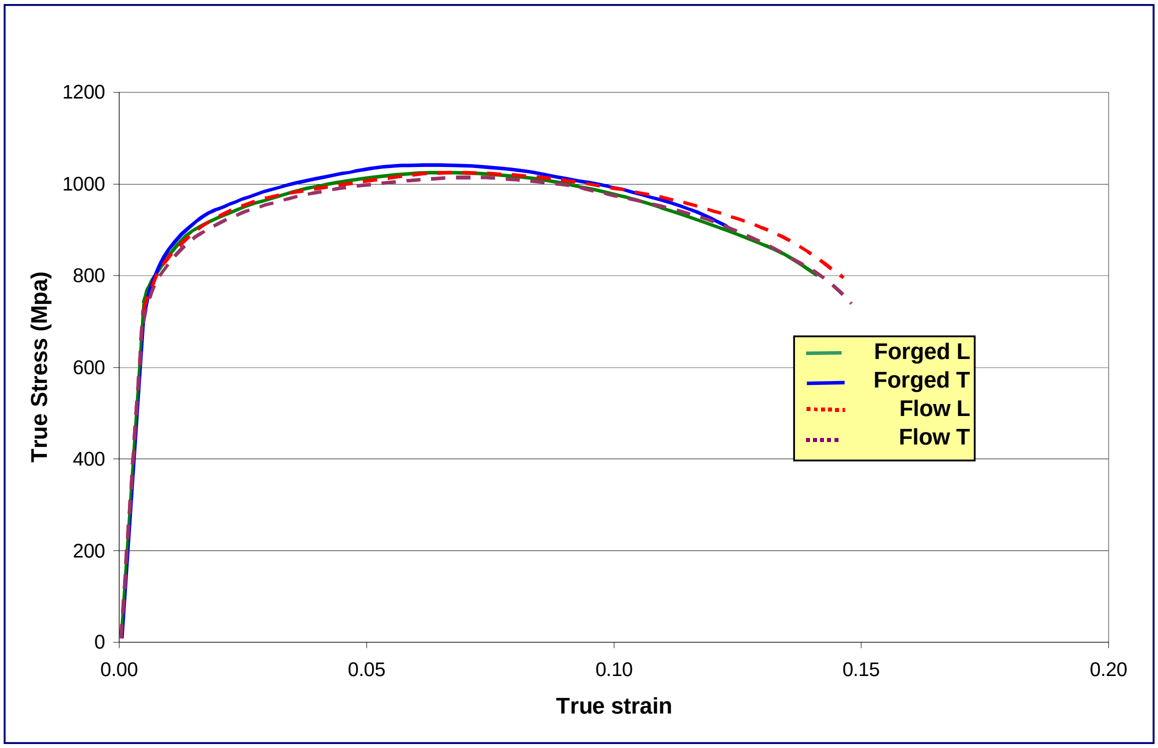


Figure 13: Tensile test results of samples taken in the flowformed case and forged ring in the hardened condition (L=axial direction, T=circumferential direction)

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.

REFERENCES

[1] H.J. Bunge; Texture Analysis in Materials Science (ed. Butterworths, London, 1982)
[2] P. Van Houtte; *Text. Microstruct.* **13** (1991), p.199
[3] L.S. Toth, J.J. Jonas, D. Daniel and R.K. Ray; *Metall. Trans.* **21A** (1990), p.2985
[4] D. Daniel, J. Savoie and J.J. Jonas; *Acta Metall. Mater.* **41** (1993), p.1907
[5] C.C. Wong, T.A. Dean and J. Lin; *Int. J. Machine Tools & Manufacture* **43** (2003), pp.1419

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.

Flow Forming of Aircraft Engine Components

Jean Savoie

Pratt & Whitney Canada

INTRODUCTION

- Aircraft engine components are assemblies of several parts that are manufactured using various processes: deep drawing, machining …
- Deep drawing can require expensive tooling and is performed in numerous steps, increasing lead-time.
- With 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.

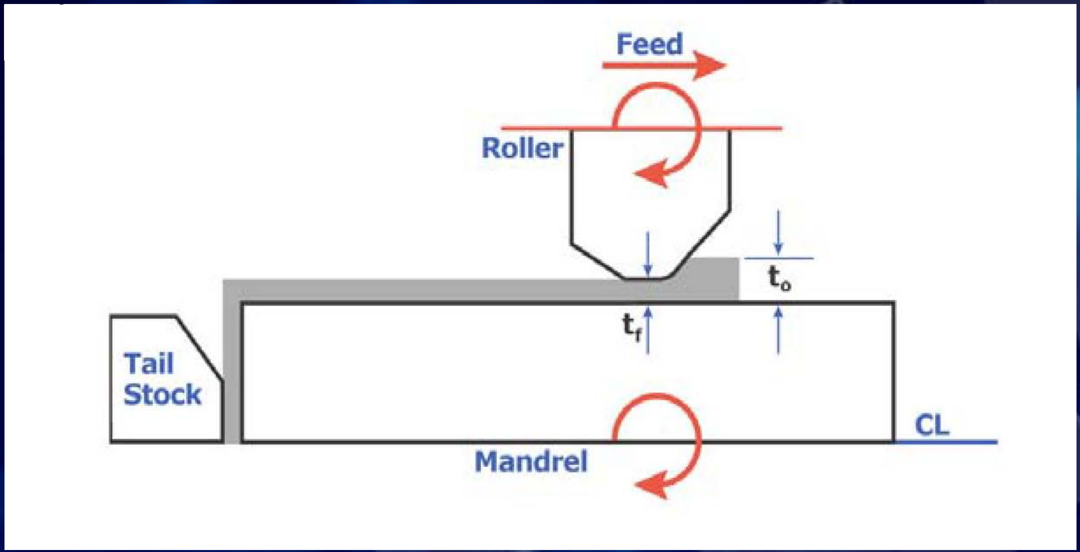
INTRODUCTION

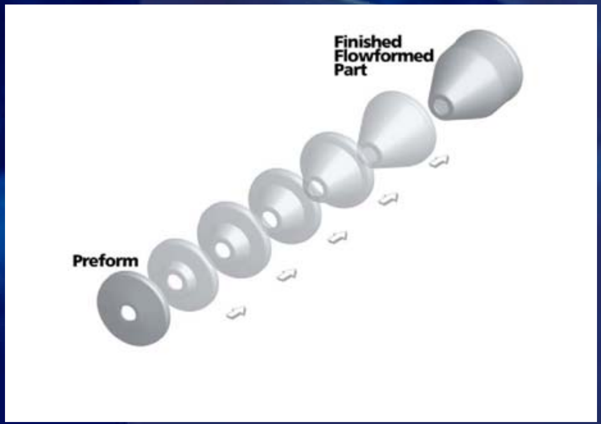
- For these reasons, the use of near net shape manufacturing methods is becoming inevitable.
- An alternative forming process is here investigated: flow-forming, process well adapted to axisymmetric parts (reduction of forming steps, welding and machining).
- Metallurgical and mechanical properties of a flowformed case will be presented and compared with material characteristics of parts manufactured by machining of forged rings.

OUTLINE

- Flowforming process
- Case study: case gas generator
- Metallurgical and mechanical properties of the flowformed and annealed case (before hardening)
- Comparison with machined case (before hardening)
- Hardened condition
- Conclusions and further work

FLOWFORMING





- Form rotationally symmetrical hollow parts. A compressive force is applied 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.

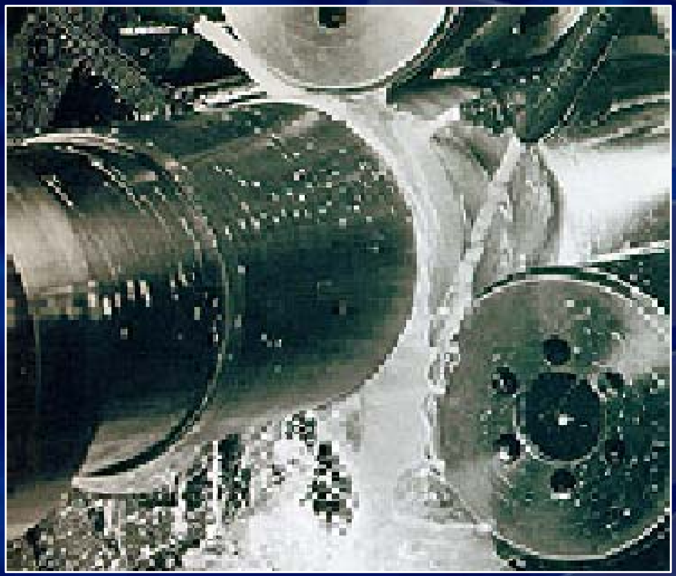
Basic Principle of Flow-forming (forward)

FLOWFORMING

Flow-forming Machine (Leifeld ST65-132)

Min. dia. 1.2 in.; max. dia 25.6 in.; max length 118 in.

FLOWFORMING



Key process parameters:

- Preform shape (and process)
- Mandrel shape
- Mandrel angular velocity
- Feed rate (axial velocity)
- Roller shape and layout
- Number of rollers
- Number of passes
- Final annealing

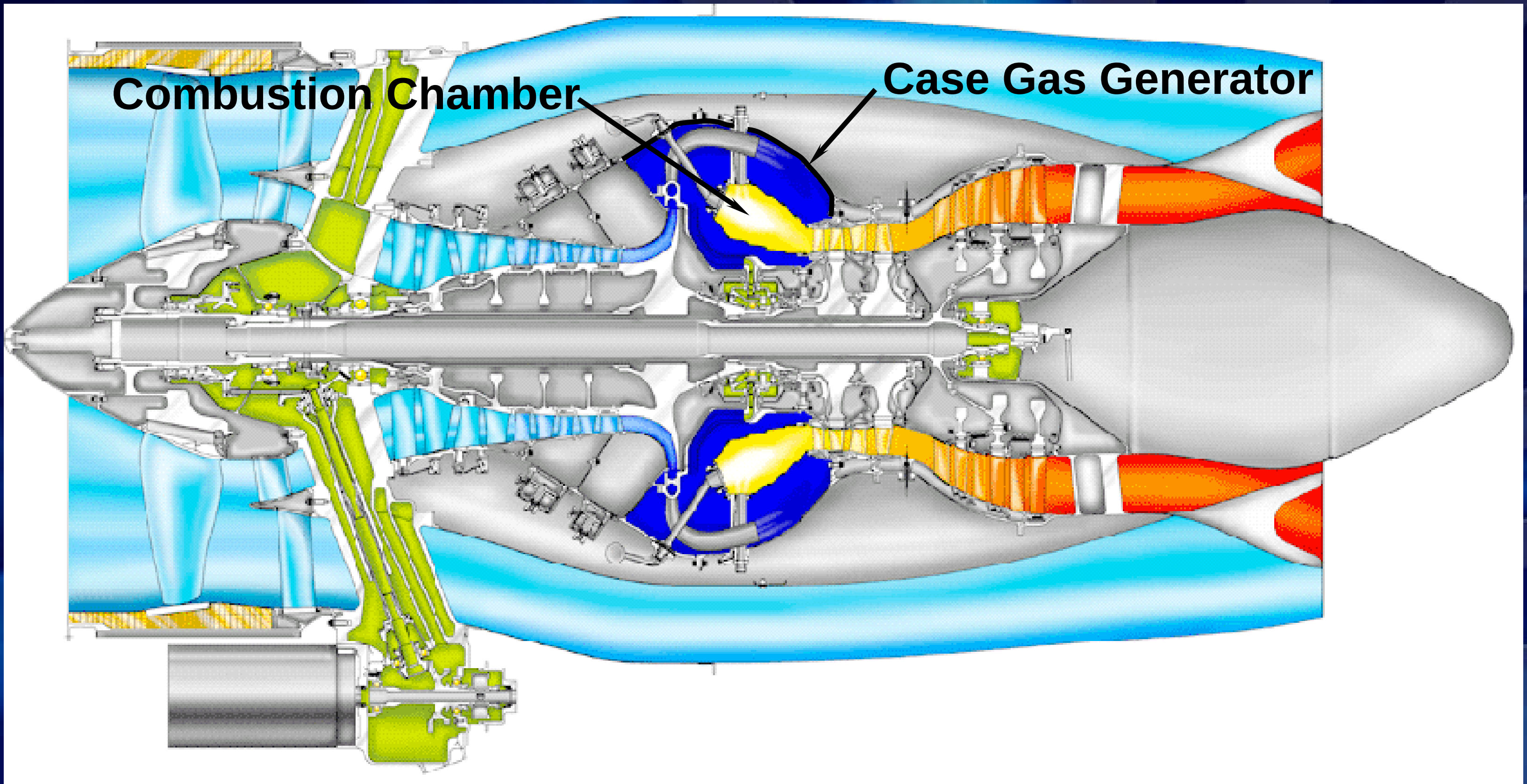
FLOWFORMING

- Flowforming can produce parts of varying wall thicknesses as well as varying internal diameters.
- Most engines 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.

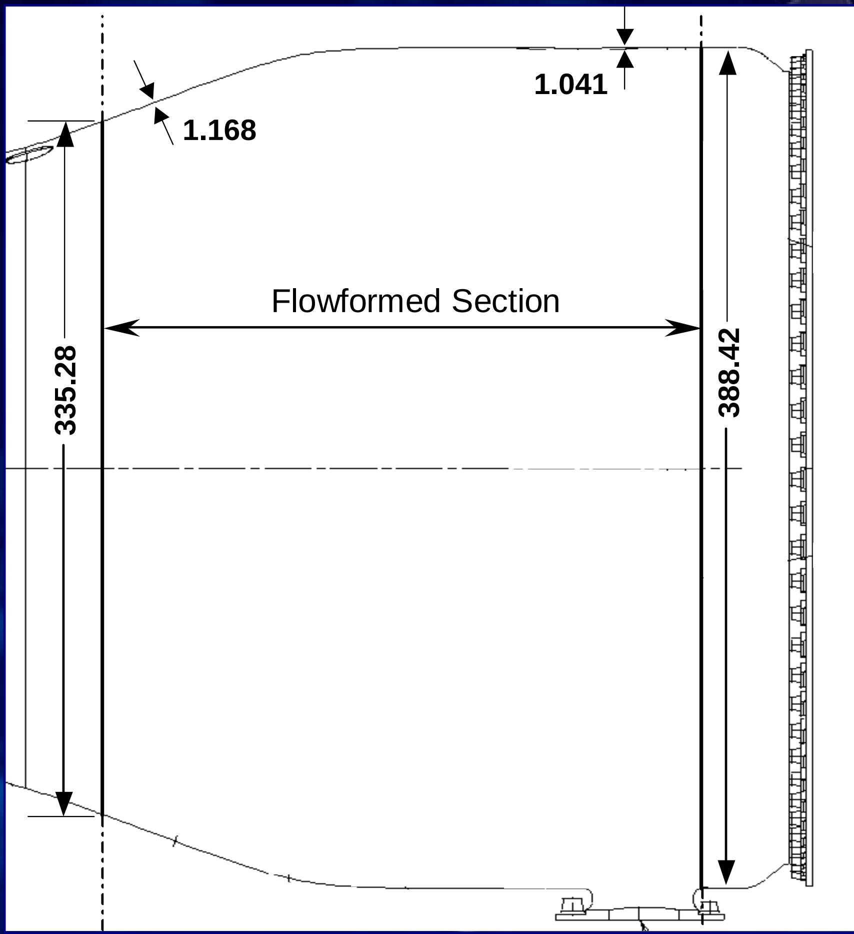
CASE STUDY: GAS GENERATOR CASE

- **Gas-generator cases belong to components well suited for flowforming. They hold the pressurized air from the compressor and force it to flow inside the combustion chamber.**
- **They are thus pressure vessels subjected to cyclic stresses and relatively high temperatures. Hence, metallurgical and mechanical properties are critical.**

Cross Section of a Turbofan



CASE STUDY: GAS GENERATOR CASE

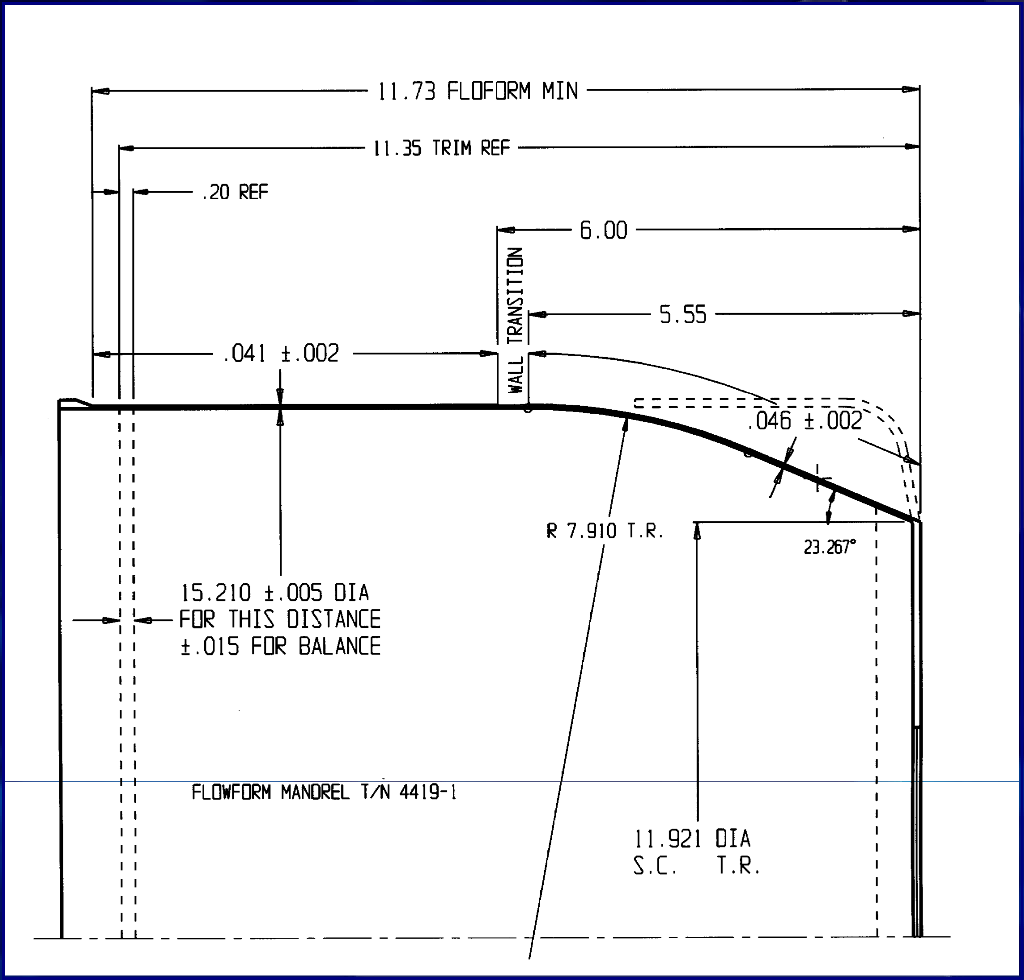


• Material is a ferritic/martensitic stainless steel SS410 (12.5%Cr, <0.75%Ni, <0.15%C).

• After machining/forming and final assembly, the cases are hardened and tempered to obtain the wished microstructure and hardness.

Case Gas Generator of one of our engine

CASE STUDY



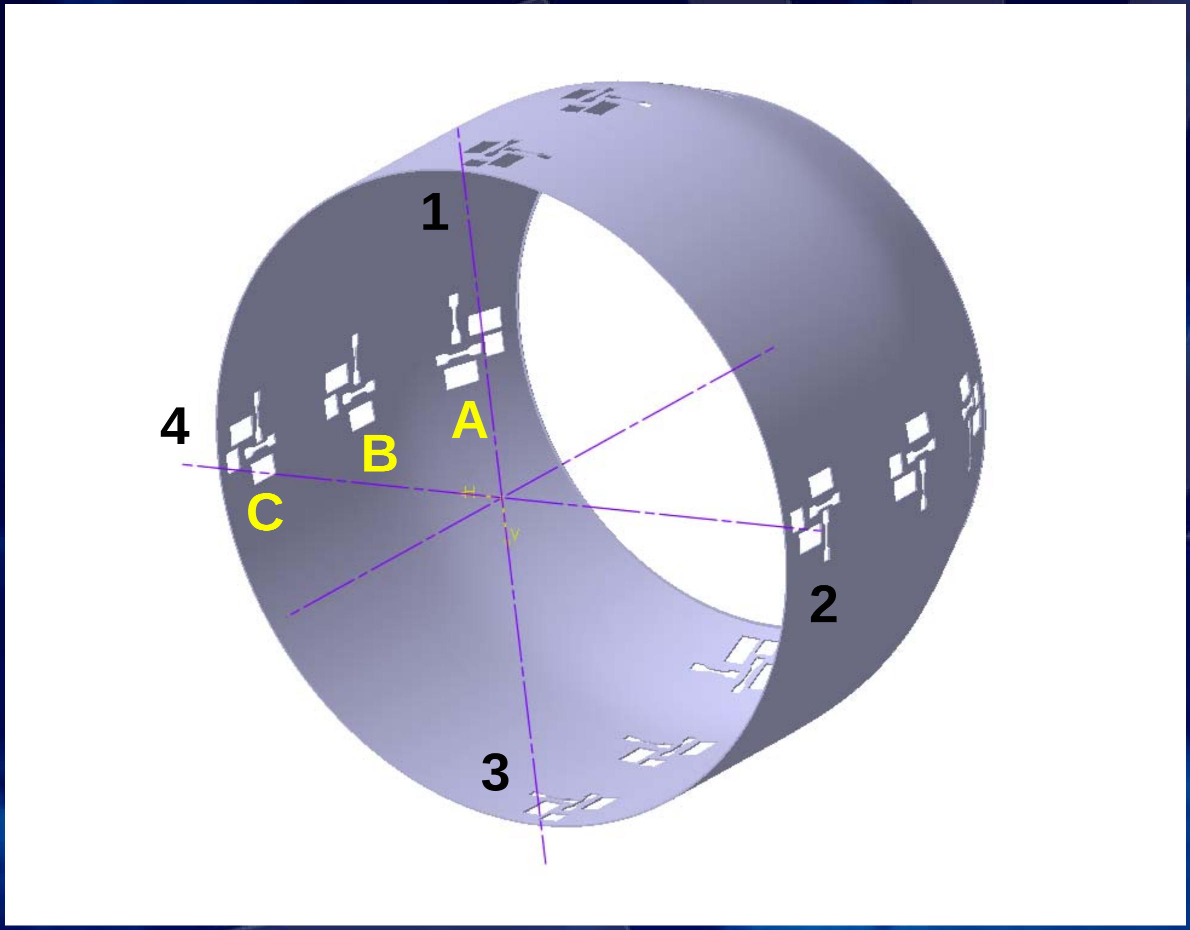
- The traditional way: machine the case out of forged rings
- At least 30% cost reduction
- Deep drawn preform from rolled and annealed sheet 2.795mm thick
- Flowformed in one pass using a two-roller machine (63% reduction)
- Microstructure recrystallisation (30min@745ºC, then gas cooled)

Preform Shape and Mandrel Geometry

METALLURGICAL AND MECHANICAL PROPERTIES

- We will discuss four main topics:
  - microstructure
  - tensile properties
  - crystallographic texture.
  - low-cycle fatigue (LCF) life (for hardened case)
- Samples were extracted at various locations on the flowformed case.

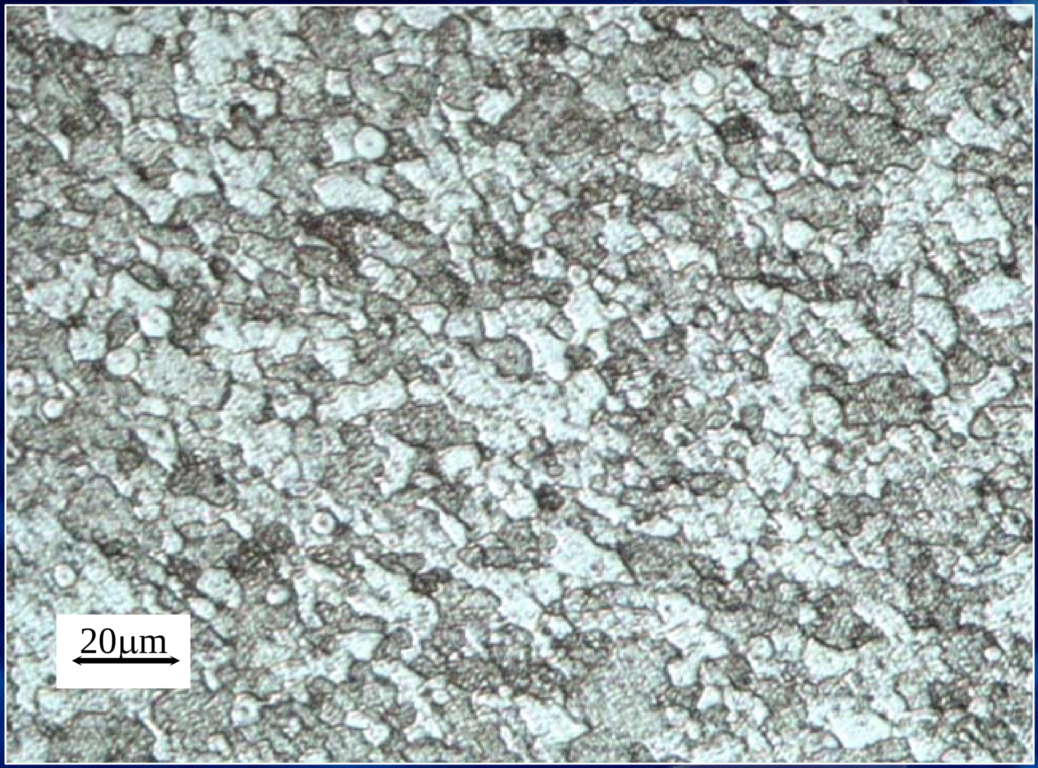
METALLURGICAL AND MECHANICAL PROPERTIES



Sample Extraction

Rectangular samples are cut for metallographic and crystallographic texture investigations. Gauge geometry of small tensile samples: 2.5mmx10mmxthickness. 1=initial rolling direction.

MICROSTRUCTURE



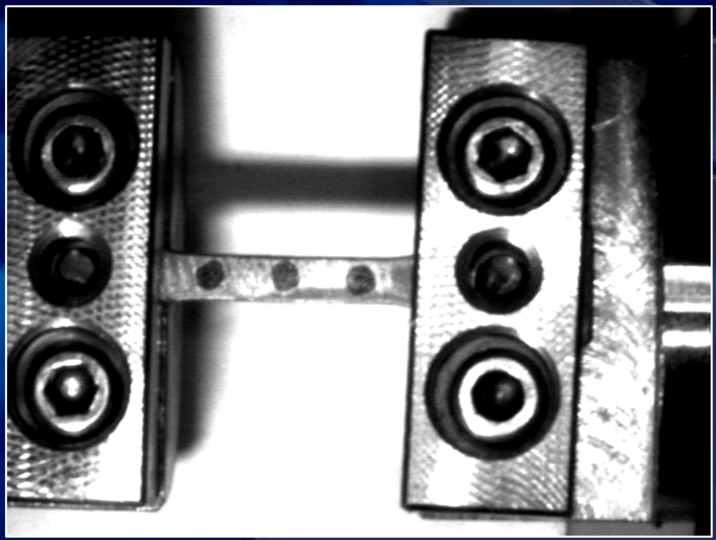
- Equiaxed grains - size 9μm
- Hardness: 84 HR-B
- Homogeneous microstructure

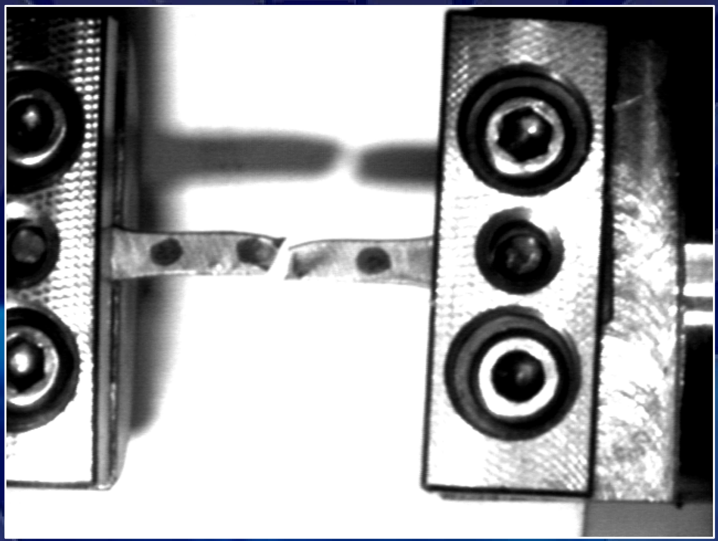
Microstructure of Flowformed and Annealed Case (Sample B1)

TENSILE TESTS

- Measured at at constant displacement (0.0212 mm/sec) with a Messphysik video extensometer (point measurement module) along the axial (L) and circumferential (T) directions.

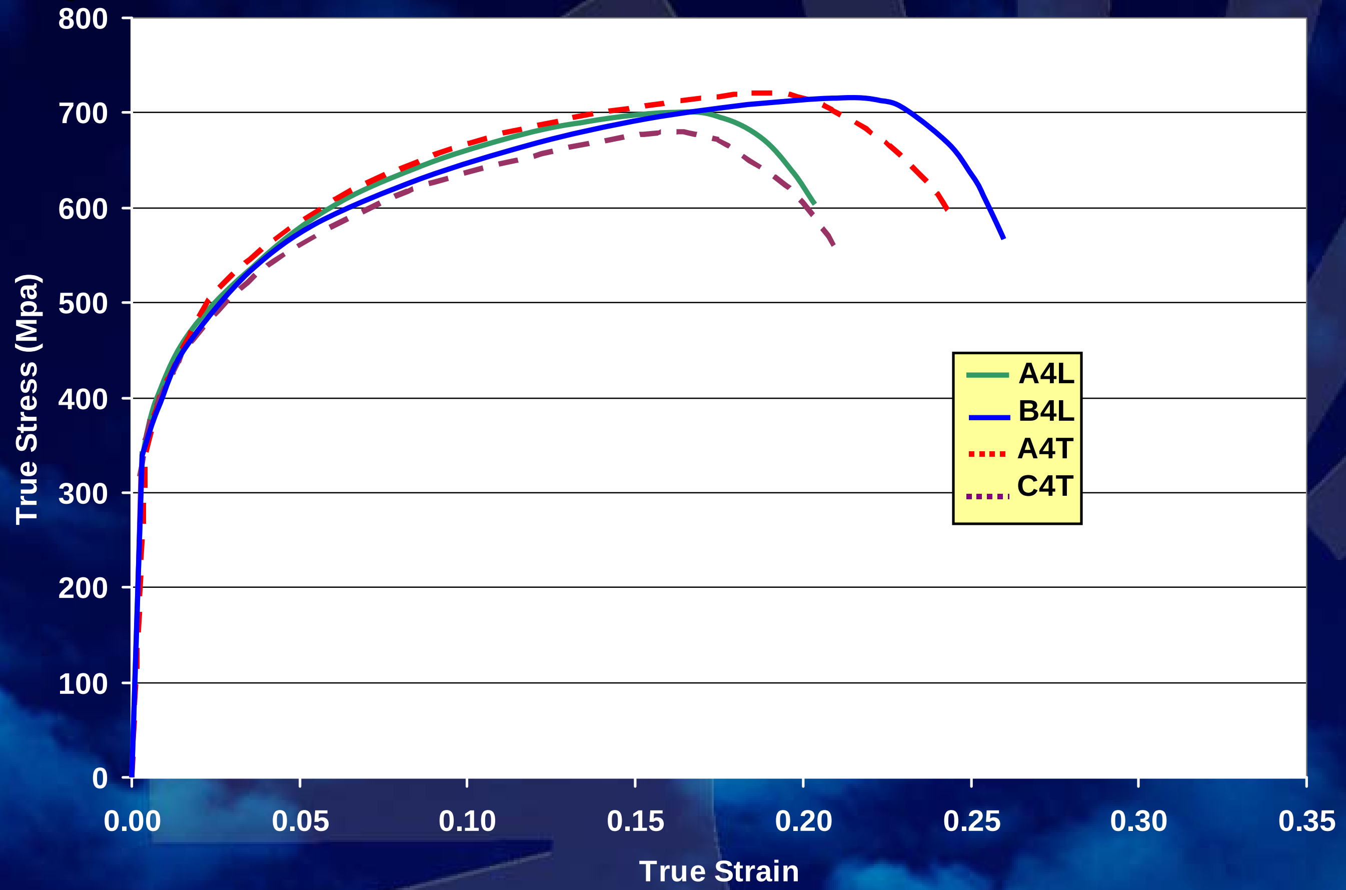
- Positions (X and Y) of 3 points were recorded together with the force at 60Hz. The deformation calculated from the average deformation of the 3 pairs of points.





Tensile samples before and after testing

TENSILE TESTS



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

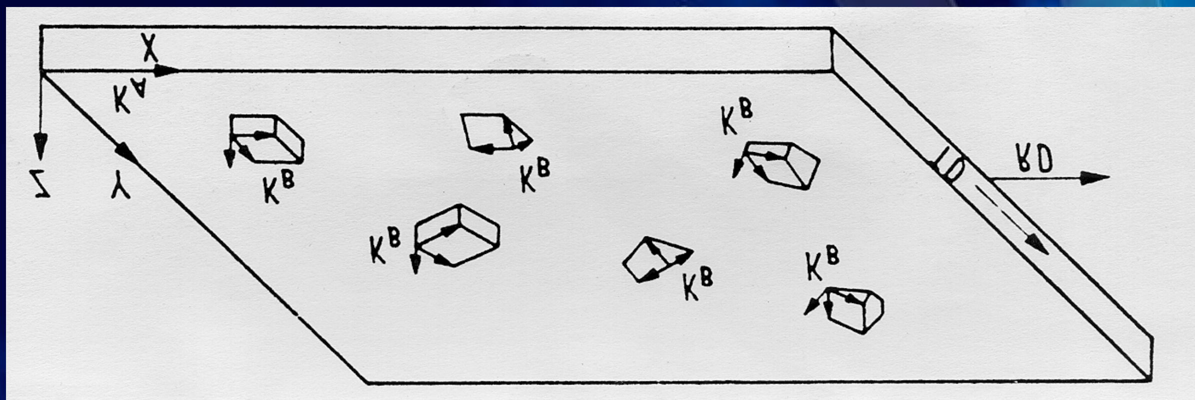
TENSILE TESTS

- Tensile data exceed by far the minimum requirements of the aerospace specification AMS5504 for annealed SS410 sheet:
  - yield: 207Mpa (~350Mpa)
  - UTS: 450-650Mpa (~700Mpa)
  - elongation: 15% (up to 23%)
  - grain size: 72μm or smaller (9μm)
- Tensile properties are homogeneous throughout the part and the effect of sample orientation can be neglected.

TEXTURE REPRESENTATION

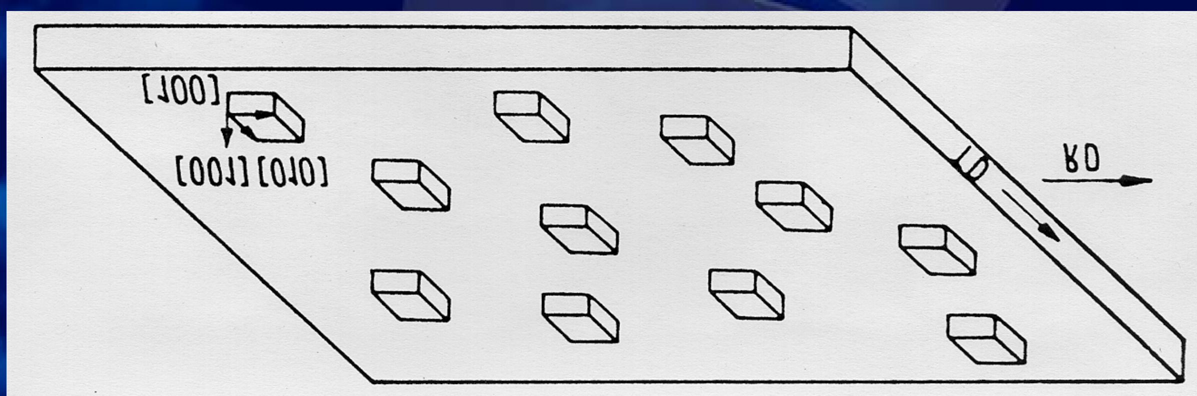
- Crystallographic textures were determined from three incomplete pole figures, (110), (200), (211).
- The Orientation Distribution Functions (ODF's) were calculated using the series expansion method and ghost corrected using the exponential method.

Texture Representation in Sheet



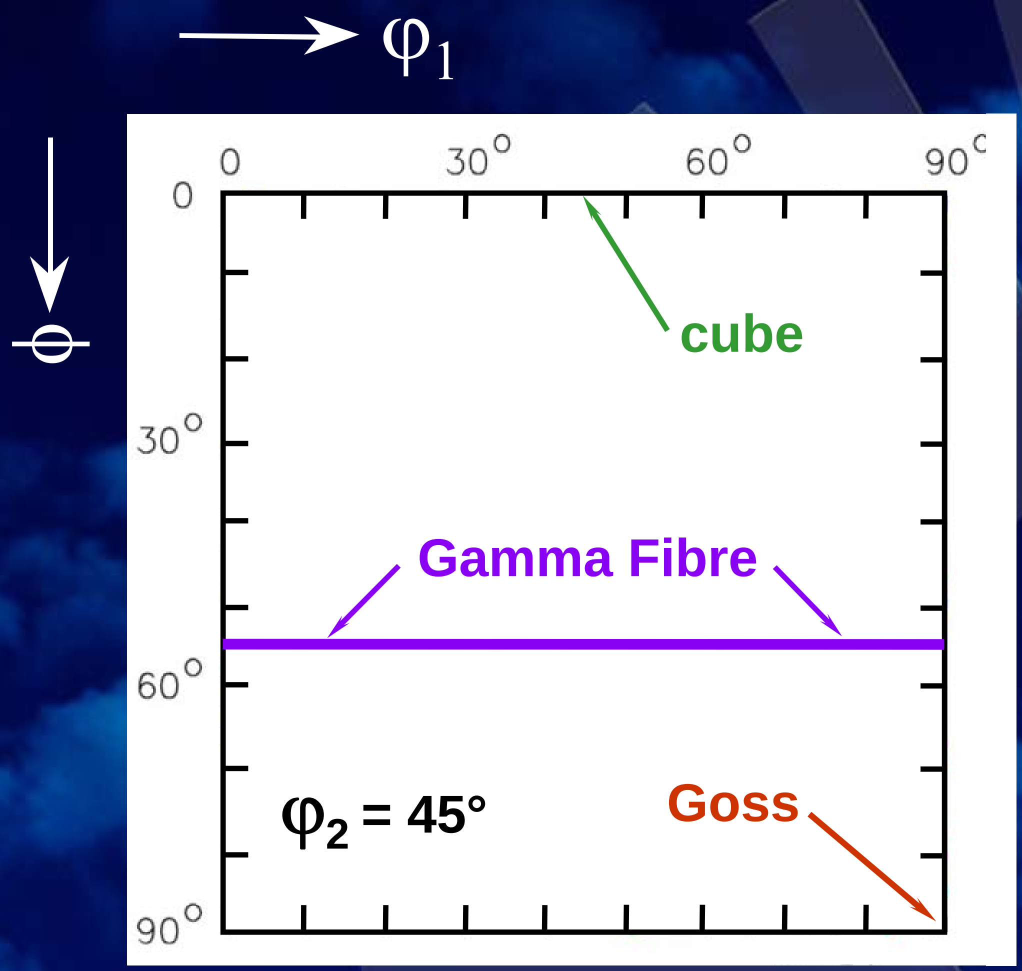
random texture

Ka: sample coordinate system
Kb: crystal coordinate system



cube texture (0°,0°,0°)
(no rotation necessary)

Texture Representation



Schematic ODF showing the positions of the main texture components on the φ_2=45° section

Gamma Fibre: (111)<uvw>

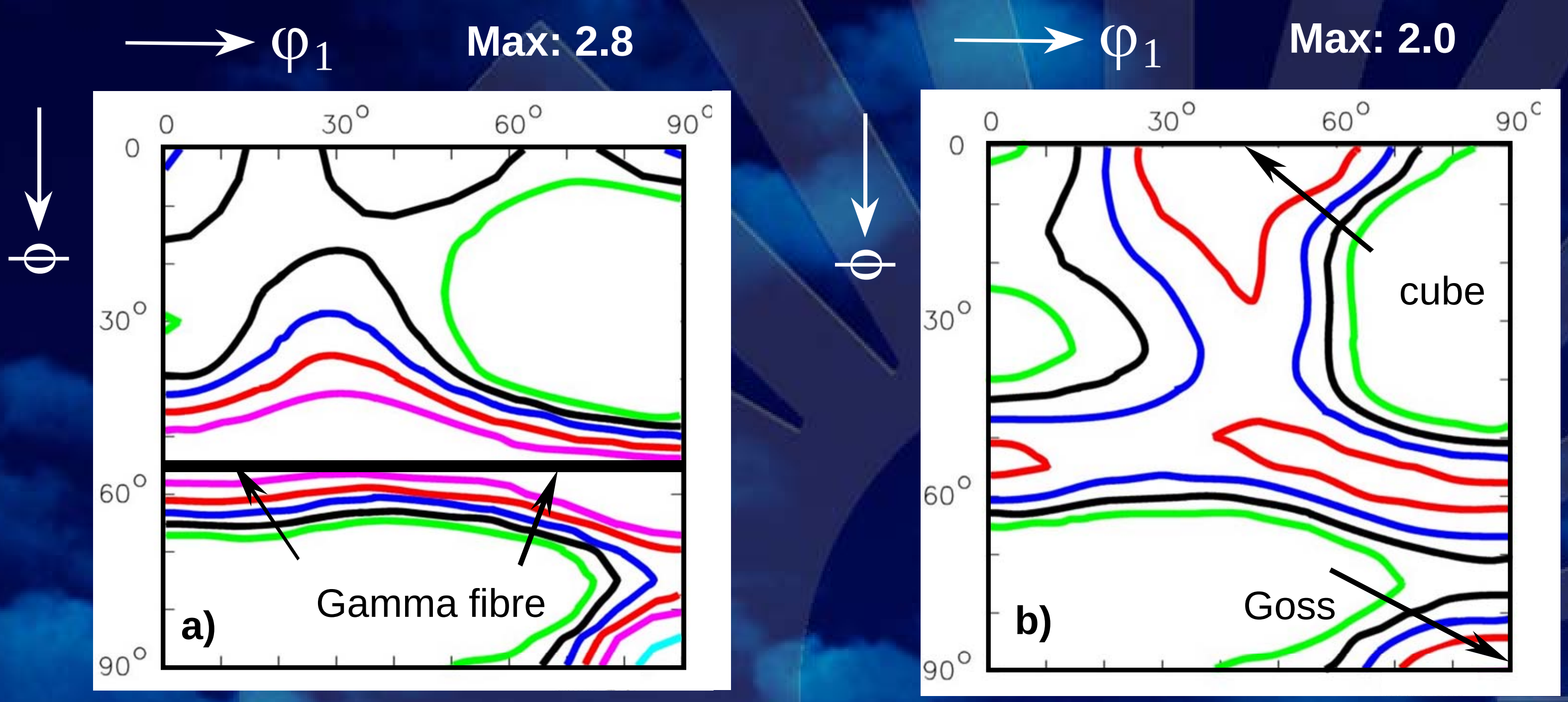
Cube: (001)<100>

Goss: (001)<110>

(hkl): plane || radial direction

<uvw>: direction || axial direction

TEXTURE REPRESENTATION



φ_2=45º ODF-sections of a) A1 sample and b) C1 sample (flowformed case). Intensity levels: 1 1.2 1.5 1.7 2.0 2.5

TEXTURE REPRESENTATION

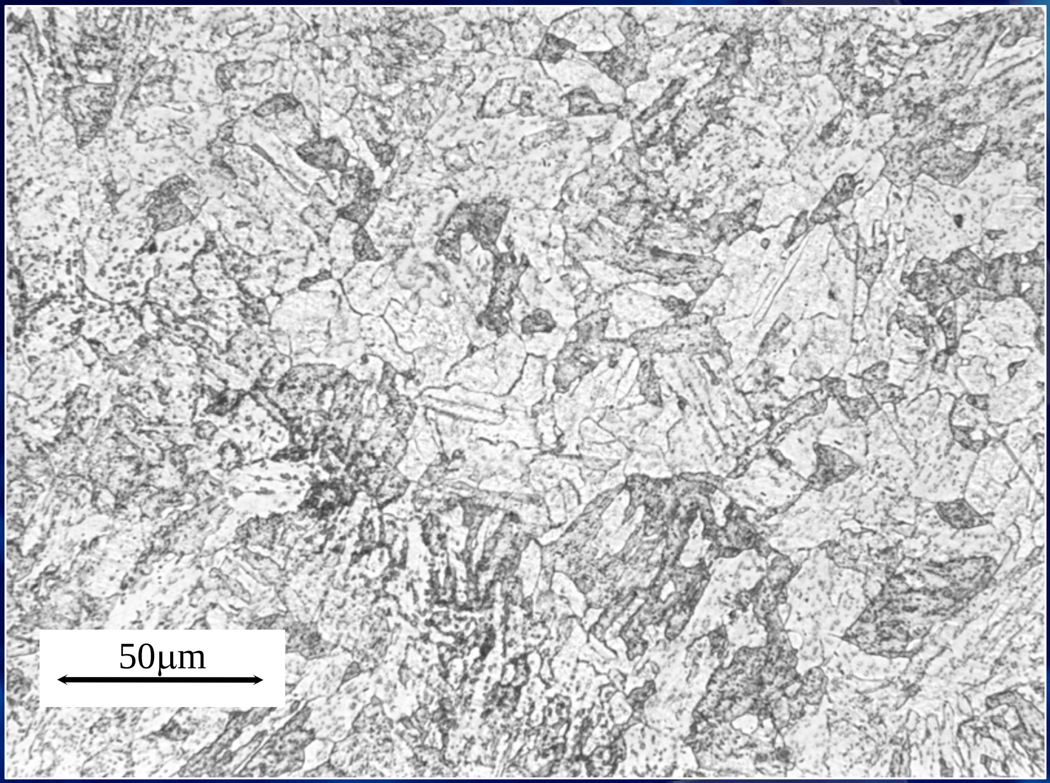
- As the texture is weak, we can assume that the recrystallisation mechanism is such that it favours the occurrence and growth of a large spectrum of nuclei that randomise the texture.
- The resulting properties can only be close to isotropic. It should be noted that the presence of a uniform gamma-fibre (independently of its intensity) does not induce planar anisotropy.
- Before drawing more conclusions, the as-deformed textures and orientation imaging mapping (OIM) investigations will have to be performed.

COMPARISON WITH MACHINE CASE

COMPARISON WITH MACHINE CASE

- 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.

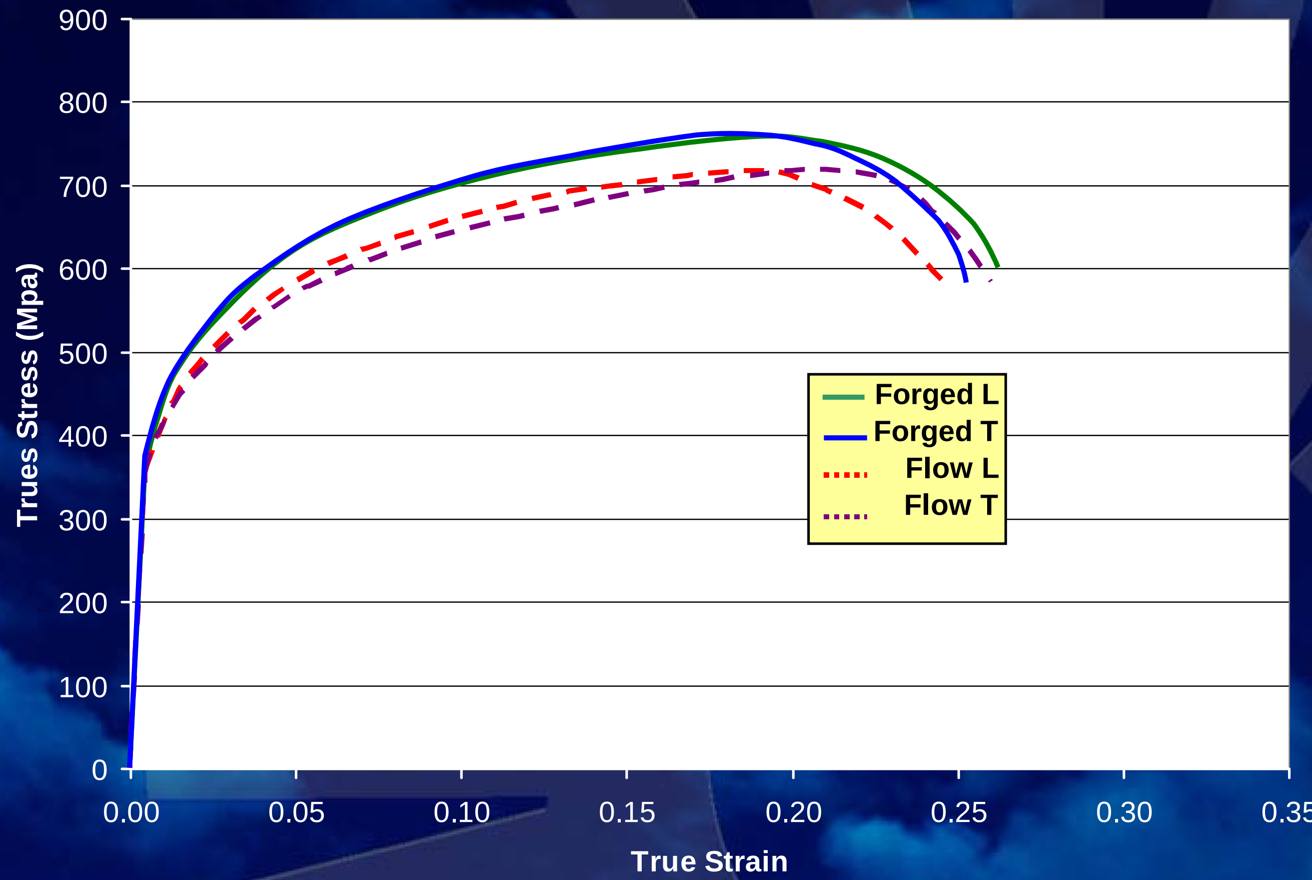
COMPARISON WITH MACHINE CASE



- Mix of ferrite and tempered martensite
- Equiaxed grains - size 25μm
- Hardness: 84.5 HR-B
- Homogeneous microstr.

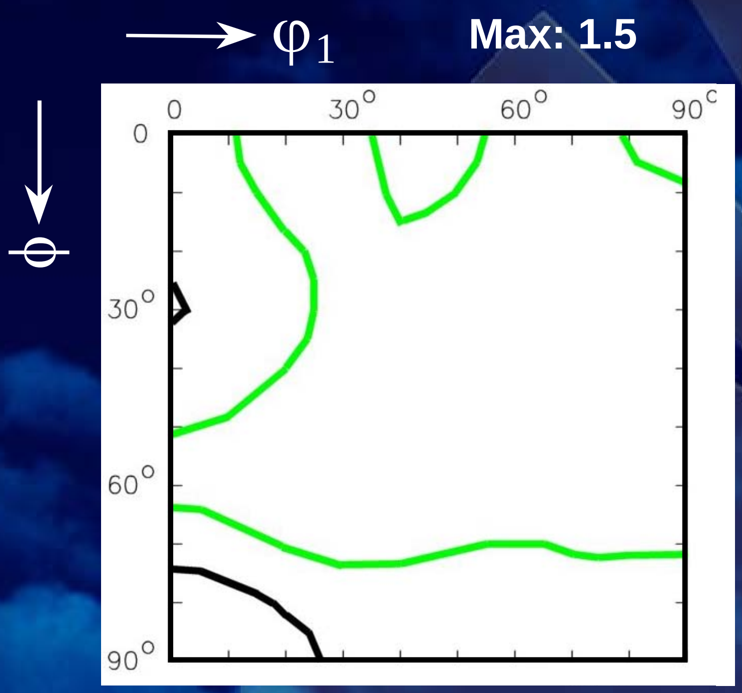
Microstructure of Forged Ring

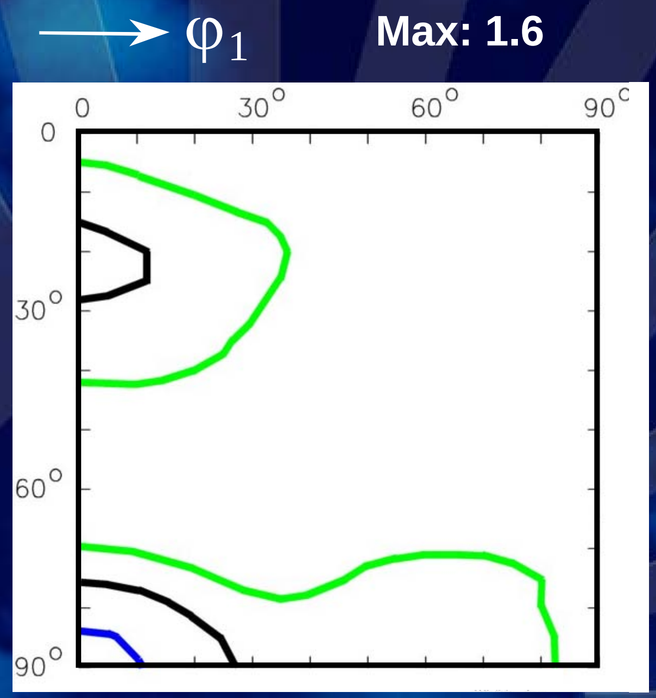
COMPARISON WITH MACHINE CASE



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

COMPARISON WITH MACHINE CASE





φ_2=45º ODF-sections of a) A1 sample and b) C1 sample (forged ring). Intensity levels: 1 1.2 1.5

COMPARISON WITH MACHINE CASE

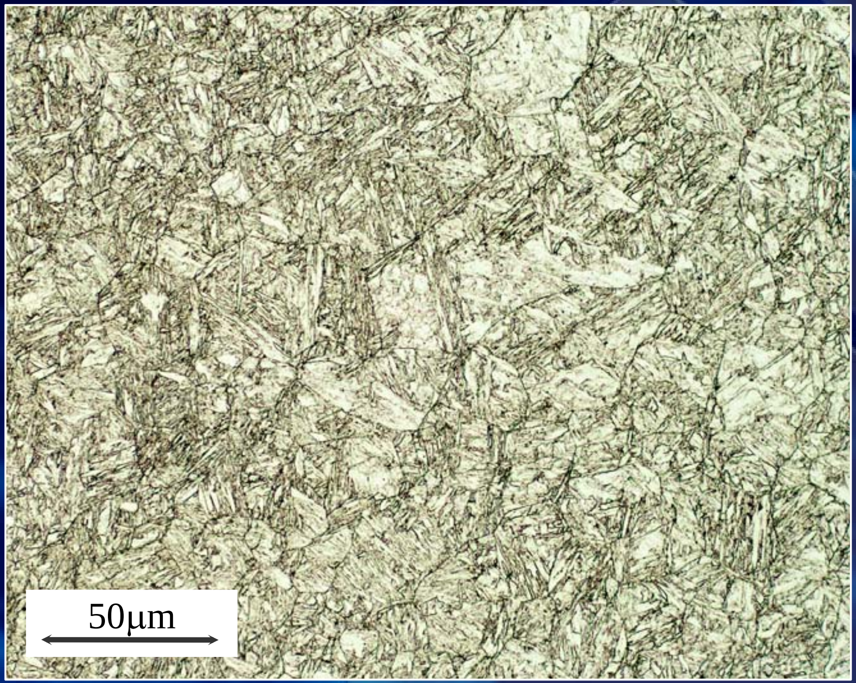
- The yield stresses are comparable for the machined and flowformed parts.
- The ultimate stresses, however, are higher by about 40Mpa in the machined part:
  - martensite in the forged material
  - structure not fully recovered?
- Finally, as expected, the crystallographic texture is nearly random with a maximum orientation density or probability f(g)=1.6 (nearly perfectly isotropic)

HARDENED CONDITION

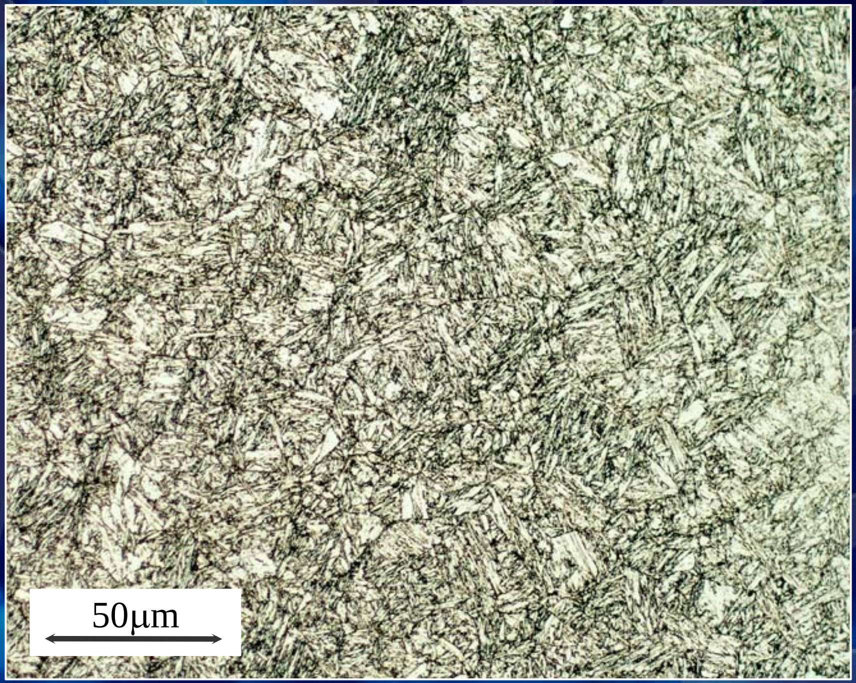
HARDENED CONDITION

- 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.

HARDENED CONDITION



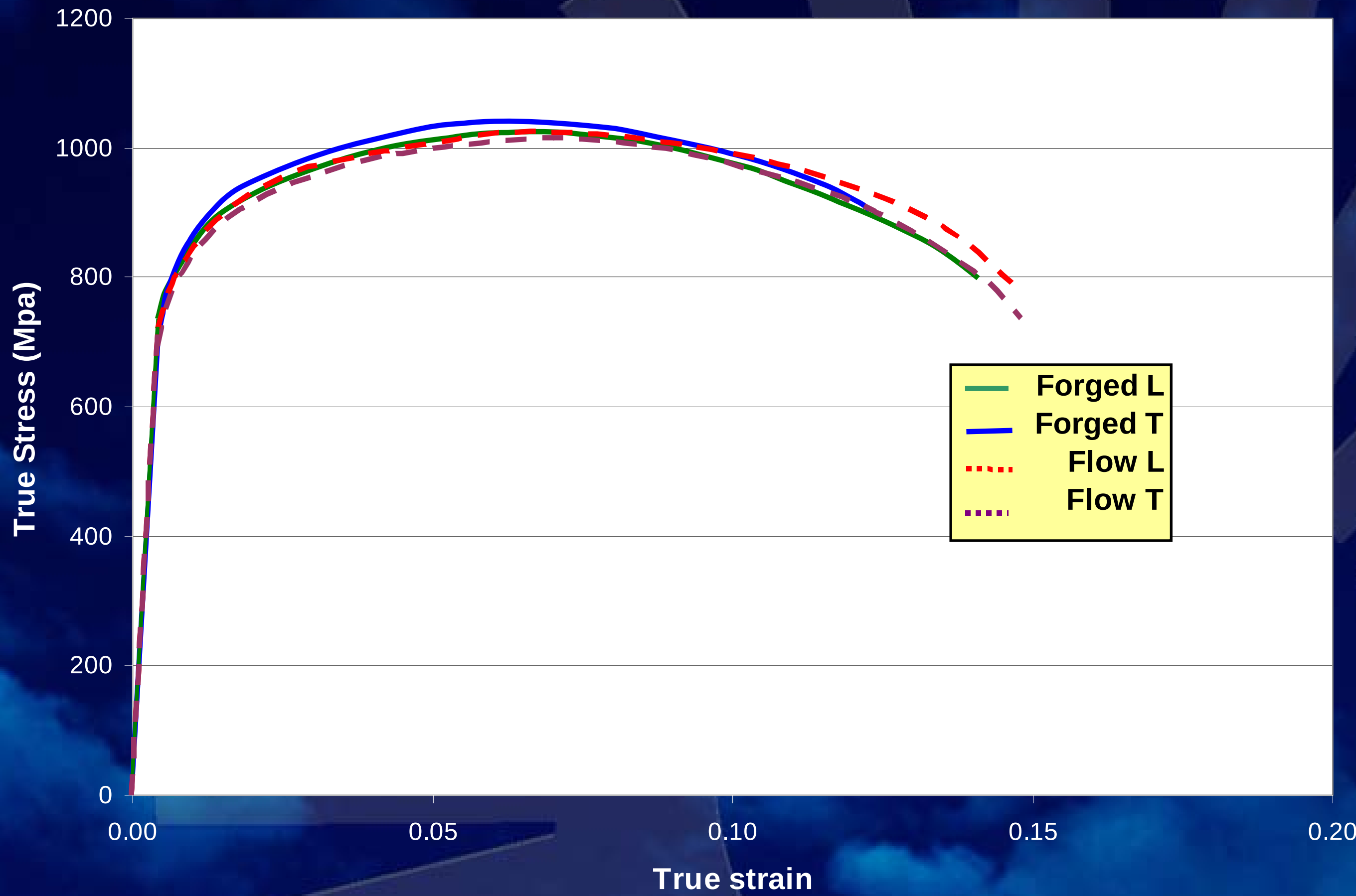
a)



b)

Microstructure in the hardened condition
a) flowformed part (31HR-C) and b) machined part (30HR-C)

HARDENED CONDITION



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

HARDENED CONDITION

- 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:
  - forged structure not fully recovered?!

HARDENED CONDITION

- Crystallographic textures were not measured.
- However, they should be even closer to random after experiencing two phase-transformations (ferrite to austenite to martensite).

Transformation Laws	Variants	Orientation Relationships
Bain (**B**)	3	{100}γ//{100}α and <100>γ//<110>α
Kurdjumov-Sachs (**K-S**)	24	{111}γ//{110}α and <110>γ//<111>α
Nishiyama-Wassermann (**N-W**)	12	{111}γ//{110}α and <112>γ//<110>α

Transformation laws in steels (assuming no variant selection)
austenite ↔ ferrite/bainite/martensite

HARDENED CONDITION

Low Cycle Fatigue (LCF)

- In the engine program under consideration, we decided not to take into account LCF tests on specimens extracted from the flowformed case.
- LCF tests were performed using 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.

CONCLUSIONS

- Flowforming is an alternative forming method to produce axisymmetric parts at lower costs than the traditional machining of forged rings.
- 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.

FURTHER WORK

- Perform equivalent study on Inconel parts.
- Evaluation of use of partly recovered flowformed case to refine final microstructure and enhance properties.
- Add details (flanges, weld lips, bosses, …) on flowformed shell to get (as close as possible) the final shape.

AKNOWLEDGEMENTS

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

MICROSTRUCTURE: grain size

TESTING REPORT
METALLOGRAPHY – GRAIN SIZE

M05112102

Purchase order #:	4500720991
Part description:	Flow Formed
Part #:	MD3064090
MT #:	2005-952
Engine #:	PW615
Material Spec.:	AMS 5504
Heat code:	Annealed
Testing Specification:	ASTM E 112

GRAIN SIZE DISTRIBUTION ALONG THE 3 ORTHOGONAL DIRECTIONS

	0°		90°		180°		270°	
	Location	Gr.size no.	Location	Gr.size no.	Location	Gr.size no.	Location	Gr.size no.
A	A1c	10,98	A2c	10,97	A3c	10,91	A4c	10,66
	A1a	11,09	A2a	11,14	A3a	11,20	A4a	10,94
	A1OD	10,62	A2ID	10,64	A3OD	10,95	A4ID	10,50
B	B1c	11,89	B2c	11,54	B3c	11,30	B4c	11,01
	B1a	11,57	B2a	11,36	B3a	11,28	B4a	10,94
	B1OD	11,17	B2ID	10,99	B3OD	10,93	B4ID	10,71
C	C1c	10,82	C2c	10,54	C3c	10,72	C4c	10,62
	C1a	11,02	C2a	10,71	C3a	11,01	C4a	11,03
	C1OD	10,89	C2ID	10,22	C3OD	10,63	C4ID	10,12

Microstructure of Flowformed and Annealed Case (Grain Size)

MICROSTRUCTURE: hardness

Purchase order #: **4500720991**

Part description: **Flow Formed**

Part #: **MD3064090**

MT #: **2005-952**

Engine #: **PW615**

Material Spec.: **AMS 5504**

Heat code: **Annealed**

Testing Specification: **ASTM E 112**

Scale	HV 500
Bloc Calibration	900020442

		0°			90°			180°			270°		
Location		HV	Equiv. HRB	Loc.	HV	Equiv. HRB	Loc.	HV	Equiv. HRB	Loc.	HV	Equiv. HRB
A	A1c	161	83,70	A2c	159	82,86	A3c	158	82,81	A4c	163	84,28
	A1a	161	83,54	A2a	162	83,90	A3a	162	84,00	A4a	165	84,87
	A1OD	166	85,20	A2ID	166	85,05	A3OD	164	84,45	A4ID	168	85,66
B	B1c	160	83,35	B2c	166	85,03	B3c	158	82,65	B4c	162	83,80
	B1a	162	83,83	B2a	165	84,66	B3a	162	83,95	B4a	163	84,21
	B1OD	167	85,43	B2ID	167	85,32	B3OD	164	84,37	B4ID	162	83,87
C	C1c	166	85,07	C2c	164	84,41	C3c	163	84,08	C4c	158	82,75
	C1a	165	84,88	C2a	164	84,38	C3a	162	83,79	C4a	163	84,17
	C1OD	164	84,48	C2ID	166	84,96	C3OD	171	86,37	C4ID	163	84,13

Microstructure of Flowformed and Annealed Case (Hardness)

FLOWFORMING

TENSILE TESTS

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

Tensile test data of all samples of the flowformed case (L=axial direction, T=circumferential direction).

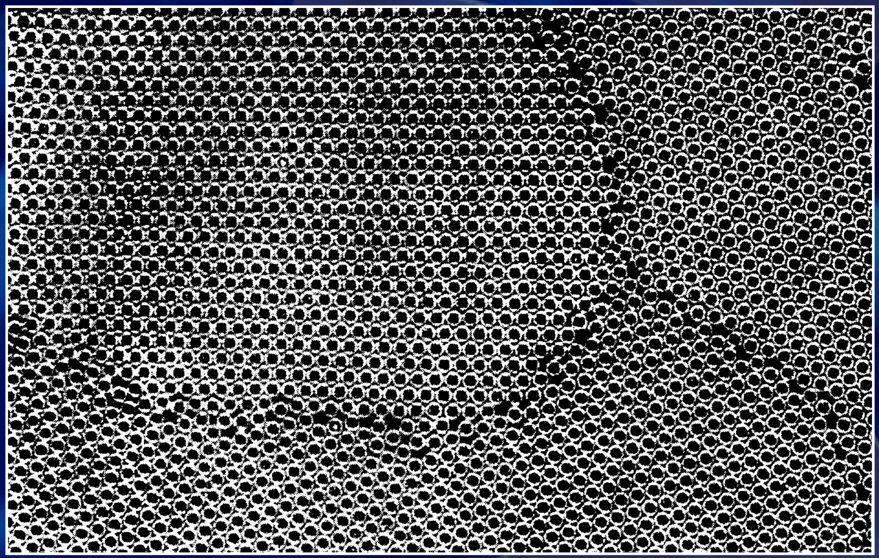
Results of samples 1/3 and 2/4 are presented together as they correspond to symmetrical positions on the case: 0º/180º and 90º/270º, respectively

TEXTURE REPRESENTATION

Crystal Lattice

- **To each grain is associated a specific crystallographic orientation. The orientation is determined by how the crystal lattice is orientated in (with respect to) the sample.**

- **The crystal lattice is repeated within a grain until a grain boundary is reached. At the boundary, the regular pattern is disturbed. In adjacent grains, the crystal lattice is usually differently orientated.**



Soap Bubble Model of a Polycrystal

TEXTURE REPRESENTATION

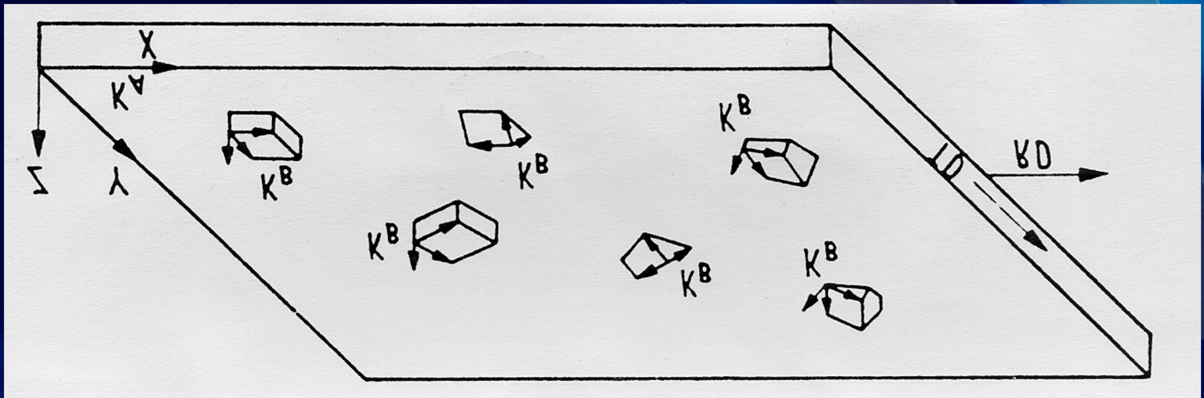
- **Notion of texture is normally associated to polycrystals:**
  - **volume decomposed into several grains, each one associated with an orientation:**
    - ✓ **Miller indices (cube): {001}<100>***
      {crystal plane||sheet plane}, <crystal direction||RD>
    - ✓ **Euler angles (cube): $(\varphi_1, \phi, \varphi_2) = (0°, 0°, 0°)$:**
      rotation: sample ↔ crystal coordinate system.

- **Random distribution of grain orientations:**
  - **the material has a *random texture*.**

- **Non-random distribution of grain orientation:**
  - **the material has a given *texture*;**
  - **macroscopic *anisotropies* may result.**

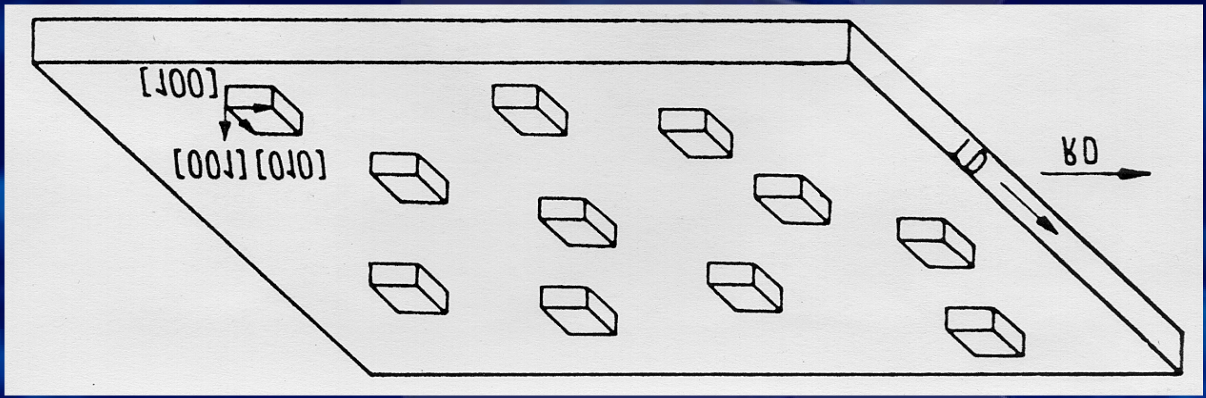
* {001} : family of specific planes (001), (001), …
<100> : family of specific directions [100], [100], ...

Texture Representation in Rolled Sheet



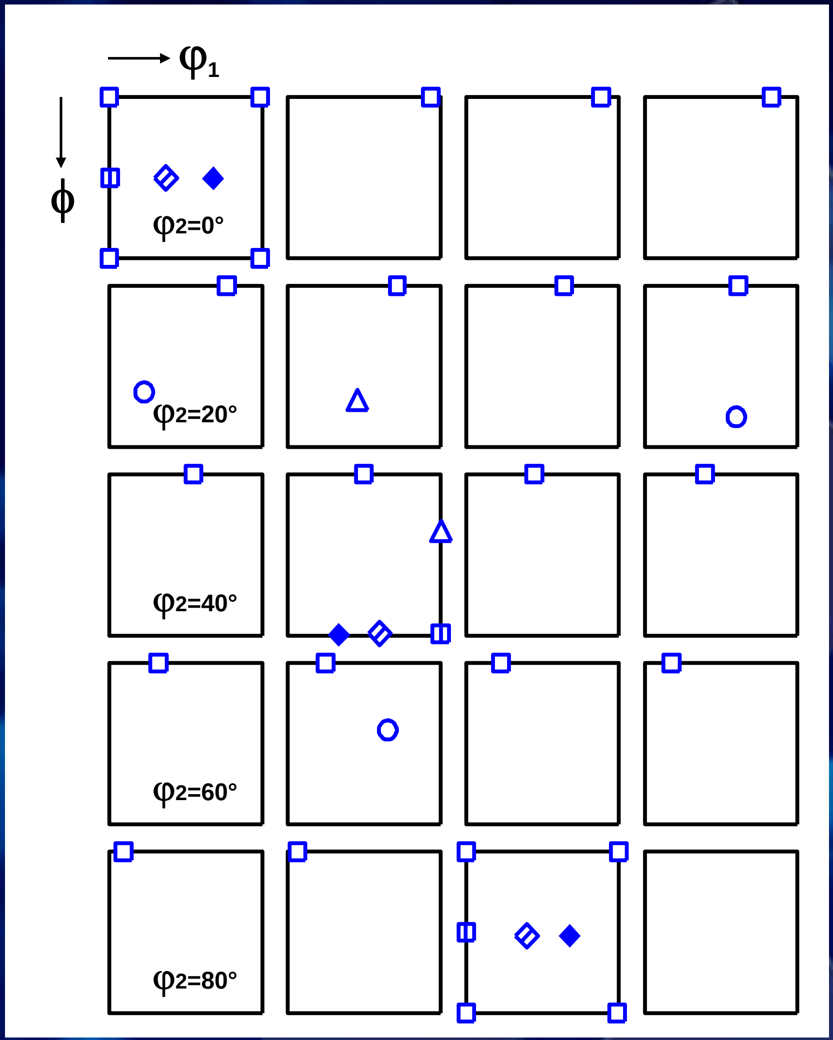
random texture

Ka: sample coordinate system
Kb: crystal coordinate system



cube texture (0°,0°,0°)
(no rotation necessary)

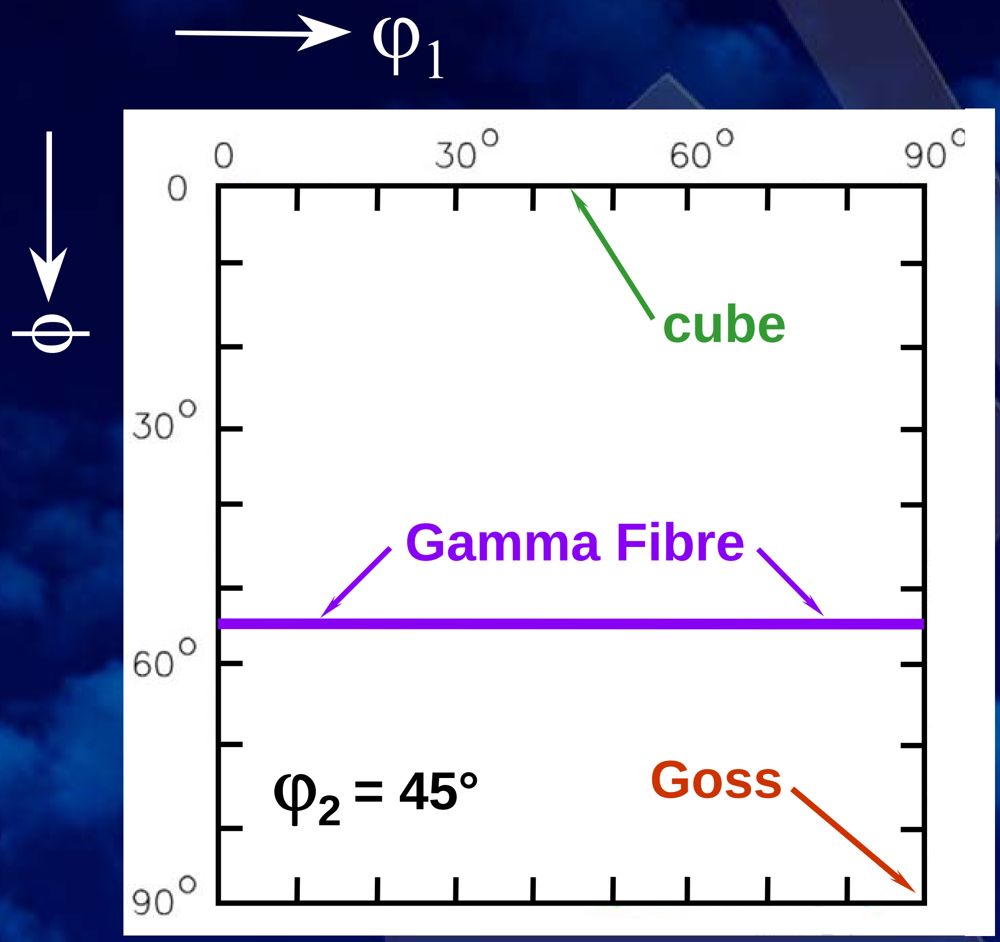
Texture Representation



Schematic ODF showing the positions of the main texture components in Al and its alloys

- Cube {001} <100>
- Goss {011} <100>
- Brass {011} <211>
- P {011} <uvw>
- Copper {112} <111>
- S {123} <634>

Texture Representation



Schematic ODF showing the positions of the main texture components on the φ_2=45° section

Gamma Fibre: (111)<uvw>

Cube: (001)<100>

Goss: (001)<110>

(hkl): plane || radial direction

<uvw>: direction || axial direction

TEXTURE REPRESENTATION

- These ODF's are similar to the ones obtained after rolling at intermediate reduction and recrystallisation of alpha steels.
- 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).

COMPARISON WITH MACHINE CASE

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

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

HARDENED CONDITION

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

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