TECHNICAL REPORT

CUSTOMER NAME: **European Space Agency**

PROJECT NAME: **ESA - Phase II**

TITLE: **Executive Summary**

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Report Status

☒ Completed	☐ Pending Approval	☐ Work in Progress	☐ N/A

Contents

REFERENCES

The following is a list of references that are used or are relevant to this document.

REF. [1] GKN Document, Heat treatment trials of shear formed SS 21-6-9_VOLS_10289790

REF. [2] Spincraft Document 6.2 Inspection Report

REF. [3] Spincraft Document D7.2 Manufacturing Verification Report

REF. [4] Spincraft Document D8.2 Nozzle Development plan

REF. [5] GKN Document, Heat treatment trials of shear formed SS 21-6-9_VOLS_10289790

GLOSSARY

Annealing	A form of heat treatment to remove work hardening that takes material above its recrystallisation temperature and alters its properties to increase the ductility and make it more workable
Blank	The initial flat disk shape cut from plate or sheet from which the final cone is formed
Contractor	Spincraft ETG (SETG)
Datum	A reference from which to take a measurement
Envelope	A part manufactured to the same or similar shape to the final component, from which the final part will be extracted by machining
GKN Aerospace	Customer and Co- Researcher with European Space Agency (ESA) and SETG
HT	Heat Treatment
Profile/form	The shape or shape tolerance of a surface or 3D body
Requalification	Additional final forming step for post HT minor profile correction
Spincraft ETG (SETG)	Spi Engineering Technologies Group
Stress Relieving	A form of heat treatment that does not exceed the critical range and so does not alter the material properties. It is to reduce or eliminate internal stresses caused as a result of working the material to remove work hardening

1.0 EXECUTIVE SUMMARY

This report details the outcomes and knowledge gained from the feasibility study of Phase 2. For background, GKN in collaboration with ESA, developed manufacturing feasibility project in Phase 1 Project of nozzle extensions using metal spinning and shear forming solutions.

Phase 2 built on the knowledge gained from Phase 1 and sought to formulate different spin forming solutions to improve the dimensional and physical properties of the inner nozzle extensions and develop concepts (including testing) for outer nozzle extensions.

The finished spun cones' success was verified through inspection of geometry profile, dimensional and material testing. Test reports and manufacturing verification documents were submitted.

Suggestions for further development in the future were outlined to ensure improved feasibility, repeatability, cost reduction and the mechanical properties of the manufacturing trials as compared to the ones from traditional manufacturing processes.

2.0 BACKGROUND

The European space industry developed sandwich technology for liquid propulsion engine nozzles, presently adopted for the Ariane 6 main stage (Vulcain 2.1) and for the FLPP Expander Technology Integrated Demonstrator (ETID). The technology is currently based on fabrication, welding and forming of the initial parts followed by channel milling and laser welding.

A significant cost reduction was identified to be achievable by targeting the manufacturing solution and using metal spinning to replace complex fabrication and associated testing requirements Spin forming as a manufacturing method is not common in the European space industry.

Phase 2 project was conducted as a manufacturing demonstrator of the feasibility of using metal spinning to make nozzle extensions. Spin forming processes were analogous and comparable to the sandwich nozzle manufacturing of milling of cooling channels, laser welding of upper and lower nozzle cones. This was in the sense of using inner and outer cones sandwiched together, one on top of the other.

3.0 FEASIBILITY STUDY

A feasibility study was conducted to investigate the supply chain for the raw materials needed for Phase 2, specifically Carpenter 21-6-9. Procurement of Phase 2 project materials was undertaken, with thickness and size optimisation done to enable spin forming out of single sheet metal for each part of each nozzle (internal and external cones), to minimise welding operations and recurring costs.

The possibilities of joining metal and forming sheet in Carpenter 21-6-9 was studied, as well as the feasibility of using the inner cone as a tool for the outer cone for sandwich technology spin forming. Another consideration in the feasibility study was the risks and challenges related to the mechanical properties of the material. Concerns were identified by GKN of:

- Large grain size as it is an indicator of low material life properties. Large grain size was thought to be a result of the cold work introduced into the material during the forming processes and heat treatment(s) that was conducted.
- The hardness of the final product with potential to be greater than the maximum allowable value of100HRB.
- Dimensional requirements needed to be within tolerance

Phase 2 objectives were to address grain size and hardness issues by exploring ways to minimise cold working during forming which can create strain hardening and by reducing heat treatment which can create grain growth. Mitigation to reduce the likelihood of these risks was conducted by GKN to understand the heat treatment process and SETG sought their support on related engineering issues. Outer nozzle forming trials (thinner material compared to the inner) were conducted using conventional spinning (as per Phase 1). With initial trials based on novel spinning methodology of spinning an outer nozzle directly over an inner nozzle (sandwich technology) to achieve good conicity and concentricity.

A structured development programme was broken down into sequential, and in some cases parallel, Projects P1 to P6. This was to further develop the spin forming process for sandwich technology for liquid engine propulsion nozzle extension manufacture and address the concerns of grain growth, profile conformity and hardness issues. The Key Projects (P1 to P6) are described in Table 1 below.

ID	Key Objectives				
1	Metallurgy / Grain size & Heat treatment: Addressed in GKN Heat Treatment Report				
2	Metallurgy / Hardness: These were addressed in GKN Metallurgy and Heat Treatment Report				
3	Profile control: To address profile tolerance and achievement of the Ogive Shape				
4	Cost and future capability: to understand the commercial viability of the proposals				
Project	**Project Description**	1	2	3	4
P1	Full size Carpenter inner nozzle from welded sheet	X	X		
P2	Subscale Carpenter inner nozzle from pre-machined sheet	X	X	X	
P3	Subscale Carpenter inner nozzle from rolled and welded preforms				X
P4	Subscale Inconel inner nozzle from rolled and welded preform				X
P5	Subscale Carpenter outer nozzle	X	X	X	
P6	Subscale 253MA inner and Carpenter outer nozzle by optimised sandwich technology process			X	X

Table 1: Key Project Objectives

The Feasibility Study identified that material could be sourced to support the requirements of the Projects trials, based on changes proposed by Spincraft which were discussed and agreed with ESA and GKN. GKN provided Inconel 718, for Key Project 4, and Carpenter 21-6-9 was available in 6.79mm thickness from stockists for the other Key Projects. 253MA was available in 12mm thickness from the stockists for the inner cone of Key Project 6.

Spincraft proposed and undertook a manufacturing programme to investigate and to establish operating parameters and methods to facilitate the execution of the Key Projects.

4.0 MATERIAL SPECIFICATIONS

Weight optimisation in launch vehicles is vital, however steel is the required material for this application due to the temperatures and forces experienced rocket nozzles. Whilst materials do exist which can withstand these temperatures, there can be payoffs in strength, cost, weight, etc. which make them less appropriate for this application.

These material requirements result in the alternatives being limited to specific types of stainless steel. Carpenter 21-6-9 was specified in the scope of work and was confirmed in clarifications with ESA and GKN as the primary requirement for Phase 2. Inconel 718 was specified by GKN as the requirement for Key Project 4.

4.1 Carpenter 21-6-9

Carpenter 21-6-9, so named for its composition: 21Cr-6Ni-9Mn, is a high-strength, oxidising-resistant stainless steel which is often used in the aerospace industry. It has the added benefit of good formability properties which make it well suited to a manufacturing process such as spin forming.

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N
≤0.040	≤1.00	8.00 - 10.00	≤0.060	≤0.030	19.00 - 21.50	5.50 - 7.50	≤0.75	≤0.75	0.15 - 0.40

Table 2: Carpenter 21-6-9 Properties

4.2 Inconel 718

For key project 4, GKN supplied Inconel 718 which maintains high strength, oxidation and corrosion resistance while maintaining its superior ductility under extreme environments.

C	Mn	P	Si	S	Cr	Ni	Mo	Co	Ti	Cu
≤0.08	≤0.35	≤0.35	≤0.35	≤0.015	17-21	50-55	2.8-3.3	≤1	0.65-1.15	≤0.3

Table 3: Inconel 718 Properties

The proposal for Phase 2 was based on the selection of Carpenter 21-6-9 in thicknesses of 12mm and 6.79mm. However, investigations with the supply chain were unable to source any 12mm material from stock but did identify an adequate supply of 6.79mm material. To obtain 12mm material would have required a new mill run but the associated costs significantly exceeded the material budget of the project. After separate consultations with ESA and GKN, a proposal by Spincraft to use 6.79mm (Carpenter 21-6-9) was agreed as the revised basis for Phase 2.

5.0 MANUFACTURING

5.1 Manufacturing Objectives

Key objectives for Phase 2 were to; achieve an acceptable grain size, achieve an acceptable level of hardness and to achieve acceptable dimensional accuracy. GKN provided support to develop the heat treatment parameters and verify that the resultant material properties met requirements. Spincraft performed inspection to verify that the parts meet dimensional requirements at the following stages: after shear forming, after spinning and after machining of outer profile

5.2 Spin Forming Process

Spin forming is a manufacturing process whereby sheet metal or tubing is pushed by a roller into an axisymmetric shape on a lathe. Shear forming is an allied process that is similar to spin forming but has some unique characteristics which makes it more suited to certain geometries. The schematic in Figure 2 illustrates the difference between the two processes.

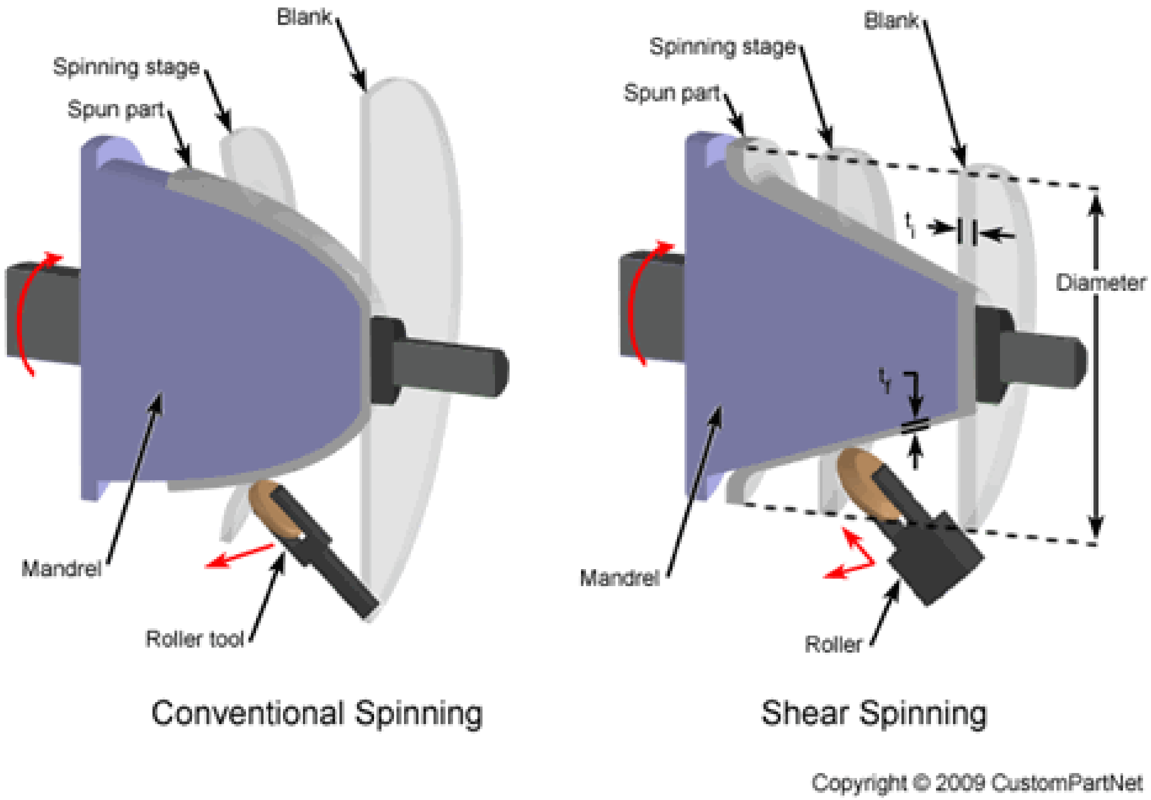

Figure 1: Effects of mandrel nose profile

For the Feasibility Study, due to the steep angle of the nozzle, it was agreed that the most efficient solution was to form in two stages, as proven in Phase 1. In the first stage, the part would be shear formed into a cone shape (Figure 2, right hand view) where the initial material thickness would be reduced to almost half. Final thickness would then be determined by the angle of the cone. This proved an efficient way to move large amounts of material in a controlled manner. In the second stage, material movement is significant, thereafter spun to achieve the final profile (Figure 2, left hand view).

ESA Phase 2 Process traceability matrix

PROJECT ID / MANUFACTURING PROCESS	Preforming (plate prep)	Inspection 1	Shear Form 1	Inspection 2	Heat Treatment 1	Inspection 3	Spin form 2	Inspection 4	Heat Treatment 2	Inspection 5	Requalify	Inspection 6	Turning 1 (w.t.)	Turning 2 (Final height)	Inspection 7	Final Inspection Reports
Key Project 1, job number 025815-2-1, ASM 4																
Material: Carpenter 21Cr-6Ni-9Mn	Spincraft Drawing Number MSN6084						Spincraft Drawing Number MSN6085									
ESA-087619-001C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087619-002C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Key Project 2, job number 025815-2-2, ASM 2																
Material: Carpenter 21Cr-6Ni-9Mn	Spincraft Drawing Number MSN6085						Spincraft Drawing Number MSN6085									
ESA-087619-003C	✓	✓	✓	✓	✓	✓	This stage not required - proceeded to Requalification				✓	Not completed because of requalification failure				
ESA-087619-004C	✓	✓	✓	✓	✓	✓					✓	✓	✓	✓	✓	✓
ESA-087619-005C	✓	✓	✓	✓	✓	✓					✓	✓	✓	✓	✓	✓
Key Project 3, job number 025815-2-3, ASM 1																
Material: Carpenter 21Cr-6Ni-9Mn	Spincraft Drawing Number MSN6027						Spincraft Drawing Number MSN6085									
FAB-2c	✓	✓	This stage not required - proceeded to Spin/Shear Form				✓	✓	✓	✓	✓	Not completed because of requalification failure				
FAB-3c	✓	✓					✓	✓	✓	✓	✓					
FAB-1c	✓	✓					✓	✓	✓	✓	✓					
FAB-4c	✓	✓					✓	✓	✓	✓	✓					
Key Project 4, job number 025815-2-4, ASM 1																
Material: Inconel Alloy 718	Spincraft Drawing Number MSN6028						Spincraft Drawing Number MSN6085									
ESA-087619-001I	✓	✓	This stage not required - proceeded to Heat Treatment		✓	✓	Not completed because of weld failure									
ESA-087619-002I	✓	✓			✓	✓										
ESA-087619-003I	✓	✓			✓	✓										
Key Project 5, job number 025815-2-5, ASM 1																
Material: Carpenter 21Cr-6Ni-9Mn	Spincraft Drawing Number MSN6084						Spincraft Drawing Number MSN6085									
ESA-087620-001C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087620-002C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087620-003C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Key Project 6, job number 025815-2-6, ASM 1																
Material: Carpenter 21Cr-6Ni-9Mn and 253MA	Spincraft Drawing Number MSN6084						Spincraft Drawing Number MSN6085									
ESA-087620-004C Outer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087620-005C Outer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087620-006C Outer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087619-001MA Inner	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087619-002MA Inner	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA-087619-003MA Inner	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 4: Process Traceability Matrix

6.0 MANUFACTURING DISCUSSION

SETG Document D3.2-Technical Requirements Specification REF. [5] discussed verification requirements of the produced cones to be done through dimensional and material testing. Dimensional inspection of the cones was done by SETG after forming and compared to the drawing provided by ESA. Results of these inspections were presented in the formal Inspection Report and separate inspection reports provided as part of the Technical Package.

Dimensional tolerancing and deviation data for each cone was also detailed in the inspection report REF. [6]. As also seen in Phase 1 of the trials, geometric movement during the heat treatment process was revealed by the post heat treatment inspection. There were areas that locked on, others were off showing uneven axial profile of the cones. Additional research is important to ascertain the effectiveness of fixturing and to minimise this to a level adequate for next stage forming.

Requalification is SETG terminology that refers to a technique used for geometric correction of formed parts, not just spun formed parts. Typically, it is used on parts which have undergone other processes such as heat treatment or partial machining and have, as a result, experienced a minor change in shape. The intent is that no significant cold work is done during requalification. No material reduction will take place, the part is essentially re-seated against the mandrel so that consistent contact on the inner surface of the part is re-attained. This technique is also used in other forming processed such as press forming where a 're-strike' of a part on the same tooling is used to perform geometric correction. Generally, most cones were requalified successfully except for those which failed to lock on the mandrel.

Project 6: Sandwich Cones Conicity Evaluation

The general ogive shape was achieved for both the inner and outer cones. However, there were runout issues during turning where conicity, concentricity and evaluation issues were encountered. Inspection Report REF. [6] details the measured vs nominal values showing significant deviation. Research on conicity error evaluation is rare, because more variables are involved and the mathematical model is not easy to be linearized during conicity error evaluation.' This reflects how difficult is its to gain accurate quantitative data from sandwich cone spin forming in terms of achieving true concentricity or conicity.

It is evident from the manufacturing results the parts achieved the representative ogive shape but did not meet the drawing to specified tolerances. Despite these out of tolerance deviations, the trials showed the spinning development is close to the design intent. SETG are confident that further developments will produce conforming parts to the drawing requirements.

6.1 Heat Treatment Study by GKN

GKN presented a in Heat Treatment Report D9.2 regarding microstructure and hardness of the relevant cones investigated. Microstructural observations showed that 990°C for 20 minutes was selected as suitable heat treatment to restore the microstructure. The microstructure was not completely restored after 20 minutes for the high strained part, but these experiments was done in a pre-heated furnace. In production the part will be loaded in the furnace at room temperature, and therefore be subjected to a longer time at temperature which will be sufficient to restore the microstructure. Hardness all heat treatments restored the hardness for the low strain part. Some difference in hardness for the different heat treatments can be found for the high strain parts. GKN concluded that these differences will not have a significant effect during further processing. The selected heat treatment of 990°C for 20 minutes restored the hardness to the as received hardness.

6.2 Gallery Of Final Status of all Projects P1 To P6

Project 1

Project 2

Project 3 (All failed - weld seam fracture)

Project 4 (All failed, endcap and weld seam fractures)

Project 5

Project 6

7.0 CONCLUSION

One of the main objectives of the ESA Phase II project was to determine the spinnability of materials at minimum cost and in the process identify possible failure modes, defects and how to mitigate them. SETG conducts thorough design and manufacturing reviews for tool selection, thus there is confidence that the rollers used for the ESA project were suitable and appropriate for each cone's forming requirements.

The primary requirements of Phase 2 Project were to ensure that:

(a) The design shall be representative of the flight part shape, generally this was achieved as seen from the inspection results

(b) Parts shall be formed by metal spinning processes, this was achieved

(c) Parts shall be compatible with sandwich nozzle manufacturing this was also achieved

There were several parameters that needed to be assessed when conducting failure mode analyses. Process variables like tooling setup, workpiece geometry, machine and forming parameters, roller path, feed rate and spindle speed are essential in shear forming of cones. It can be seen how so many variables affect spinnability of materials and how some failure modes are a result of other failure modes, for example the mandrel not being truly axisymmetric has a resultant effect of the part not locking on to result in under-reduction, elongation or flying off the tooling setup. SETG use trial & error methods in optimisation and recording process variables for continued improvement in spinning quality.

Therefore, more understanding of the mechanics of Carpenter 21Cr-6Ni-9Mn, stainless steel and other materials used in this Project is required to gain a deeper understanding of its failure modes during spinning. It should also be noted how material science and the mechanics of spinning are multidimensional and variable, thus shear forming shall always be a continuously improving process with more research and development.

Conclusion for each failure mode cannot be drawn from a single factor but rather from consideration of multiple interactions of process limitations, material roughness, instability, geometric deviations, tooling parameters and spinning mechanics at play. This then shows how shear forming of cones is a complicated process which requires continued optimization and operator experience acquired from endless trial and error methodology.

Overall, there is potential for future improvement when both mandrel design and process parameters are investigated further and improved.