Materials Innovation Case Study:

QuesTek's Ferrium® M54® Steel for Hook Shank Application

SUMMARY

QuesTek's Ferrium® M54® steel for application in U.S. Navy hook shanks is a notable materials innovation that serves as a current time-to-market baseline for a structure-critical aerospace product. Developed and first commercialized in four years with formal qualification three years later, this innovation was accelerated by the application of computational modeling tools and extensive ferrous materials databases, staff at QuesTek and highly capable companies that they brought to the project, and the strong support of the U.S. Navy throughout the innovation process. Although the non-technical challenges of scheduling small manufacturing runs of new materials and products in commercial production schedules inhibited the overall timeline, this ultimately successful innovation illustrates the strong benefit of implementing the tools that form the core of the Materials Genome Initiative. The following case study explores the specific actions that led to this success in more detail through the development of a "reverse roadmap," which captures and classifies the key activities that accelerated or inhibited the innovation process.

BACKGROUND

QuesTek originally developed Ferrium® M54® in response to the U.S. Navy's Small Business Innovation Research (SBIR) solicitation N07-032, "Innovative Material for Enhancing Landing Gear Life." The objective of this Phase 1 solicitation was to develop an improved alloy at a lower cost than current materials such as 4340, 300M, and Aermet® 100 used at the time in landing gear applications.[1] Phase 1 of the solicitation also specifically called for designing the alloy through modeling and simulation with feasibility confirmed through limited coupon testing. As the innovation process proceeded and in response to the needs of the U.S. Navy, the application shifted to a replacement for HY-TUF steel used in the T-45 hook shank on U.S. Navy carrier aircraft.

Founded in 1997, QuesTek Innovations LLC is a small business recognized as a global leader in Integrated Computational Materials Engineering (ICME). The company, which carried out 55 Phase I SBIR/STTR projects and 23 Phase II projects from 2002-2015,[2] uses its proprietary Materials by Design® method for developing a range of materials. While QuesTek provided materials and process design expertise as well as the overall project management for the Ferrium® M54® innovation, they also engaged a number of partners in the production of the material and the T-45 hook shank itself, especially at the intermediate and commercial scale. Specifically, the following companies had important roles in the innovation process:

- Latrobe Specialty Metals Company, which was acquired by Carpenter Technology in 2011
- SIFCO Forge, a division of SIFCO Industries, Inc.
- Bodycote, specifically in the area of heat treating
- Pankl Aerospace Systems, especially in the areas of machining and final part assembly

[1] Navy SBIR FY07.1 Proposal Submission Instructions, http://www.acq.osd.mil/osbp/sbir/solicitations/sbir20073/navy073.pdf, accessed 01/26/16.
[2] http://www.questek.com/example-projects.html, accessed 02/08/16.

In addition to these companies, the U.S Navy was also an important partner in this project. Not only did they fund Phase I of the solicitation, but they also provided continued SBIR support and were the eventual customer for the T-45 hook shank deployed at the end of the innovation process (see Figures 1a and 1b).

Thanks to the efforts of QuesTek and its partners, the Ferrium® M54® innovation is now a premium-quality steel that offers ultra-high strength and toughness. Rig testing of prototype components demonstrated a more than doubled lifespan compared with HY-TUF steel and the U.S. Navy has estimated a $3 million savings from implementing the M54 product into its T-45 hook shanks.[3] Additional applications for Ferrium® M54® Steel include aircraft landing gear and arresting tailhooks, shock struts, tow bars, drive shafts, actuators, blast containment devices, fasteners, oil and gas running cases, and other highly loaded components.

Figure 1a. Completed Ferrium M54 steel T-45 hook shank [NAVAIR Public Release #2014-712 Distribution Statement A-"Approved for public release, distribution is unlimited."]

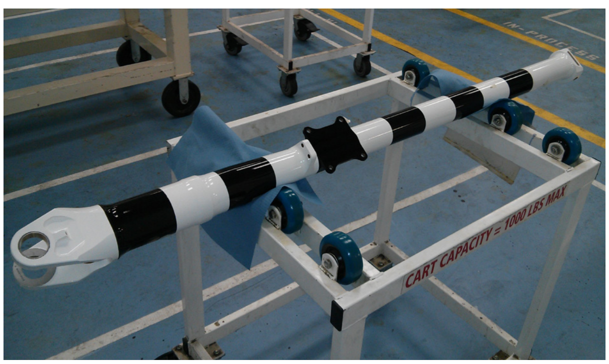


Figure 1b. Location of the hook shank on the aircraft

REVERSE ROADMAP

The materials innovation process employed to develop Ferrium® M54® Steel is outlined in a "reverse roadmap," which captures events that have already occurred, as compared with a traditional forward-looking roadmap. The reverse roadmap is presented on a time scale divided into four major categories: Design, Development, Manufacturing, and Deployment. The analytical framework in Figure 2 outlines the general structure of the reverse roadmap and can be applied to materials innovation processes across a broad range of materials, applications, and markets.[4]

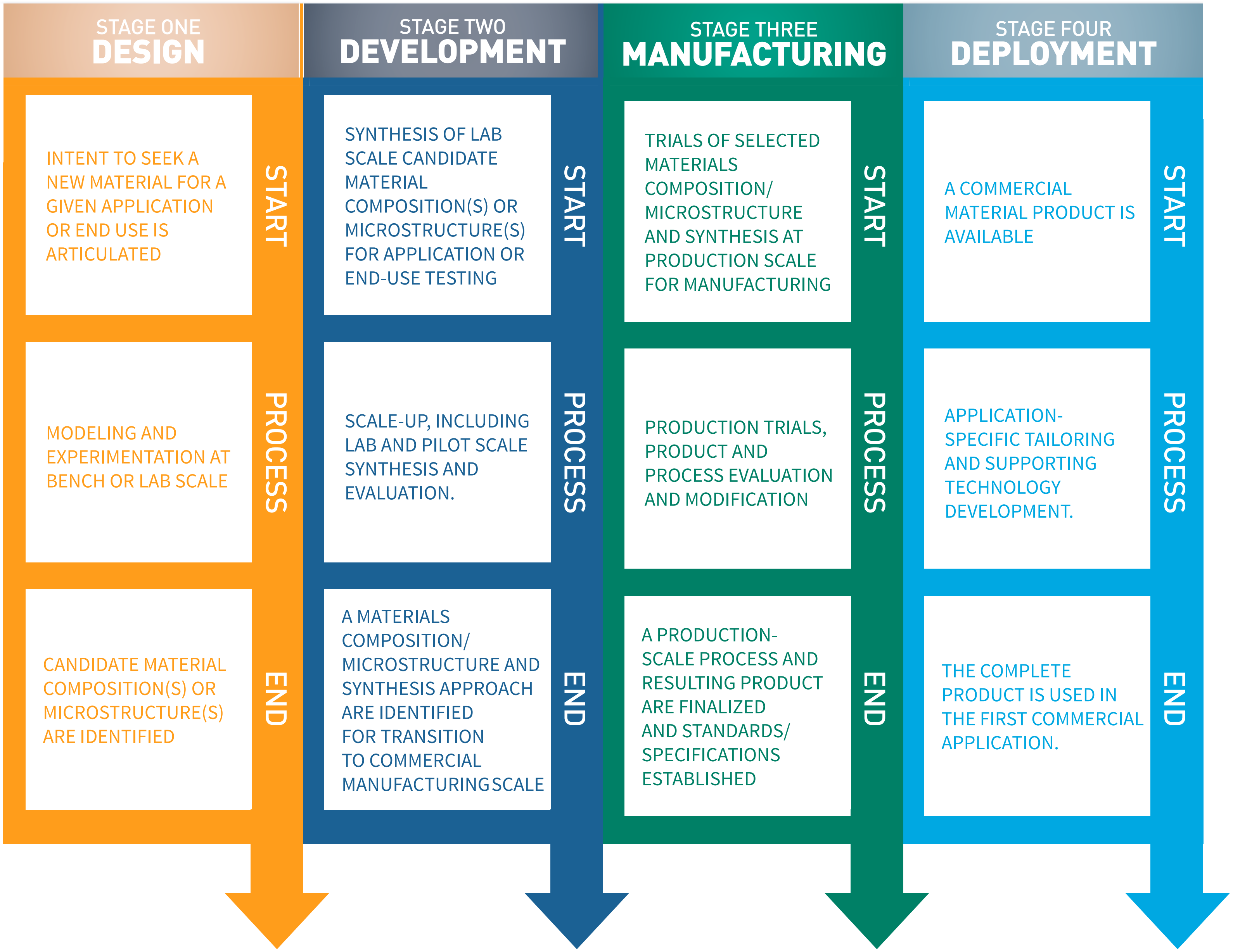
The reverse roadmap includes four primary elements:

1. Activities that occurred over time
2. Discrete events occurred at a specific point in time (e.g., milestone)
3. Factors that decreased the time needed to complete an activity (or, "accelerators"), which are shown to the right of an activity pointing backwards in time
4. Factors that increased the time needed to complete an activity (or, "inhibitors"), which are shown to the left of an activity pointing ahead in time.

The reverse roadmap constructed for Ferrium® M54® steel was developed by gathering information from QuesTek and other partners in the value chain through a combination of literature review, one-on-one interviews, a workshop at QuesTek in October 2015, and follow-up communications and reviews. It outlines the innovation over the nine-year period from the initiation of the Design stage in January 2007 (submission of Phase I SBIR proposal) through the completion of the Deployment stage in December 2015 (completion of the first set of hook shanks) and is presented in stages: Design and Development (Figure 3a), Manufacturing (Figure 3b), and Deployment (Figure 3c). Additional detail on the activities that occurred in each of the four stages is included in the text that follows.

[3] J. Grabowski, "Flying Cybersteels", presented to Steel Research Group, March 25, 2014, http://chimad.northwestern.edu/docs/SRG2014/SRG2014_Grabowski.pdf, accessed 01/26/16.
[4] "Quantitative Benchmark for Time to Market (QBTM) for New Materials Innovation", Report by Nexight Group and Energetics, Inc., January 2016.

Figure 2. Analytical Framework for Time to Market for Materials Innovation



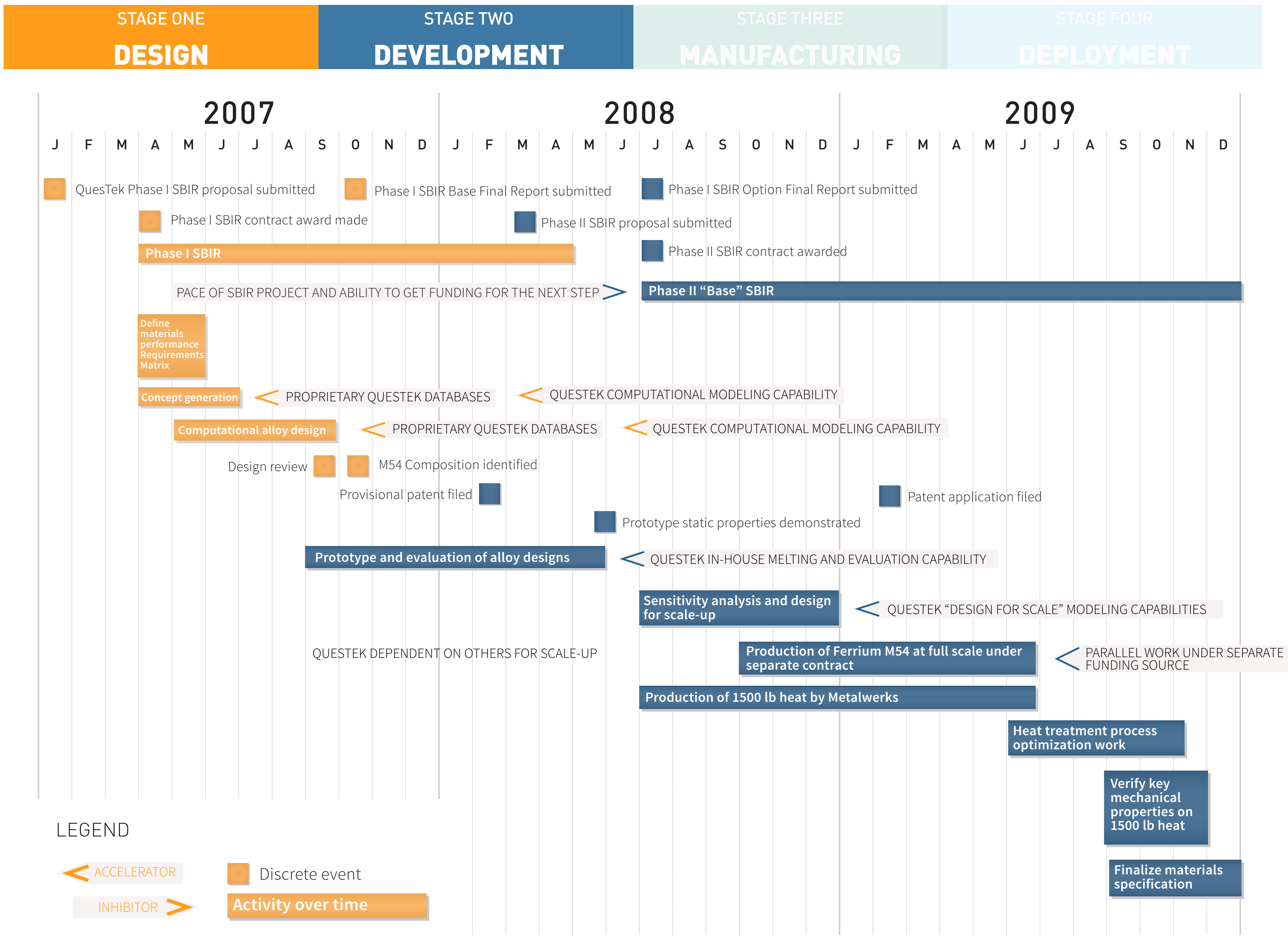

STAGE ONE
DESIGN
STAGE TWO
DEVELOPMENT
STAGE THREE
MANUFACTURING
STAGE FOUR
DEPLOYMENT
2007
2008
2009
J F M A M J J A S O N D
QuesTek Phase I SBIR proposal submitted
Phase I SBIR Base Final Report submitted
Phase I SBIR Option Final Report submitted
Phase I SBIR contract award made
Phase II SBIR proposal submitted
Phase I SBIR
Phase II SBIR contract awarded
PACE OF SBIR PROJECT AND ABILITY TO GET FUNDING FOR THE NEXT STEP
Phase II "Base" SBIR
Define materials performance Requirements Matrix
Concept generation
PROPRIETARY QUESTEK DATABASES
QUESTEK COMPUTATIONAL MODELING CAPABILITY
Computational alloy design
PROPRIETARY QUESTEK DATABASES
QUESTEK COMPUTATIONAL MODELING CAPABILITY
Design review
M54 Composition identified
Provisional patent filed
Patent application filed
Prototype static properties demonstrated
Prototype and evaluation of alloy designs
QUESTEK IN-HOUSE MELTING AND EVALUATION CAPABILITY
Sensitivity analysis and design for scale-up
QUESTEK "DESIGN FOR SCALE" MODELING CAPABILITIES
QUESTEK DEPENDENT ON OTHERS FOR SCALE-UP
Production of Ferrium M54 at full scale under separate contract
PARALLEL WORK UNDER SEPARATE FUNDING SOURCE
Production of 1500 lb heat by Metalwerks
Heat treatment process optimization work
Verify key mechanical properties on 1500 lb heat
Finalize materials specification
LEGEND
ACCELERATOR
INHIBITOR
Discrete event
Activity over time

Figure 3b. Manufacturing Stage

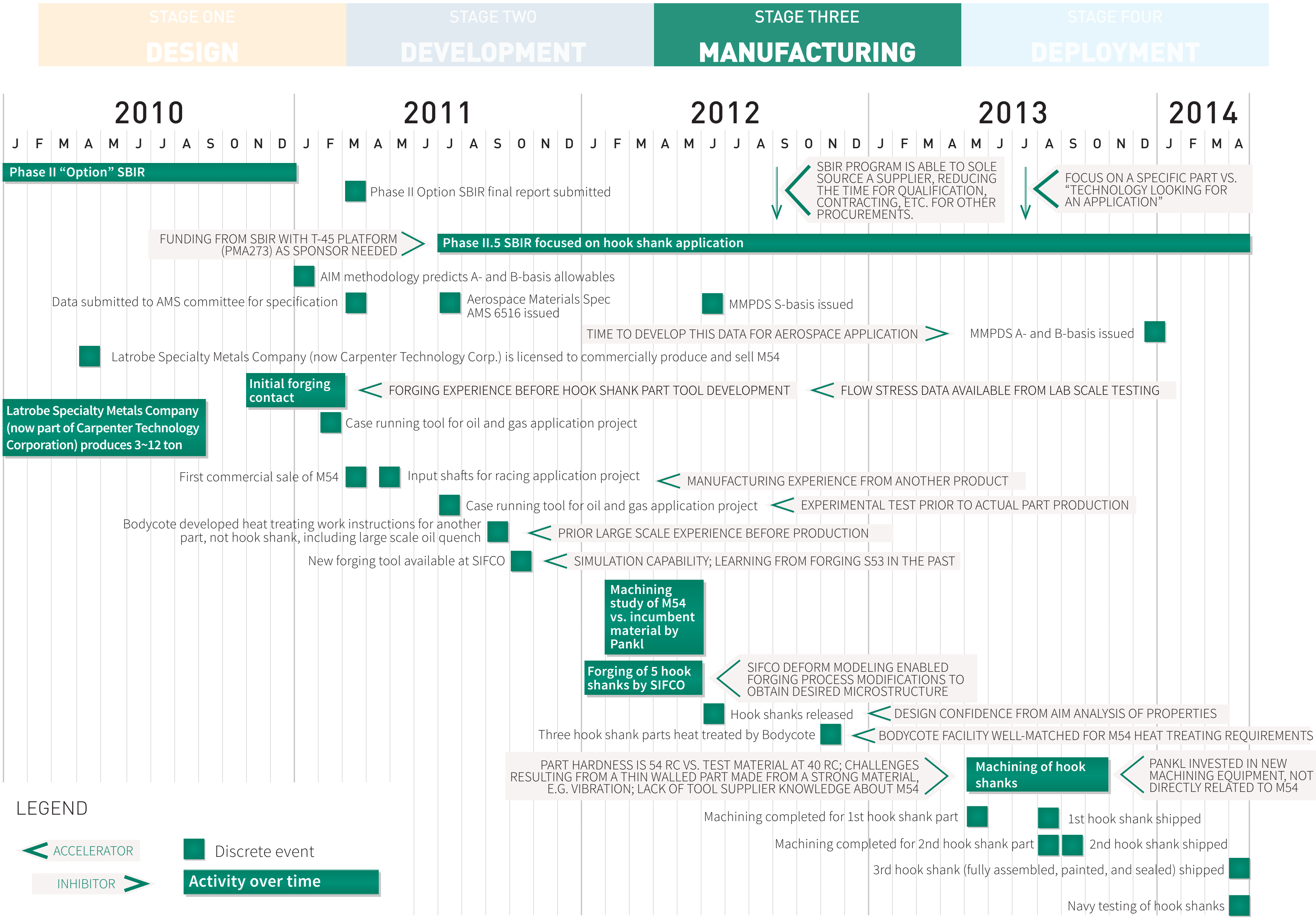
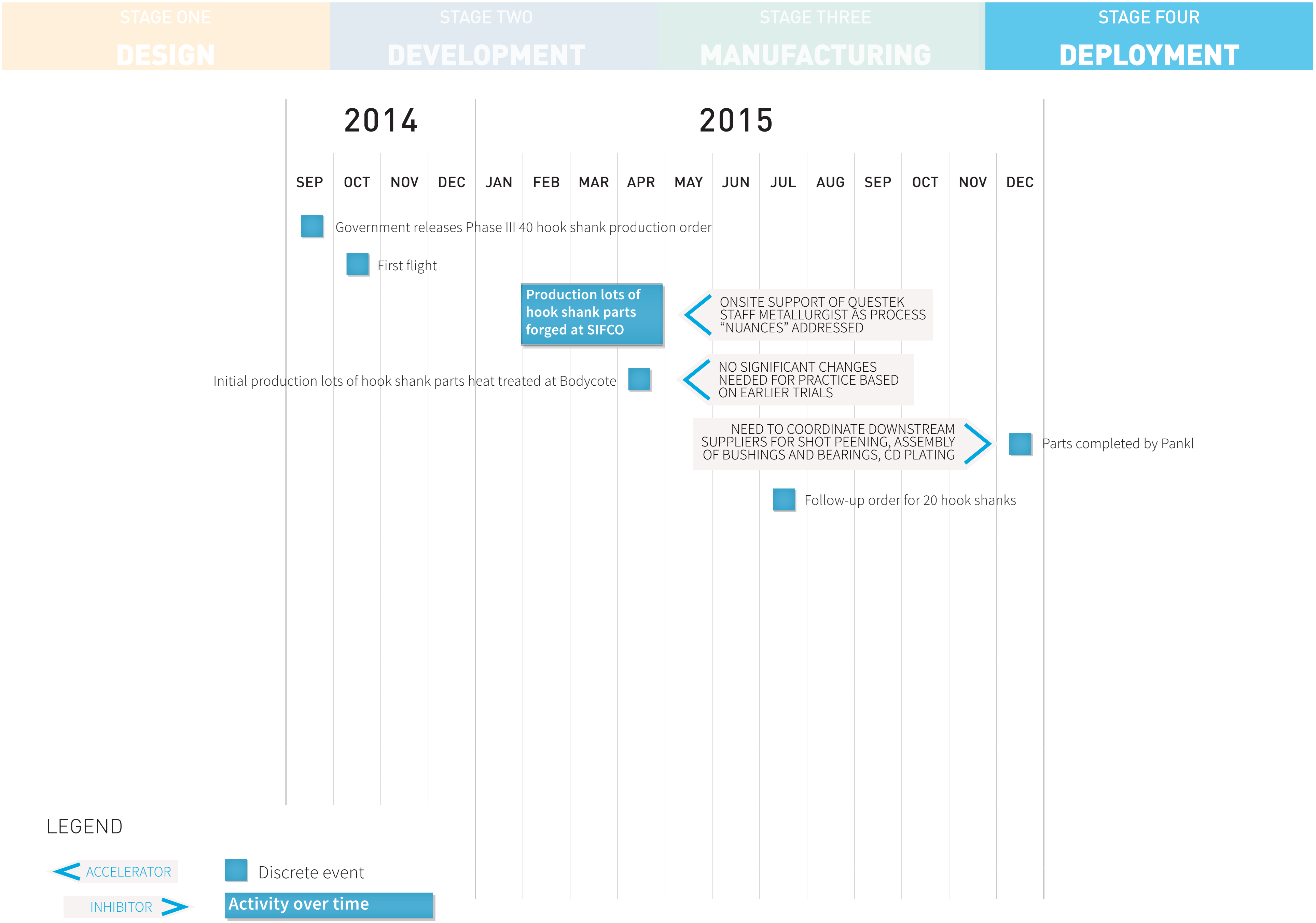


Figure 3c. Deployment Stage



Design Stage

The Design stage occurred over an approximately eight-month period from January to October 2007, beginning with QuesTek's response to the Navy's SBIR solicitation N07-032, "Innovative Material for Enhancing Landing Gear Life".[5] With the contract award, QuesTek developed a materials performance requirements matrix for the improved alloy, then generated and computationally designed materials that could potentially meet the specified requirements. The availability of QuesTek's existing proprietary databases (not publicly available) to inform the modeling as well as the extent of computational modeling capability at QuesTek were significant accelerators in moving toward a set of prospective alloy compositions.

Through the design review process, the M54 alloy composition was identified as the most promising material and was the subject of further focus in the Development stage. The bench-scale melting and evaluation that QuesTek conducted as part of the process to evaluate prospective candidate materials also initiated the Development stage.

Development Stage

Overlapping the end of the Design stage, the Development stage occurred over an approximately 28-month period beginning in Sept. 2007 and concluding at the end of 2009 with a materials specification and process for transition to full-scale manufacturing. Intellectual property protection efforts were also made in this stage, including filing a provisional patent in early 2008 and a more complete filing in early 2009, with the eventual patent issued in 2015.[6]

During the Development stage, QuesTek used their in-house bench scale prototyping capabilities to evaluate the M54 composition and develop an understanding of the microstructures and mechanical performance as a function of processing. This effort resulted in the specification of a pilot material composition that was produced in a 1500 lb. heat by Metalwerks and processed into test products for heat treatment process testing. The need to externally process the test material inhibited the work's progress, as it needed to be scheduled among other production work Metalwerks was undertaking at the time.

The processing details identified by QuesTek in the Development stage were supported by QuesTek's "design for scale" modeling.[7] This modeling supported the casting process as well as subsequent thermomechanical processing needed to produce a pilot material form suitable for mechanical property evaluation and development of the materials and processing knowledge needed to move into the Manufacturing stage. The production of the M54 alloy for another application also accelerated the innovation process at this stage, as QuesTek was able to leverage production experience and an understanding of the requirements for high-performance landing gear applications.

Manufacturing Stage

The Manufacturing stage was carried out over a 54-month period from January 2010 through April 2014. This involved enlisting the help of partner companies to commercialize the M54 material and ultimately produce commercial-ready hook shanks.

As the M54 innovation process transitioned from Development stage to Manufacturing stage, additional SBIR funding became available through the T-45 platform with PMA273 as sponsor that enabled continued progress on the M54 materials innovation: Phase II "option" funding to provide support for the continued scale-up activities and Phase II.5 funding to produce the hook shank application. While the time required to identify and secure this funding was an inhibitor in the innovation's progress, the SBIR program's ability to sole source QuesTek as the supplier helped to reduce the time required for qualification and contracting. The available funding also focused the application for M54 on the T-45 hook shank.

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[5] Navy SBIR FY07.1 Proposal Submission Instructions, http://www.acq.osd.mil/osbp/sbir/solicitations/sbir20073/navy073.pdf, accessed 01/26/16.
[6] "Lower-cost, ultra-high-strength, high-toughness steel", US Patent 9051635 B2, June 9, 2015, http://www.google.com/patents/US9051635, accessed 01/27/16.
[7] G. B. Olson, "Genomic materials design: The ferrous frontier", Acta Materialia, v. 61, 2013, pp. 771-781.

With funding secured, QuesTek moved forward with commercializing the M54 alloy. An important milestone in this process was licensing the Latrobe Specialty Metals Company to produce it using their state-of-the-art vacuum induction melting and vacuum arc remelting (VIM/VAR) equipment, which enabled the production of the premium-quality product needed to achieve target mechanical properties. Latrobe produced three 12-ton heats of the M54 composition in the Manufacturing stage that helped accelerate the process by not only providing the materials for the hook shank components, but also enabling the development of key material specifications. The development of materials specifications is critical to the production of high-performance aerospace alloys used in flight-critical applications, as they are needed to obtain the required Aerospace Materials Specification designation. QuesTek was able to obtain this designation (AMS 6516) for the M54 alloy in early 2011.[8]

As QuesTek stabilized the manufacturing process and began readying M54 for commercial use, they also developed design allowables. To obtain a Metallic Materials Properties Development and Standardization (MMPDS) allowable designation, 10 lots of the material must be produced. QuesTek used the Accelerated Insertion of Materials (AIM) analysis technique[9] along with data from three production heats to predict its MMPDS design minima. This effort gave the US Navy's T-45 program office the confidence to fund manufacturing and rig testing of three M54 steel landing gear hook shanks before it was even approved in MMPDS,[10] accelerating the overall innovation process.

With the alloy ready, QuesTek proceeded with manufacturing the hook shanks. This involved engaging outside companies to take on the key steps in the hook shank manufacturing process: forging of the components, heat treatment, machining, and assembly. The following companies contributed to the manufacturing process:

- **SIFCO Forge (forging supplier)** – SIFCO leveraged their prior experience in forging high-performance steels of similar composition, such as Ferrium S53, and available flow stress data to assist in forging modeling, which proved to be a key accelerator. SIFCO also had specific experience in forging hook shanks, and had developed a new forging die for hook shank forging that enabled incorporation of flow stress considerations for M54. (See resulting forged hook shank in Figure 4.)
- **Bodycote (heat treatment)** – Bodycote was well suited to heat treat hook shank components, as their equipment set-up matched the M54 alloy's needs well. In addition, Bodycote's prior experience in heat treating another M54 part for oil and gas application with a similar process flow accelerated the process of identifying a suitable heat treatment approach.

Figure 4. Forged Ferrium M54 Hook Shank

- **Pankl (machining and assembly)** – Prior to the machining of the hook shank parts themselves, QuesTek facilitated a machining study of M54 versus Aermet® 100 to develop production parameters.[11] As processing moved to the machining of the actual heat treated M54 parts, some machining issues arose, resulting from some machining processes being carried out in an initial study on a material with lower hardness (Rc 40)

[8] "Questek's Ferrium® M54™ Alloy Achieves SAE AMS 6516 Specification", August 3, 2011, http://www.questek.com/filebase/src/Press_Releases/QuesTeksFerrium%C2%AEM54%E2%84%A2Ach.pdf, accessed 01/27/16.
[9] G. B. Olson, "Genomic materials design: The ferrous frontier", Acta Materialia, v. 61, 2013, pp. 771-781.
[10] "Questek's Ultra-High Strength, High Toughness Ferrium® M54™ Steel Receives Approval For Inclusion In Aerospace Industry MMPDS Handbook ", January 7, 2014, http://www.questek.com/filebase/src/Press_Releases/FerriumM54SteelApprovedinM.pdf, accessed 01/27/16.
[11] "Machining Investigation of Ferrium M54", http://www.questek.com/filebase/src/Articles/FerriumM54MachiningStudy.pdf , accessed 03/18/16.

versus the actual parts (Rc 54), as well as the part geometry, specifically thin-walled sections. In addition, inexperience on the part of the tooling supplier with the M54 material was an inhibitor. Pankl did help accelerate the process through a recent investment in new machining equipment that, while not directly related to the M54 hook shank production, was beneficial to it.

In parallel with the process development for the M54 hook shank parts, QuesTek worked on other applications for the M54 alloy. These included a case running tool for oil and gas application as well as input shafts for a racing application. These parallel developments provided valuable technical information on the processing of M54.

In the latter part of the Manufacturing stage, three hook shanks were completed, one of which was fully assembled and painted. At the conclusion of the Manufacturing stage, the initial hook shanks were available for testing by the U.S. Navy.

Deployment Stage

The Deployment stage comprised approximately 16 months from September 2014 through December 2015, initiated by a production order for 40 hook shanks. Somewhat coincident with this order was the first flight of the hook shank, a milestone in the innovation process.

SIFCO forged the production hook shank parts, with valuable onsite support from QuesTek metallurgical staff to address questions as they arose. Heat treating at Bodycote proceeded without problems thanks to the work done in the Manufacturing stage. Pankl's machining and final assembly experienced some delays due to the need to coordinate downstream suppliers for process steps such as shot peening, assembly of bushings and bearings, and Cd plating. Nonetheless, the assembled hook shanks were completed by the end of 2015, ahead of the original March 2016 promise date. This milestone completed the Deployment stage of the Ferrium® M54® materials innovation.

CONCLUSION

The materials innovation process for Ferrium® M54® steel was based on a foundation of metallurgical knowledge and incorporated best-available computational tools, experimental tools, and digital data—the three main elements of the Materials Innovation Infrastructure envisioned in the Materials Genome Initiative.[12] The extent of QuesTek's metallurgical knowledge coupled with its depth of expertise, breadth of available data, and access to state-of-the-art commercial computational modeling tools were key accelerators in the M54 Design, Development, and Manufacturing stages. Specifically, QuesTek's Materials by Design® approach, the "design for scale" process modeling assisting scale-up, and the AIM-based acceleration of design property determination played important roles in accelerating the innovation process.

Inhibitors to the overall materials innovation process included two important, but essentially non-technical, components:

1. **Financial support for the innovation process** – While the SBIR funding stream that QuesTek relied on was valuable in providing the "fuel" for small business innovation and research for companies like QuesTek, the program can also slow the pace of progress through its funding cycles, funding levels, and required approval and review processes. The strong application-specific driver and overall effectiveness of the U.S. Navy team helped to countering this inhibitor.
2. **Use of external companies in scale-up and manufacturing** – These companies, while highly capable and experienced, are engaged in the production of a range of commercial products into which they have to fit trials of new materials and products. Faster progress, especially in the early scale-up work, would have been enabled by the availability of dedicated intermediate-scale development equipment and capabilities that could be accessed as needed.

[12] "Materials Genome Initiative for Global Competitiveness", June 2011, https://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf, accessed 12/30/15.

The Ferrium® M54® steel innovation process is a strong representation of the current baseline for a product with a structure-critical application and illustrates accomplishment of the MGI goal of a new materials innovation in less than 10 years. The understanding of its overall timeline, accelerators, and inhibitors provide important input to benchmarking the time-to-market for materials innovations.

ACKNOWLEDGEMENTS

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