Procurement Readiness Optimization – Forging Advanced Systems Technologies
(PRO-FAST)

Government contract: PROFAST SP4701-14-D-7012
Subcontract No.: 2015-506

Forging Process Improvement Using Intensive Quenching

Final Report

July 31, 2019

Michael Aronov
IQ Technologies, Inc.

Table of content

.

Abstract

This report presents results of the application of the Direct from Forge Intensive Quenching (DFIQ^{TM}) process to steel forgings obtained in the project's Investigation, Development, Testing and Implementation stages. For proving and quantifying of the DFIQ process benefits, a portable 600-gallon IQ water tank was designed and built. Forgings of different configurations, ranging in weight from 4 to 80lb and made of plain carbon, alloy and high-alloy steels were subjected to the DFIQ process. DFIQ trials were conducted at three forging shops: Bula Forge & Machine of Cleveland, Ohio, Welland Forge of Welland, Ontario and Clifford-Jacobs Forgings of Champaign, Illinois (both of the IMT Forge Group). The following material mechanical properties were evaluated: tensile strength, yield strength, elongation, reduction in area and impact strength. Data obtained on the mechanical properties of DFIQ forgings were compared to that of forgings after applying a conventional post-forging heat-treating process. Values of heat transfer coefficients in the DFIQ tank were determined experimentally using a special probe. This data was needed for calculating an optimal dwell time when quenching forgings in the DFIQ tank. It was shown that the application of the DFIQ process allows elimination of the normalizing process and, in some cases, quench and tempering processes. The use of the DFIQ process significantly reduces energy consumption and work-in-process handling costs, as well as a production lead-time since a post-forging heat-treating process will be eliminated for many forgings.

1. Executive Summary

High-temperature thermo-mechanical treatments of steel (forging, rolling, extrusion, etc.) followed immediately by rapid quench cooling, improves mechanical properties of steel compared to the conventional high-temperature thermo-mechanical treatments when parts are allowed to cool to room temperature prior to further heat treatment. Rapid cooling of the part right after completion of the plastic deformation improves the material's mechanical properties due to "freezing" of the dislocations in steel created by plastic deformation and due to formation of the finer material microstructure. This report presents results of the application of the Direct from Forge Intensive Quenching (DFIQ^{TM}) process to steel forgings obtained in project Investigation, Development, Testing stages and Implementation stages.

The work was conducted under the government contract PROFAST SP4701-14-D-7012 (subcontract No. 2015-506) funded by Defense Logistics Agency (DLA) and managed by Advanced Technology International, Inc. The key project participants are as following: IQ Technologies, Inc. of Akron, Ohio, three forging shops (Bula Forge & Machine, Inc. of Cleveland, Ohio, Welland Forge of Welland, Ontario and Clifford Jacobs Forge of Champaign, Illinois – both of the IMT Forge Group) and DANTE Solutions of Cleveland, Ohio. The following work was done over the course of the project:

- A thorough literature search was conducted and the applicability of the DFIQ method to forgings produced by the above forging shops was evaluated. Production forging most suitable for the proposed process were identified. A financial feasibility of the DFIQ method was evaluated based on the analysis of the expected benefits and capital investment needed for the method realization.
- A portable 600-gallon DFIQ system was designed, fabricated and installed at Bula Forge & Machine. The DFIQ system allows quenching of forgings of up to 120lb. A concept of the proposed DFIQ method was proved by conducting a material characterization study using actual forgings (keys) made of different steels. The following material properties were evaluated: tensile strength, yield strength, elongation, reduction in area, impact strength and steel grain size. Material properties were determined by NSL Metallurgical Lab and Tensile Testing Metallurgical Lab both of Cleveland, Ohio. Mechanical properties obtained for the DFIQ keys were compared to that of the standard keys.
- Values of heat transfer coefficients in the DFIQ tank were determined experimentally by DANTE Solutions using a special probe. This data was needed for calculating an optimal dwell time when quenching forgings in the DFIQ tank.
- The DFIQ process was applied to the specified actual production forgings produced by the above three forging shops. The following production forgings made of different plain carbon, alloy and high-alloy steels were processed at the above three forging shops in the portable DFIQ water tank: pintle adapters, lugs, tines, disks, hubs, glands, stoppers, clamps, yokes, drum supports and gear shaft blanks. All forgings were subjected to non-destructive magnetic particle inspection. Mechanical properties obtained for the production DFIQ forgings were compared to that of the standard forgings as well as to the part specifications.

The following benefits from implementing of the DFIQ process were proved:

- Shorter lead time and significant energy savings due to elimination of traditional normalization and hardening processes currently used for part heat treatment.
- Elimination of the use of environmentally unfriendly and hazardous quench oil and associated costs (part washing, cleaning, etc.).
- Production of forging with better mechanical properties resulting in better competitiveness and more robust parts in the marketplace.
- Possibility of using less expensive less alloy steel for the same part performance characteristics.

The following conclusions were made:

- DFIQ process was proven to work for a variety of steel forgings having different geometries and made of different steels.
- DFIQ process can be used successfully to produce microstructures and properties that meet product requirements, while saving energy by eliminating a reheat step prior to final heat treatment.
- The forging microstructures appear to be similar for the conventional and DFIQ processes, and in some cases, the DFIQ microstructure was found to be slightly coarser (but still acceptable) than the conventionally processed forgings.
- Strength and hardness values were acceptable in all cases. The strength properties tended to be higher for DFIQ treated forgings, most likely due to a higher cooling rate. For example, the material characterization study showed that for 4140 steel DFIQ forgings with an ASTM grain size greater than 7.0, the tensile and yield strength improved by 6-7%, while the value of the impact strength more than doubled and material plastic properties improved by more than 50%.
- One of the main DFIQ process benefits is that the heat from hot forging can be used with DFIQ to eliminate the need for a second or even third reheat.
- DFIQ process applicability is subject to hardenability of the steel being used, part geometry, and more importantly to the manufacturing steps that follow hot forging operation.
- If thermal treatment after forging is the final heat treatment, then DFIQ has sound benefit as it should produce the desired properties and eliminate a reheating step.
- If a forging will be machined and carburized as a final step, grain size is important since grain boundaries provide the easiest carbon diffusion path into the part. The smaller the grain size the more effective the carburizing process. Hence, cooling rate after forging can be a benefit for DFIQ.
- Application of the DFIQ process, in some cases, allows elimination of the normalizing and quench and tempering processes followed after forging resulting in significant reduction of a production lead-time and work-in-process handling costs.

2. Introduction.

This project was conducted under the government contract PROFAST SP4701-14-D-7012 (subcontract No. 2015-506) funded by Defense Logistics Agency (DLA) and managed by Advanced Technology International, Inc. The key project participants were as following: IQ Technologies, Inc. of Akron, Ohio, three forging shops (Bula Forge & Machine, Inc. of Cleveland, Ohio, Welland Forge of Welland, Ontario and Clifford Jacobs Forge of Champaign, Illinois) and DANTE Solution of Cleveland, Ohio.

There is a need in the machine-building and manufacturing industries to improve performance characteristics of critical steel parts and to increase a power density of various machines and mechanisms. Forging and post-forging heat treatment are critical steps in the steel part manufacturing process, affecting part quality, cost, and overall production lead time. Forgers are striving to reduce lead times, improve quality of forgings, and reduce the costs of heat treating operations. Many forging companies outsource post-forging heat treatment that usually includes normalizing, annealing and quench and temper. Forging companies often perform extra steps to achieve the required mechanical properties, adding cost and lead time.

2.1 Background.

One of the ways for making the forging process more efficient and for improving mechanical properties of steel during the “forging phase” of manufacturing steel products is quenching forgings right after the plastic deformation is competed while forgings are still hot. As it was shown in reference [1], the high-temperature thermo-mechanical treatments (HTTMT) of steel (forging, rolling, extrusion, etc.) followed immediately by rapid quench cooling, improves mechanical properties of steel compared to the conventional HTTMT process when parts are allowed to cool to room temperature prior to further heat treatment. Table 1 presents data on the improvement of mechanical properties for test samples made of AISI 1040 steel after forging followed by quenching and after conventional heat treatments. In both cases, the test samples were quenched in water after forging and were tempered at about 400^0F.

Table 1 Mechanical properties of AISI 1040 steel after HTTMT

Method	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Reduction in area, %
Conventional HTTMT, normalize then reheat, water quench + temper	1,422	1,246	2	16
HTTMT followed immediately by water quenching	1,972	1,570	7	40

As seen from Table 1, the tensile strength and yield strength increased by more than 20% after HTTMT followed immediately by quenching compared to the conventional plastic deformation process. The plastic properties of material improved by more than double. Author of [1,2] has made a conclusion that the HTTMT followed immediately by quenching can be successfully applied for production of steel strips, sheets and wires. Authors [3] reported that HTTMT coupled with quenching improves mechanical properties of low alloy and stainless steels as well.

Rapid cooling of the part right after completion of the plastic deformation improves material mechanical properties due to the following two reasons:

a) "Freezing" of the dislocations in steel that are created by plastic deformation of the part.
b) Formation of the finer grains in the microstructure of the material compared to the conventional plastic deformation processes.

Note that rapid cooling of parts right after completion of the forging operations is effective also in cases when parts require further heat treatment (for example, carburizing and quenching). The substitution of the rapid cooling for normalizing or annealing (conducted after forging per the current practice) will provide forged parts with a better microstructure and hence with better mechanical properties.

The forging process followed immediately by quenching is not widely used in the industry due to the following three major reasons:

a) Conventional quenching in oil is not suitable for forging shops operations due to fire hazards.
b) The use of conventional water quenching is applicable only to forgings made of "water quench" grades of steel and to parts of simple shape due to possible crack formation.
c) "Forgers" are traditionally not "heat treaters" and do not wish to invest or delve into the heat treating process.

The forging process can be effectively coupled with an intensive quenching (IQ) process. The IQ process is an alternative method of quenching steel parts in highly agitated water, and then in air [4,5]. An extremely high cooling rate within the martensite formation range provided by the IQ method will further augment the effect of the rapid cooling on the improvement of material mechanical properties (see Table 1 above).

During the IQ process, high ***"current"*** surface compressive stresses are developed almost immediately upon the commencement of the quench. These surface compressive stresses work similar to a die, holding the hot part and preventing the part from cracking during quenching. The quench process is interrupted at a time when these compressive stresses are at their maximum to an optimal depth, while the part core is still hot, thus allowing (a) self-tempering of the part's martensite surface layer by uniform conduction of the heat coming from the core, and (b) at the same time, maintaining ***residual*** compressive surface stresses (even in through-hardened parts).

The self-tempered, strong surface layer, combined with the presence of the ***residual*** compressive stresses, prevent the part from cracking after the IQ process is completed. In addition, the use of water as a quenchant will not create any fire hazard or other environmental problems with placing the compact intensive quenching equipment in forging shops.

Based on the information available at the beginning of the project, a value of the DFIQ technology readiness level (TRL) was estimated as 2 – Technology concept and applications are formulated. A value for the DFIQ equipment manufacturing readiness level (MRL) was estimated as 1 – Basic manufacturing implications are identified. Both the TRL and the MRL were evaluated per DOD guidelines.

2.2 Project Goal.

The project goal was to evaluate the effect of the direct from forge intensive quenching (DFIQ) process on improving forgings mechanical properties and effectiveness of the forging process (reducing of energy consumption, minimizing of post-forging heat treatment, shorten lead time, etc.). Table 2 presents project key performance indicators (KPI).

Table 2 Project KPI

Parameter	Baseline value	Requirement threshold value	Requirement objective value	How to measure
Production lead time	14-28 days	5 days	10days	Days
Heat treat cost reduction	100%	20%	30%	Dollars
Mechanical properties improvement	100%	5%	10-20%	%
Alloy cost reduction	100%	10%	15%	Dollars

3. Project Approach.

3.1 Project Stages.

The project included the following four stages: Investigation, Development, Testing and Implementation. In the project Investigation stage, a thorough literature search on the application of the DFIQ process was conducted. An applicability of the DFIQ method to forgings produced by the above forging shops was evaluated and production forging most suitable for the proposed process were identified. A financial feasibility of the DFIQ method was evaluated based on the analysis of the expected benefits and capital investment needed for the method realization.

The goal of the project Development stage was to prove a concept of the proposed DFIQ method by conducting a material characterization study. A portable DFIQ system was designed, fabricated and installed at Bula Forge & Machine. Actual forgings (keys) made of different steels were specified for the material characterization study. Mechanical properties obtained for the DFIQ forgings were compared to that of the standard forgings. Since the results obtained were favorable, the project Testing stage was initiated.

In the project Testing stage, the DFIQ process was applied to the specified actual production forgings produced by the above three forging shops. Mechanical properties obtained for the DFIQ forgings were compared to that of the standard forgings as well as to the parts specs. The following benefits from implementing of the DFIQ process were proved:

- Shorter lead time and significant energy savings due to eliminating of the traditional normalization and hardening processes currently used for part heat treatment.
- Elimination of the use of environmentally unfriendly and hazardous quench oil and associated costs (part washing, cleaning, etc.).
- Production of forging with better mechanical properties resulting in better competitiveness and more robust parts in the marketplace.
- Possibility of using less expensive less alloy steel for the same part performance characteristics.

Based on the results obtained in the Testing stage of the project, Clifford-Jacobs Forge decided to initiate the project Implementation stage at its facilities. Clifford-Jacobs Forge specified three production forgings to be subjected to the DFIQ process and conducted an economical evaluation of the benefits provided by the DFIQ process for these forgings. IQ Technologies, Inc. provided Clifford-Jacobs Forge with a quote for the production DFIQ system and for a quenchant cooling system. Clifford-Jacobs Forge evaluated a return on investment and decided to acquire the DFIQ unit. In addition, PC Forge of Port Colborne, Ontario (another forging shop of the IMT Forge Group) specified one more part for the DFIQ process implementation – a yoke bar.

3.2 Portable 600-gallon DFIQ Unit.

For implementing the DFIQ process, a portable IQ unit was designed and fabricated. Fig.1 shows a picture of the DFIQ unit. The DFIQ unit approximate dimensions are 140"Wx40"Dx90"H. The DFIQ unit uses a Daphne IntensiQuench® quenchant developed by IQ Technologies, Inc. together with Idemitsu Kosan, Ltd. of Japan. This quenchant minimizes duration of the non-controllable and non-uniform film boiling process when quenching hot forgings.

Fig. 1 Portable IQ unit.

The DFIQ unit includes the following major components: a 600-gallon stainless steel tank; a loading and unloading table for moving forgings into and from the tank; a variable speed conveyor for moving forgings from the quench bath; a manifolds equipped with a set of nozzles; a water pump; a Sludgebuster for cleaning the quenchant from the scale coming from quenched forgings; a chiller for maintaining the quenchant temperature within the specified range; and a control system.

The DFIQ unit design allows quenching of forgings either on the loading/unloading table (a "TABLE" mode of quenching), or on the tank conveyor (a "CONVEYOR" mode of quenching). A sequence of the DFIQ tank operation is the following:

a) Hot forging is placed manually onto the DFIQ tank loading/unloading table (Fig. 2 shows a hot forging on the loading/unloading table eight before quenching).
b) DFIQ tank operator starts the quench cycle by pushing the "QUENCH" button on the PLC touch screen.
c) When a "TABLE" mode of quenching is used, the loading/unloading table with the hot part moves down into the quench. The forging is kept in the quench for a predetermined dwell time, and then the loading/unloading table moves up pulling out the forging from the quench bath.

d) When the ‘conveyor’ mode of quenching is used, the loading/unloading table with the hot part moves down. When the loading/unloading table is in its lower position, it flips over dropping the forging onto the conveyor. The conveyor brings the forging from the quench and drops it into a bin. The conveyor speed is set up based on the predetermined dwell time.

Note that the quench is interrupted at a time when part current surface compressive stresses are at their maximum value. The optimal dwell time depends on the forging geometry, dimensions and type of steel and is calculated using IQ Technologies proprietary software.

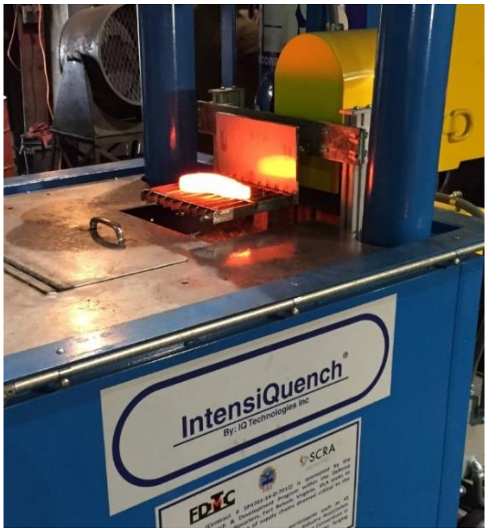


Fig. 2 Hot forging placed on DFIQ unit loading/unloading table.

4. DFIQ Trials Results and Discussion.

4.1 Material Characterization Study.

The material characterization study was conducted at Bula Forge & Machine using actual forgings - keys (Fig. 3).

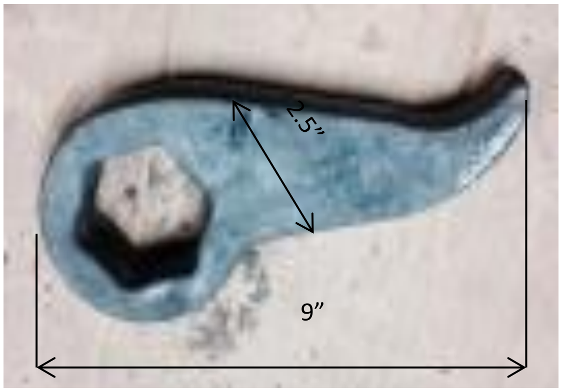


Fig. 3 Forged keys used for material characterization.

The keys were forged out of Ø2.25x10" billets using the following forging operations: pan cake, block, finish and trim. The total forging plastic deformation exceeded 50%. Table 3 presents a test matrix used for evaluation of DFIQ process. To avoid part cracking, the DFIQ process was interrupted at a time when current surface compressive stresses were at their maximum value. At this time, the key core was still hot. When the key was pulled out of the quench, the part temperature equalized throughout the key cross section resulting in self-tempering of the part surface layers. During the self-tempering process, the key temperature was between 500ºF and 400ºF for 25 minutes.

Table 3 Material characterization procedure test matrix.

Part	Type of steel	Number of keys	Heat treating process applied after forging	Notes
 Key	1045	3	Conventional: Cool in the air + oil quench + temper at 600ºF.	Results on material microstructure and mechanical properties obtained were used as baseline data.
	4140	3		
	8640	3		
	4340	3		
	1045	3	DFIQ + self-temper	Material microstructure and mechanical properties were compared to the baseline data.
	4140	3		
	8640	3		
	4340	3		
	4140	5	DFIQ + self-temper + temper at 560ºF.	
	8640	5		
	4340	5		

The following mechanical properties were determined: tensile, yield and impact strength, elongation and reduction in area. Tensile and Charpy specimens were taken from part mid radius. Mechanical properties as well as material ASTM grain size were determined by NSL Metallurgical Lab of Cleveland, Ohio. Pictures of the key's microstructure are presented in Appendix 1. Keys mechanical properties raw data are presented in Appendix 2.

As seen from figures of Appendix 1, the material for all keys at mid-radius consists of tempered martensite except for the keys made of 1045 steel that went through a conventional heat-treating process after forging. These keys were not quenched through in oil, and the material at the key mid-radius has a mixed microstructure consisting of ferrite with possible pearlite and bainite. Due to different microstructures of the key core, mechanical properties obtained for the standard keys and for the DFIQ keys cannot be compared.

To simplify the analysis of the data obtained, Table 4 presents only average values of the mechanical properties rounded to a proper significant number. Table 4 presents also data on the material ASTM grain size. As seen from Table 4, the effect of the DFIQ process on material mechanical properties were mixed when forgings were only self-tempered: some mechanical properties improved while some mechanical properties got worth compared to that of conventional heat treatment. However, the application of the DFIQ process followed by tempering at 560ºF (in addition to the self-tempering process) generally improved all material mechanical properties. For example, the improvement of mechanical properties is ranging from 4 to 21% for the tensile strength, up to 28% for the yield strength and from 13 to 120% for the impact strength. In addition, all mechanical properties (except elongation) of the DFIQ keys made of 4140 steel are the same or better compared to that of conventionally heat-treated keys made of higher alloy and more expensive 4340 steel (see also data obtained for pintle adapters made of these two steels and presented in Table 6 of Section 4.2.1).

Table 4 Key *average* mechanical properties and material grain size.

Steel	Heat-treating process applied after forging	Tensile psi	Yield psi	RA %	Elong. %	Impact ft·lb	Hardness at ¼ thickness RC	ASTM grain size
4140	**Conventional:** cooling in the air followed by quench in oil and temper at 600ºF for 2hr	252,000	220,000	26	10	5	49	8.0
	DFIQ followed by self-tempering process only.	287,000	168,000	26	14	14	52	
	DFIQ followed by self-tempering and additional tempering at 570ºF for 2hr	266,000	235,000	40	10	11	49	7.0-8.0
4340	**Conventional:** cooling in the air followed by quench in oil and temper at 600ºF for 2hr	262,000	234,000	39	14	8	51	8.0
	DFIQ followed by self-tempering process only.	286,000	184,000	14	11	13	55	
	DFIQ followed by self-tempering and additional tempering at 570ºF for 2hr	275,000	240,000	35	8.5	9	52	7.0-8.0
8640	**Conventional:** cooling in the air followed by quench in oil and temper at 600ºF for 2hr	221,000	178,000	22	12	6	49	8.0
	DFIQ followed by self-tempering process only.	295,000	177,000	7	9	14	52	
	DFIQ followed by self-tempering and additional tempering at 570ºF for 2hr	267,000	229,000	36	9	8	51	7.0-8.0

4.2 Discussion of Results Obtained.

DFIQ trials using production forgings were conducted in all three forging shops participated in the project. The forgings subjected to the DFIQ process were made of different plain carbon, alloy and high alloy steels, weighted from 4 to 80lb and covered a wide range of relatively complex geometries. All DFIQ forgings (except Pyrowear-53 spur gear shafts) were snap-tempered at 350-400ºF for 2 hours after intensive quenching before shipping to Euclid Heat Treating Co. (EHT) of Cleveland, Ohio for a final tempering and for further mechanical properties and microstructure evaluation by NSL Metallurgical (NSL) and Tensile Testing Metallurgical Laboratory (TTML) both of Cleveland, Ohio (TTML). Raw data on production forgings mechanical properties are presented in Appendix 3. For forgings processed at Bula Forge & Machine and Welland Forge, mechanical properties obtained for the DFIQ forgings were compared to that of the standard forgings. For forgings processed at Clifford-Jacobs Forging, mechanical properties of the DFIQ forgings were compared either to available historical data, or to the parts' specs. To simplify the analysis of the results, average values of the mechanical properties rounded to a proper significant number were used. DANTE Solutions, Inc. of Cleveland, Ohio conducted a metallurgical characterization of the production DFIQ forgings in conjunction to the material mechanical properties [6]. The section below includes findings of both the DANTE Solutions and the IQT.

4.2.1 Processing of Pintle Adapters and Lugs at Bula Forge & Machine.

Figure 4 presents pictures of the lug and pintle adapter. Table 5 presents characteristics of forgings processed at Bula Forge & Machine and heat-treating processes used. A typical forging temperature used at Bula Forge & Machine is 2,150°F. After final tempering at 1,180°F, material hardness at mid-radius was about 30RC for both the standard pintle adapters and for the DFIQ pintle adapters made of 4340 steel and 4140 steel. After final tempering at 1,100°F, material hardness at mid-radius was about 37RC for both the standard lugs and for the DFIQ lugs. Figures A5-A7 in Appendix 1 present photos of the pintle adapters and lugs material microstructure. As seen from the figures, a tempered martensitic structure was obtained at mid-radius for all pintle adapters and lugs. The material grain size was about the same for the DFIQ pintle adapters and lugs and for the standard pintle adapters and lugs. Tables 6 and 7 present average mechanical properties and material grain size obtained for the DFIQ and standard pintle adapters and lugs.

Lug

Pintle adapter

Fig. 4 Lug and pintle adapter.

All processed DFIQ pintle adapters and lugs were subjected to the magnetic particle inspection (MPI). No quench cracks were observed in all forgings after applying the DFIQ process.

The following conclusions can be made based on the data presented in Tables 6 and 7:

a) For pintle adapters made of currently used 4340 steel:

- Application of the DFIQ process followed by tempering at 1,180°F provides required material mechanical properties: the average tensile strength for the DFIQ pintle adapters was 136,000 psi vs. 130,000 psi required and the average elongation was 23% vs. 19.7% required. Thus, the DFIQ process followed by tempering at 1,180°F allows elimination of not only the normalizing process but *all three* post-forging heat-treating operations currently used: normalizing, cycle annealing and quenching in oil. Fig. 5 shows a flow chart of the pintle adapter manufacturing process. Per Bula Forge and Machine, the elimination of the above three post-forging heat treating operations will result in the reduction of the pintle adapter production lead time by 7-8 days and the cost of the heat treatment process by at least $0.6/lb (or more than $12 per part).

Table 5 Characteristics of processed forgings and heat-treating processes used at Bula Forge & Machine.

Shop	Part name	Steel	Weight	Post-forging heat treatment		No. of parts
				Currently used	Applied	
Bula Forge & Machine	Pintle adapter	4340	17lb	Cool in air – normalize – cycle anneal – quench in oil & temper at 1,180°F to hardness of about 30RC.	DFIQ –temper at 350°F – temper at 1,180°F	7
		4140		–		5
	Lug	8637	11lb	Cool in air – normalize – quench in oil & temper at 1,100°F to hardness of about 37RC.	DFIQ –temper at 350°F – temper at 1,100°F	7

Table 6 Pintle adapter average mechanical properties and material grain size.

Steel	Heat treating processes applied after forging operations were completed	Mechanical properties					
		Tensile psi	Yield psi	RA %	Elong. %	Impact lb·ft	ASTM grain size
4340	Currently used process: normalize + cycle anneal + quench in oil & temper at 1,180°F	140,000	125,000	60	23	68	8.0
	DFIQ + cycle anneal + quench in oil & temper at 1,180°F (no normalizing process).	142,000	121,000	52	21	66	-
	DFIQ + temper at 1,180°F (no normalizing, cycle annealing and quenching in oil processes).	136,000	112,000	55	23	63	7.5
4140	DFIQ + normalize + IQ & temper at 1,180°F.	146,500	128,500	62	19	82	8.5
	DFIQ + temper at 1,180°F (no normalizing and second IQ processes).	134,000	113,000	54	20	63	8.0
Pintle adapter specs:		**>130,000**	**-**	**-**	**>19.7**	**-**	

Table 7 Lugs average mechanical properties and material grain size.

Heat treating processes applied after forging operations were completed	Mechanical properties					
	Tensile psi	Yield psi	RA %	Elong. %	Impact lb·ft	ASTM grain size
Currently used process: normalize + quench in oil & temper at 1,100°F.	151,000	139,000	34	16	18	8.0
DFIQ + temper at 1,100°F (no normalizing and second quench processes).	149,000	127,000	45	18	18	7.0

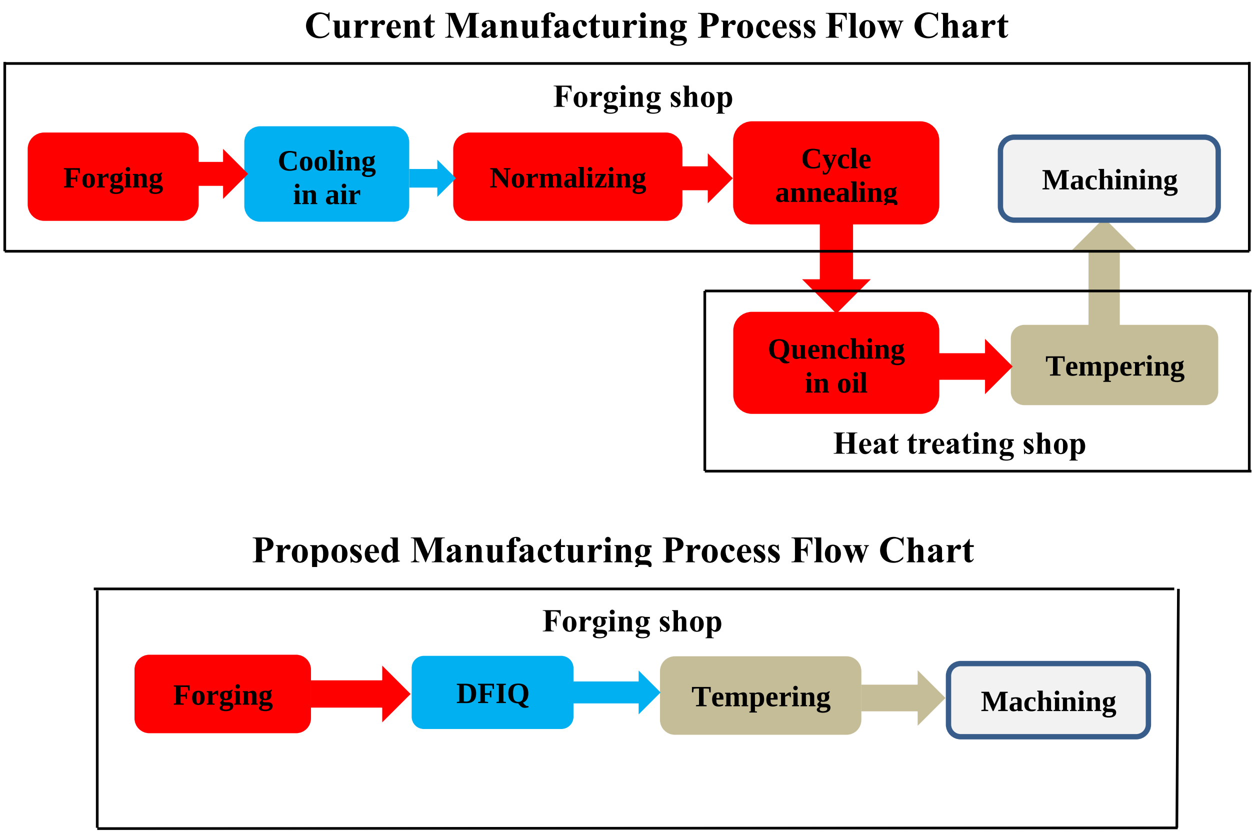


Fig. 5 Pintle adapter manufacturing process flow chart.

b) For pintle adapters made of less alloy 4140 steel:

- The application of the DFIQ process followed by tempering at 1180°F provides specified tensile strength (134,000 psi vs. 130,000 psi required), while the material elongation is barely above the specs (20% vs. 19.7% required). More testing is needed for evaluation whether less alloy 4140 steel can be substituted for more alloy 4340 steel.
- The use of the normalizing process and the second quenching process after DFIQ process provides greater material mechanical properties (except the elongation) compared to the DFIQ process followed by tempering at 1180°F.

c) For lugs:

- Application of the DFIQ process followed by tempering at 1100°F provides about the same tensile strength and impact strength as that for the conventionally heat-treated lugs, and for the DFIQ lugs are about the same. The yield strength is slightly greater for the conventionally heat-treated lugs, while the plastic properties are better for the DFIQ lugs.

4.2.2 Processing of Tines at Welland Forge.

Fig. 6 present a picture of the tine. Table 8 presents characteristics of forgings processed at Welland Forge and heat-treating processes used. A typical forging temperature used at Welland Forge is 2,250ºF. The hardness of the DFIQ tines was 56-56 RC after tempering at 400-420ºF which is within the specs. The DFIQ and standard tines average mechanical properties and material grain size are presented in Table 9, pictures of tine microstructure are presented in Appendix 5.

Fig 6 Tine.

Table 8 Characteristics of processed forgings and heat-treating processes used at Welland Forge.

Shop	Part name	Steel	Weight	Post-forging heat treatment		No. of parts
				Currently used	Applied	
Welland Forge	Tine	8650	4.3lb	Cool in air –quench in oil & temper at 460ºF to hardness of about 53-57RC.	DFIQ –temper at 400-420ºF	28
		4140				28

Table 9 Tines average mechanical properties and material grain size.

Heat treating processes applied after forging operations were completed	Mechanical properties					
	Tensile psi	Yield psi	RA %	Elong. %	Impact lb·ft	ASTM grain size
Currently used process: quench in oil & temper at 420ºF.	297,000	226,300	30	12	11	8.0
DFIQ + temper at 400ºF.	303,300	222,300	5	6	7	5.0

As seen from the Table 9, the tensile and yield strength for the DFIQ tines are about the same as that for the standard tines, while the material elongation, reduction in area and the impact strength are much better for the standard tines. A much coarser martensitic structure for the DFIQ tines could be the major factor affected steel plastic properties.

All processed DFIQ tines were subjected to MPI that revealed quench cracks in almost all DFIQ times. IQT believes that the major reasons for cracking of tines during the DFIQ process are the following:

- Too complex part shape resulting in a non-uniform martensite formation throughout the tine surface layer, which, in turn, caused formation of current tensile surface stresses during the quench.
- Too much carbon content in steel resulting in an excessive swelling of the tine core and in cancelling of the current and residual surface compressive stresses that prevent parts from cracking.
- Poor DFIQ tines plastic properties due to a course microstructure obtained for the DFIQ tines (which may be a result from the overheating of the billets prior to quenching).

A possible solution for eliminating of the tine cracking during the DFIQ process is the following:

- Use of steel having less carbon content (for example 8637 steel).
- Use of lower reheating temperature for billets prior to forging.

4.2.3 Processing of Forgings at Clifford-Jacobs Forging.

Figure 7 presents pictures of forgings processed at Clifford-Jacobs Forging. Table 10 presents characteristics of processed forgings and heat-treating processes used. A typical forging temperature used at Clifford-Jacobs Forging is 2,350ºF. Table 11 presents average mechanical properties values obtained for DFIQ forgings produced by Clifford-Jacobs Forging, historical data on mechanical properties for the same forgings subjected to the conventional post-forging heat treatment and current part specs. Photos showing the DFIQ forgings microstructure are presented in Appendix 6. Appendix 7 shows locations of the tensile specimens for all processed forgings.

Disk Hub Stopper Spur gear shaft

Gland Clamp Drum support Yoke

Fig. 7 Forgings process at Clifford-Jacobs Forging.

Table 10 Characteristics of processed forgings at Clifford-Jacobs Forging.

Shop	Part name	Steel	Weight	Post-forging heat treatment		No. of parts
				Currently used	Applied	
Clifford Jacobs Forging	Disk	5130	9.6lb	Forge – cool in air – quench in oil and temper at 1,135ºF to hardness of 28-32RC.	DFIQ –tempered at 400ºF – tempered at 1,200ºF.	5
	Hub	4140	21lb	Forge – cool in air – quench in oil and temper at 1,050ºF to hardness of 31-37RC.	DFIQ –tempered at 400ºF– tempered at 1,150ºF.	6
	Stopper	1026	12lb	Forge – cool in air – normalize. Hardness after normalizing: 137-187BH.	DFIQ – snap tempered at 400ºF – tempered at 1,400ºF.	5
	Gland[1]	15B37	80lb	Forge – cool in air – normalize - IQ and temper at 825ºF to hardness of 32-39RC.	DFIQ – tempered at 825ºF and 900ºF.	5
	Clamp	4140	23lb	Forge – cool in air – quench in oil and temper at 1,050ºF to hardness of 30-35RC.	DFIQ – tempered at 400ºF – tempered at 1,150ºF.	4
	Yoke	5130	10lb	Forge – cool in air – quench in oil and temper at 1,125ºF to hardness of 28-32RC.	DFIQ – tempered at 400ºF – tempered at 1,150ºF.	4
	Drum support	4150	20.5lb	Forge – cool in air – quench in oil and temper at 1,075ºF to hardness of 33-38RC.	DFIQ – tempered at 400ºF – tempered at 1,150ºF.	4
	Gear shaft	Pyrowear -53	21lb	Forge – cool in air – normalize – carburize – quench in oil and temper.	DFIQ – cooled in the air.	3

Note: [1] The processed glands were made of 15B37 steel instead of 4130 material normally used for these parts. The reason for this was to simulate the DFIQ process for railroad parts that are made of 15B37 steel and have a similar thickness. The current post-forging heat treatment process for the standard railroad parts is the following: forge – cool in the air – normalize – quench intensively in water – temper. Mechanical properties data obtained for the DFIQ glands were compared to that of standard railroad parts (see Table 11 below).

Table 11 Average mechanical properties for Clifford-Jacobs Forge DFIQ forgings and standard forgings and part specs.

Forging shop	Part name Steel	Heat treatment	Tensile psi	Yield psi	RA %	Elong. %	Impact at 70°F ft·lb	Part hardness RC	ASTM grain size
Clifford Jacobs Forging	Stopper 1026	Standard	76,000	45,200	56	29	-	149BHN	-
		DFIQ	76,900	47,500	64	32	-	149BHN	7.5
		Specs	70.000	36,000	30	30	-	-	-
	Disk 5130	Standard	136,000	124.000	48	16	-	31	-
		DFIQ[1]	121,400	107,000	51.8	15.4	20.8	31	5.0
		Specs	-	-	-	-	-	25	-
	Hub 4140	Standard	137,000	116,000	56	17	-	35	-
		DFIQ	140,300	121,500	40	14.8	31.7	34	2.5
		Specs	125,000	105.000	35	15	-	28-33	-
	Gland 15B37 (railroad part)	Standard[2]	132,500	110,000	50	14.5	-	33	-
		DFIQ[3]	127,000	107,500	34.5	13	-	33.5	1.5-2.5
		Specs[4]	-	70,000	-	14	-	32-39	-
	Yoke 5130	Standard	121,000	103,000	39	14	-	28	-
		DFIQ	130,500	117,000	22.5	9.5	-	30	1.5-2.5
		Specs	-	-	-	-	-	25	-
	Clamp 4130	Standard	127,000	101,000	55	18	-	31	-
		DFIQ	127,500	112,500	65	18.3	-	32	2.5-4.0
		Specs	125,000	105,000	35	15	-	28-33	-
	Drum support 4140	Standard	163,000	151,000	57.7	17.5	-	33	-
		DFIQ	137,000	120,250	43.5	14.3	-	30	2.5-4.0
		Specs	125,000	105.000	35	15	-	28-33	-

Notes: [1] DFIQ disks were tempered at 1,200°F (which is 65°F greater than that used for standard disks).

[2] Standard heat treatment for railroad parts made of 15B37 steel is as following: normalize + IQ + temper at 825°F.

[3] DFIQ glands were tempered at 900°F.

[4] Specs for railroad parts.

As seen from Table 11, mechanical properties for the DFIQ stoppers and clamps are about the same or better compared to that of the standard forgings. The results for other forgings are mixed: some mechanical properties of the DFIQ forgings are better, while some properties were worst. For example, for 5130 steel disks, the plastic properties are about the same for the DFIQ and standard parts, while standard disks have greater tensile and yield strength compared to that of the DFIQ disks. All DFIQ forgings were subjected to a magnetic particle inspection. No quench cracks were observed in all processed forgings except in one drum support. A too coarse microstructure is the major factor effecting the crack formation in this part.

4.2.4 Effect of Material Microstructure on DFIQ Forgings Mechanical Properties.

Analysis of data presented in Tables 6, 7. 9 and 11, shows that the effect of the DFIQ process on forging mechanical properties depends significantly on the material grain size. Table 12 summarizes this observation.

Table 12 Effect of steel microstructure on DFIQ forgings mechanical properties.

Parts	Steel	ASTM grain size after DFIQ	Forgings mechanical properties after DFIQ compared to conventional heat treatment
Pintle adapters	4340	7.0-7.5	All mechanical properties are generally better or the same.
Lugs	8637		
Keys	4140, 4340, 8640		
Stoppers	1026		
Tines	8650	5.0-6.0	Some mechanical properties are the same while some mechanical properties are worse.
Disks	5130		
Clamp	4130	2.5-4.5	All mechanical properties are generally better or the same.
Hubs	4140	1.5-4.0	All mechanical properties are generally worse.
Yokes	5130		
Drum supports	4140		
Glands (railroad parts)	15B37		

The following conclusions can be made:

- For processed forgings having the ASTM grain size of 7.0 and greater after the DFIQ process, the DFIQ method generally provides better or about the same mechanical properties as the conventional post-forging heat treatment. For this grain size, average values of improvements of mechanical properties would be most beneficial.
- The effect of the DFIQ process on material mechanical properties is generally mixed for forgings having the grain size within the range of 2.5 to 6.0: some mechanical properties were improved or didn’t change, while some mechanical properties got worse after using the DFIQ process (with the exception for the DFIQ clamps, which mechanical properties are superior compared to that of the standard clamps in spite of the fact that the ASTM grain size of the clamp’s material was within the range of 2.5-4.5).
- When the ASTM grain size is less than 2.5, all mechanical properties for the DFIQ forgings are generally worse compared to that of the standard forgings.

During the hot forging process, the coarse grain structure in the billet is broken up and replaced by finer grains. A further refinement of the material microstructure takes place during the post-forging heat treatment process. The steel microstructure becomes finer every time the steel is heated up above the austenite transformation range (above the Ac_3 temperature) and cooled down to a temperature below the transformation range of austenite to other steel microstructures (perlite, bainite, etc.). This further refinement is usually absent when using the DFIQ process. Therefore, the billet initial grain size and the material grain size after forging operations are especially important when applying the DFIQ process. Since the grain size of forgings greatly depends on the forging temperature, controlling of the reheating furnace temperature becomes very important for avoiding of the development of the coarse austenite microstructure.

Table 13 presents maximum safe forging temperatures for carbon and alloy steels of various carbon contents [7]. Table 14 presents typical forging temperatures used by forging shops participating in the project. From inspection of Tables 12 and 13, Bula Forge & Machine uses a forging temperature that should pose no issues with any of the alloys that they forge in terms of overheating. The same is true of Welland Forge. Clifford-Jacobs Forging uses a higher forging temperature, and overheating is a possible issue.

However, experience with the forging industry has shown that many forgers use temperatures in excess of these values for these same alloys with no overheating problems.

Table 13 Maximum safe forging temperatures for carbon and alloy steels of various carbon contents

Carbon content, %	Maximum safe forging temperature, ºF	
	Carbon steels	Alloy steels
0.1	2,350	2,300
0.2	2,325	2,275
0.3	2,300	2,250
0.4	2,275	2,250
0.5	2,250	2,250
0.6	2,200	2,200
0.7	2.175	2,150

Table 14. Typical forging temperatures.

Company	Forging temperature
Bula Forge & Machine	2,150 °F (furnace)
Welland Forge	2,250 °F (induction)
Clifford-Jacobs Forging	2,350 °F (furnace)

Per the opinion of Dr. Ferguson from DANTE Solutions [6], overheating should not be an issue as long as temperature never exceeds 2,450°F and a quality bar stock is used. A comment is warranted concerning induction heating for forging. Since induction heating involves heating by induced Eddy currents, and there is a surface to core temperature gradient, the possibility of overheating the billet surface exists. While Welland Forge reports a forging temperature of 2,250ºF, the temperature gradient in the billet prior to forging was not known.

It is important to note that as it follows from Tables 6, 7, 9 and 11, all DFIQ forgings met the parts specification regardless of their material grain size. However, once again, to improve part mechanical properties, it is necessary to provide a fine material microstructure after forging. Note also that the part microstructure after DFIQ (and hence material mechanical properties) will be further improved in cases when the part requires additional to DFIQ heat treatment (for example carburizing, carbo-nitriding, etc.).

4.2.5 Processing of Pyrowear-53 Gear Blanks at Clifford-Jacobs Forging.

The goal of processing of the Pyrowear-53 gear blanks was to evaluate the effect of the DFIQ process on the material grain size, since the currently used post-forging heat treatment process doesn't provide a specified ASTM grain size of 6.0 and finer. The standard gear blanks are cooled in the air after forging. A typical ASTM grain size after forging is within the range of 3.0 to 6.0. The following normalizing process doesn't improve neither the uniformity distribution of the grain sizes throughout the forging, nor the size of the grains. Moreover, for some areas of the forging, the material grain size even increases after normalizing.

A premise for applying the DFIQ process to the Pyrowear-53 gear shafts was the following. Some areas of the part are at least partially recrystallizing during the forging and following cooling from forge, which leaves them primed for grain growth during the post-forging heat treatment cycle. The DFIQ process may lock in un-recrystallized grains of forge so that the followed normalizing refines the grains instead of growing them.

To maximize the effect of the DFIQ process, the Pyrowear-53 billets were heated up prior to forging to the temperature of 2,100ºF instead of the usually used temperature of 2,350ºF. The gear blanks were placed in the reheating furnace in three different areas: at the front, middle and back of the furnace. Table 15 presents data on the material grain size obtained for three DFIQ Pyrowear-53 gear blanks and one standard gear blank. Fig. 8 shows the grain size sample location map.

As seen from Table 15, the material ASTM grain size obtained for the DFIQ Pyrowear-53 gear blanks was within the range of 5.5 to 7.5. The material grain size was below the required minimum value of 6.0 only in two areas for the forging made of the billet located at the reheating furnace front and in one area for the gear blank made of the billet located at the furnace back. The obtained microstructure for the DFIQ Pyrowear-53 gear blanks was more uniform compared to that of the standard Pyrowear-53 gear blank having the ASTM grain size of 1.0 to 7.5.

Table 15 ASTM grain size obtained for Pyrowear-53 gear blanks for forging temperature of 2,100ºF.

Post-forging heat treatment	Billet location in the furnace	Sample location						
		1	2	3	4	5	6	7
DFIQ	Front	6.0	6.0	6.0	6.0	6.0	5.5	5.5
	Middle	6.5	7.0	6.5	7.0	6.5	7.0	6.5
	Back	7.0	7.0	6.5	7.0	7.5	5.5	6.5
Standard	Unknown	7.5	7.5	5.5	7.0	6.5	4.0	1.0

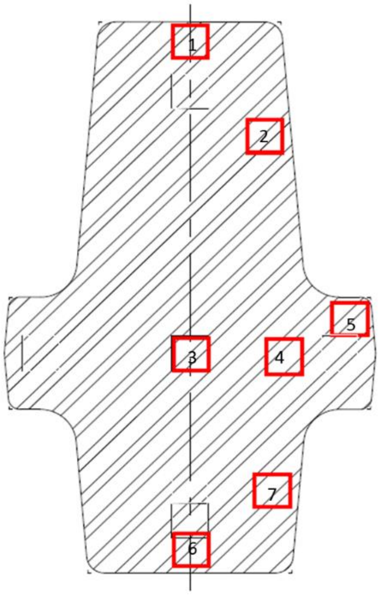


Fig.8 Grain size sample location map.

4.3 Determining of Heat Transfer Coefficient in the DFIQ Tank.

When applying the DFIQ process, the quench should be interrupted at a time when surface current compressive stresses are at their maximum value for avoiding part cracking during intensive quenching. The optimal dwell time is determined using IQ Technologies' proprietary software. One of the most important input parameters for the computer program is a value of the heat transfer coefficient (HTC) in the DFIQ unit. The HTC characterizes an intensity of the heat extraction rate from the forging being quenched. It depends on the quenchant physical and thermal properties, quenchant agitation rate, temperature, etc. The HTC is usually determined experimentally by using special probes equipped with a set of thermocouples.

A probe for evaluating of the HTC in the DFIQ unit was designed and fabricated by DANTE Solutions (Fig. 9). The probe was equipped with a set of thermocouples place on its surface and in the core. Experiments were conducted at Akron Steel Treating Co. of Akron, Ohio. The probe was heated up in a neutral salt bath furnace prior to quenching in the DFIQ unit. The hot probe was manually transferred from the furnace and placed onto a special fixture fabricated by IQ Technologies that was attached to the DFIQ tank loading/unloading table (Fig. 10). The temperature readings were taken every millisecond. The cooling curves obtained by the probe was processed by special software for calculating of the HTC. An example of the cooling curve is presented in Fig. 11. The obtained value of the HTC in the DFIQ unit is not presented in the report since this information is considered as confidential.

Fig. 9 Probe assembly.

Fig. 10 Hot probe prior to quenching in DFIQ unit.

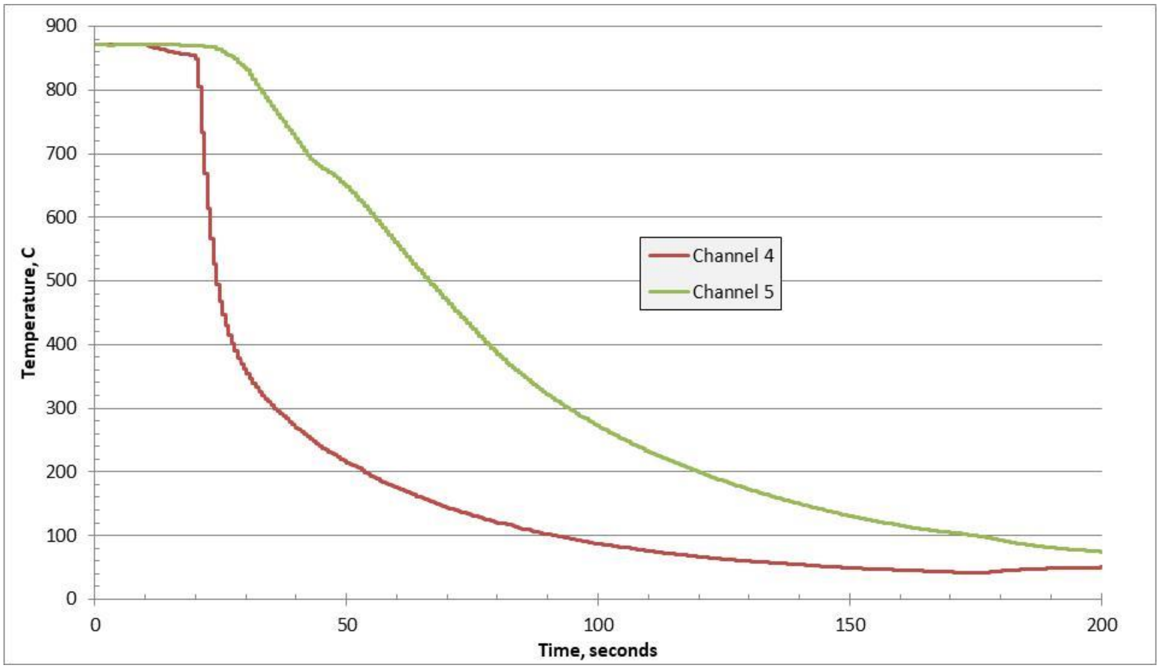


Fig. 11 Example of cooling curve.

5. DFIQ Process Commercialization.

The following path to the DFIQ process commercialization was established and implemented during the project:

- Conduct DFIQ demonstrations at forge shops (these activities will be continued through a potential extension of the DFIQ project).
- Conduct DFIQ presentations at technical conferences. The DFIQ project results were presented to the following conferences:
    - FIA Technical Conference 2016
    - FIA Technical Conference 2018
    - Forge Fair 2019
- Coordinate public demonstration of the DFIQ process on YouTube.
- Publish papers in technical and trade magazines.

First potential customers for commercializing of the DFIQ process are Clifford-Jacobs Forging and PC Forge (both of the IMT Forge Group). Clifford-Jacobs Forging is considering installing of a production DFIQ unit at its facility for processing large forgings (railroad application, mining application and utility service application). IQT provided Clifford-Jacobs Forging with a preliminary quote for the DFIQ unit and for the quenchant cooling system for maintaining the quenchant temperature within the allowable range. A preliminary evaluation of the ROI value conducted by Clifford-Jacobs Forging showed that the ROI will be less than 2 years due to a full elimination of the post-forging heat treatment for most forgings to be processed in the DFIQ unit and due to the reduction of the shipping costs (Table 16).

Table 16 Projected annual savings for Clifford-Jacobs Forging

Part	Annual quantity	Annual production lb	Current heat treatment	Heat treatment cost $/lb	Total heat treatment cost $	Shipment cost $/lb	Total shipment cost $	Total savings $
Railroad application	6,500	1,117,000	Normalize	0.4	468,000	0.1	117,000	585,000
Mining application	1,000	80,000	Q & T	0.6	48,000	0.2	16,000	64,000
Utility service application	250	18,000	Q & T	0.25	4,500	0.2	3,600	9,100
							Total savings:	658,100
							Return on investment:	<18 months

PC Forge identified a customer willing to accept DFIQ process for one of its products: a yoke bar – a component of the truck fifth wheel locking system. PC Forge conducted an ROI analysis (Table 17) and requested a quote from IQT for the production DFIQ unit.

Table 17 Projected annual savings for PC Forge

Parameter	Value
Cost of current heat treatment (quench in oil and temper)	\$0.2/lb
Cost of part shipment to heat treating shop and back	\$0.1/lb
Cost of DFIQ process (includes DFIQ unit and tempering furnace amortization cost, operating expenses, cost for cooling quenchant, tempering process cost, etc.)	\$0.1/lb
Savings due the use of DFIQ process	\$0.2/lb
Annual production of DFIQ forgings	400,000 parts
Forging weight	5lb
Total weight of DFIQ forgings	2,000,000lb
Total annual savings	\$400,000
Return on Investment	About 1 year

6. Conclusions.

a) The 600-gallon DFIQ system designed and built by IQT is a compact, portable unit that can be used in a forge shop environment with little interference of existing facilities. The DFIQ unit allows quenching of forgings on the loading/unloading table (one part at a time), or continuously on the unit conveyor.

b) A material characterization study conducted for three different alloy steels showed that the DFIQ process generally improves all material mechanical properties. It was proved that mechanical properties of the DFIQ 4140 steel are the same or better compared to that of conventionally heat-treated higher alloy and more expensive 4340 steel. This DFIQ process benefit opens a possibility of substitution of lower alloy steels for high alloy steels resulting in a significant material cost saving.

c) A total of twelve different production forgings were subjected to the DFIQ process over the course of the project. The forgings were made of different plain carbon, alloy and high alloy steels, weighted from 4 to 80lb and covered a wide range of relatively complex geometries.

d) The material microstructures of the production DFIQ forgings appears to be similar to that of the forgings after a conventional post-forging heat treatment, and in some cases, the DFIQ microstructure was found to be slightly coarser (but still acceptable) than the conventionally processed forgings.

e) DFIQ process can be used successfully to produce microstructures and mechanical properties that meet product requirements. Strengths and hardness values of the DFIQ forgings were acceptable in all cases. The strength properties tended to be higher for DFIQ treated forgings, most likely due to a higher cooling rate. For example, the material characterization study showed that for 4140 steel DFIQ forgings with an ASTM grain size greater than 7.0, the tensile and yield strength improved by 6-7%, while the value of the impact strength more than doubled and material plastic properties improved by more than 50%.

f) The applicability of the DFIQ process is subject to the hardenability of the steel being used, part geometry, and the manufacturing steps that follow the hot forging operation.

g) The use of the DFIQ process results in tremendous energy saving by eliminating a reheat step prior to final heat treatment and, in some cases, by eliminating a post-forging heat treatment process completely. The latter, in turn, results in significant reduction of the production lead time (up to 8 days for the pintle adapters).

h) Application of the DFIQ process to Pyrowear-53 gear blanks together with the reduction of the forging temperature result in a better material microstructure: the obtained material grain size for the DFIQ forgings was within the specs and the microstructure was much more uniform compared to that of the standard gear blanks.

i) The main cracking issue was for the tines forged from 8650 and 4140 steel at Welland Forge. The major reason for crack formation was the complex tine geometry coupled with a significant thickness variation. The issues here were the interruption time of the DFIQ process relative to the amount of martensite transformed at tine different locations and a too much swelling of the part core resulting in cancelling surface compressive stresses. A change in cooling rate and the tine material could correct this issue and avoid cracking.

j) A special probe equipped with a set of thermocouples has been prepared by DANTE Solutions to measure the cooling rate provided by the DFIQ unit. The cooling curves obtained by the probe were used for determining of heat transfer coefficients when quenching forgings in the portable DFIQ unit. Data on heat transfer coefficients are needed for calculating optimal dwell times for different forgings.

k) Two forging companies (Clifford-Jacobs Forging and PC Forge both of IMT Forge Group) are considering installing of production DFIQ units at their facilities for processing different forgings.

Acknowledgement

- The FDMC PRO-FAST (Contract # SP4701-14-D-7012) is sponsored by the DLA-Troop Support, Philadelphia, PA and the Defense Logistics Agency Information Operations, J62LB, Research & Development, Ft. Belvoir, VA. DLA seeks to support the modernization of supply chains deemed critical to the warfighter.

- PRO-FAST is cost shared by program participants such as IQ Technologies and is supported by the Forging Industry Association and endorsed by the Forging Defense Manufacturing Consortium in advancing the state of the art of the North American forging industry.

- IQ Technologies, Inc. thanks and acknowledges DLA and Advanced Technology International for a financial support and project management. A special thanks to three forging shops (Bula Forge and Machine of Cleveland, Ohio, Welland Forge of Welland, Ontario and Clifford Jacobs Forge of Champaign, Illinois) for providing a substantial in-kind contribution to the project.

References.

1. M.L.Bernshtein, Thermomechanical Treatment of Metals and Alloys, Moscow, Metallurgiya, Vol. 1, 1968, 586p
2. M.L.Bernshtein, Thermomechanical Treatment of Metals and Alloys, Moscow, Metallurgiya, Vol. 2, 1968, 575p
3. Tamura, I., Ouchi, C., Tanaka, T., Sekine, H., *Thermomechanical Processing of High Strength Low Allooy Steels,* Butterworths, London, 1988.
4. Kobasko, N.I., Aronov, M.A., Powell, J.A., and Totten, G.E., *Intensive Quenching Systems: Engineering and Design*, ASTM International, West Conshohocken, USA, 2010, 252 pages.
5. Kobasko, N.I., Aronov, M.A. and Powell, J.A., Intensive Quenching of Steel Parts, ASM Handbook, Volume 4A – Steel Heat Treating, ASm International, 2013, 198p.
6. Ferguson, L. “Analysis of Metallurgical Characterization of DFIQ Process”, Technical report, DANTE Solution, 2018.
7. ASM Handbook volume 14A, Metalworking: Bulk Forming, ASM International, Materials Park, OH, 2005

Procurement Readiness Optimization – Forging Advanced Systems Technologies
(PRO-FAST)

Government contract: PROFAST SP4701-14-D-7012
Subcontract No.: 2015-506

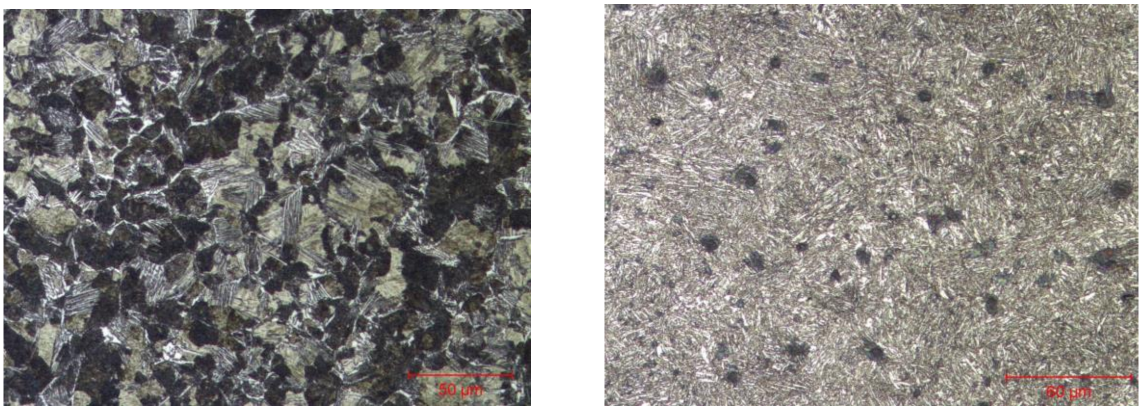
Forging Process Improvement Using Intensive Quenching

Final report

Appendices

July 31, 2019

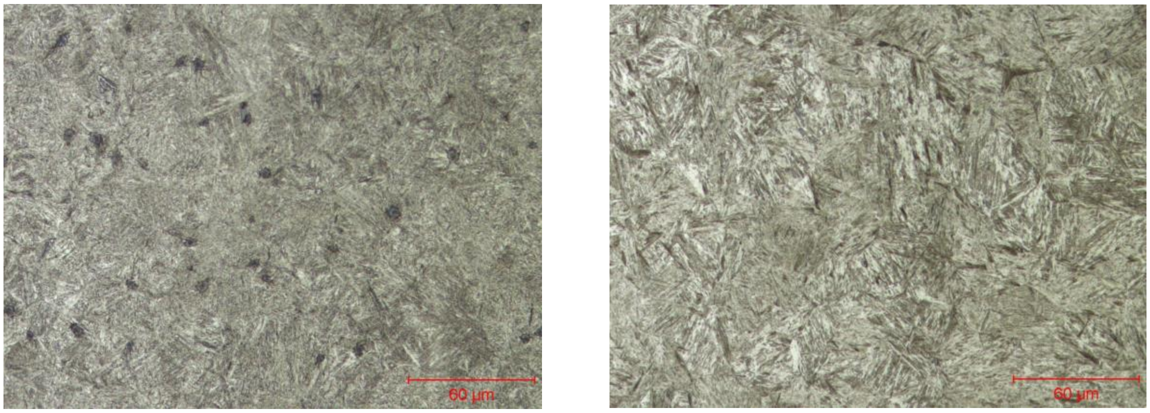
Appendix 1 – Keys microstructure.



Quenching in oil and temper

DFIQ

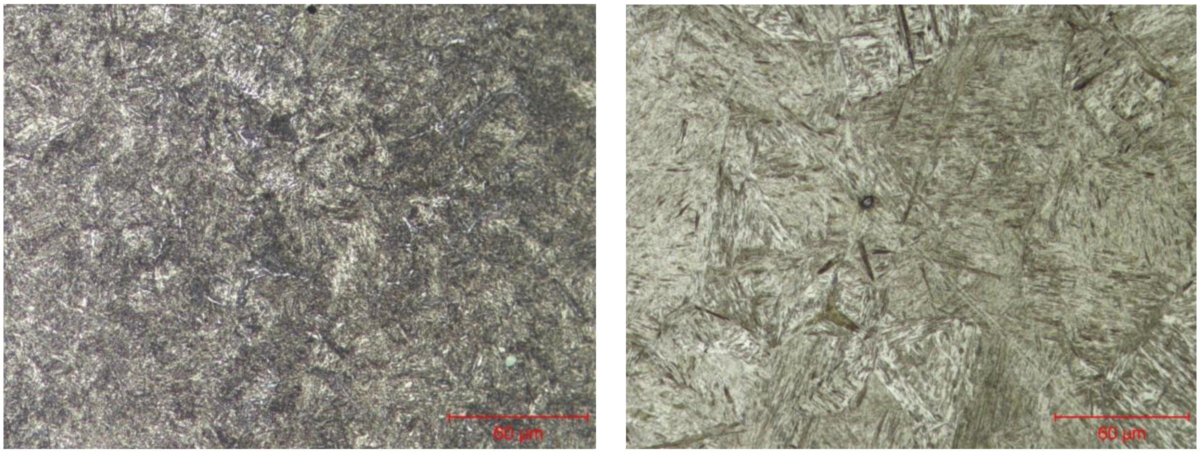
Figure A1 Microstructure of 1045 steel key



Quenching in oil and temper

DFIQ

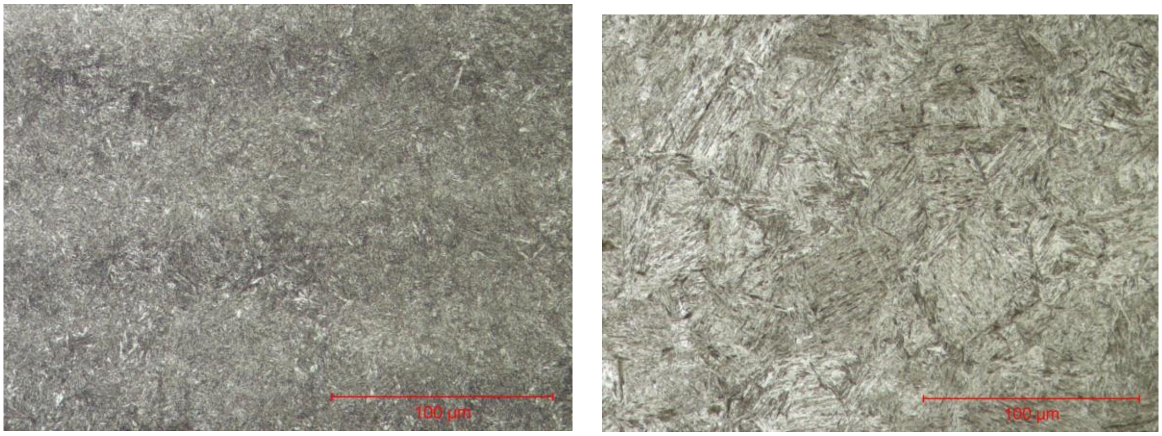
Figure A2 Microstructure of 4140 steel key



Quenching in oil and temper

DFIQ

Figure A3 Microstructure of 8640 steel key



Quenching in oil and temper

DFIQ

Figure A4 Microstructure of 4340 steel key

Appendix 2 – Key mechanical properties raw data.

Table A2 - Key mechanical properties raw data

Heat treatment process applied after forging	Steel	Tempering process	Mechanical properties					Key hardness at ¼ thickness, RC
			Tensile psi	Yield psi	RA %	Elong. %	Impact ft·lb	
Conventional: cooling in the air followed by quenching in oil and tempering.	1045	600ºF 2 hours	132,000	81,000	26	16	13	29
			130,000	79,500	37	16	16	26
			133,000	82,000	30	18	13	29
	4140		254,000	216,000	32	9	5	50
			252,000	230,000	11	8	5	48
			249,000	214,000	34	13	5	50
	4340		264,000	224,000	38	12	7	52
			264,000	223,000	40	17	7	51
			258,000	254,000	40	15	9	50
	8640		228,000	186,000	24	13	6	50
			232,500	188,300	12	10	6	48
			202,000	161,000	30	12	7	50
DFIQ process followed by part tempering.	1045	Self-tempered only	222,000	201,000	4	7	4	45
			224,000	205,000	9	8	5	45
			226,000	207,000	9	7	5	44
	4140	Self-tempered only	285,000	169,000	22	11	14	52
			285,000	164,000	39	14	16	51
			291,000	172,000	18	18	13	54
		570ºF for 2 hours after self-temper	273000	247000	37	9.5	11	50
			271000	236000	39	10	11	49
			264000	232000	41	9.5	9	50
			254000	223000	43	11	14	48
	4340	Self-tempered only	323,000	186,000	11	14	11	55
			278,000	180,000	17	8	15	54
			258,000	186,000	0	4	12	56
		570ºF for 2 hours after self-temper	286000	255000	35	9	10	53
			276000	234000	33	8	9	52
			253000	219000	36	8	8	49
			284000	251000	35	9	9	53
	8640	Self-tempered only	289,000	170,000	15	12	13	52
			291,000	195,000	6	7	12	52
			304,000	167,000	1	8	17	52
		570ºF for 2 hours after self-temper	263000	230000	39	8.5	9	50
			268000	226000	35	9	6	51
			265000	228000	36	9.5	8	49
			270000	231000	35	9	8	53

Appendix 3 – Production DFIQ forgings mechanical properties raw data.

Table A3 Processed forgings mechanical properties raw data

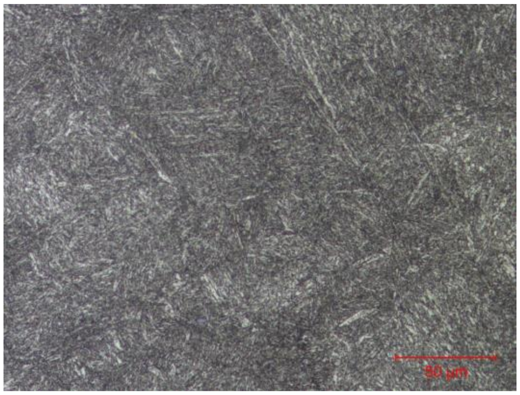
Part name Steel	Post-forging heat treatment process applied	Tensile psi	Yield psi	RA %	Elong. %	Impact at 70°F ft·lb	Part hardness	ASTM grain size
Pintle adapter 4340	Current: normalize + cycle anneal + oil quench & temper at 1,180°F.	141,000	125,000	59	24	69	XRC	8.0
		141,000	126,000	62	23	66		-
		139,000	123,000	60	22	69		-
	DFIQ + cycle anneal + oil quench & temper at 1,180°F.	143,000	123,000	47	17	66		-
		141,000	120,000	56	24	63		
		142,000	121,000	53	21	69		
	DFIQ + temper at 1,180°F	135,600	112,100	54	23	63		-
		135,000	110,000	59	24	68		7.5
		137,000	114,000	51	21	58		-
Pintle adapter 4140	DFIQ + normalize + IQ & temper at 1,180°F.	145,000	126,000	63	17	110		8.5
		148,000	131,000	62	20	55		-
	DFIQ + temper at 1,180°F	133,500	113,400	-	18	76		-
		132,000	112,000	56	20	63		-
		135,000	113,000	52	22	51		8.0
Lug 8637	Current: normalize + quench in oil & temper at 1,100°F.	145,000	120,000	34	14	20		8.0
		166,000	150,000	30	19	20		-
		163,000	146,000	39	16	15		-
	DFIQ + temper at 1,100°F	154,000	135,000	44	20	18		7.0
		148,000	123,000	44	19	20		-
		146,000	122,000	46	16	17		-
Tine 8650	Current: quench in oil & temper at 420°F.	297,000	226,000	85	12	10	56RC	8.5
		298,000	221,000	31	13	11		-
		296,000	229,000	28	11	11		-
	DFIQ + temper at 420°F	294,000	224,000	2	3	7	55RC	5.5
		304,000	220,000	4	4	8		-
		312,000	223,000	9	11	5		-
Disk 5130	DFIQ + tempered at 1,200°F.	123,000	109,000	55	17	24	30-32RC	-
		119,000	105,000	57	14	22		-
		121,000	107,000	49	15	19		5.0
		121,000	106,000	51	17	22		-
		123,000	108,000	47	14	17		-

Table A3 Processed forgings mechanical properties raw data (continued)

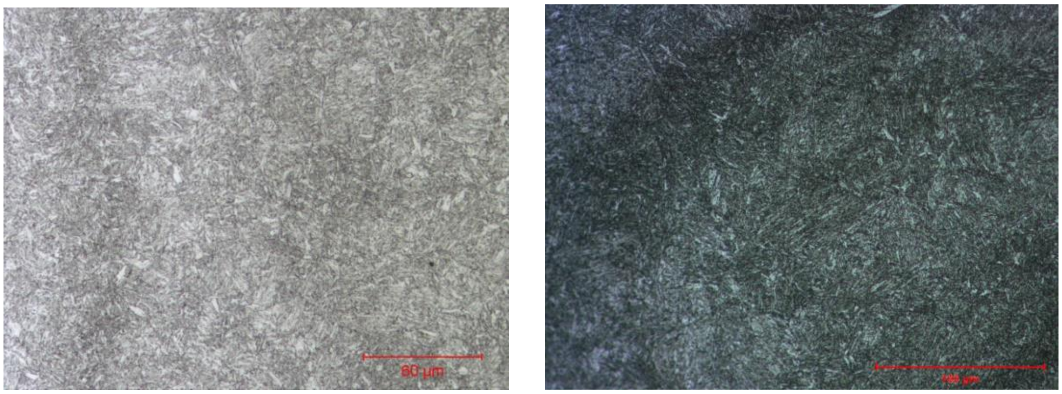
Part name Steel	Post-forging heat treatment process applied	Tensile psi	Yield psi	RA %	Elong. %	Impact at 70°F ft·lb	Part hardness	ASTM grain size
Hub 4140	DFIQ + tempered at 1,150°F.	141,000	122,000	38	15	39	33-34RC	2.5
		139,000	120,000	39	14	36		2.5
		140,000	119,000	45	17	26		-
		141,000	124,000	37	14	30		-
		139,000	120,000	42	14	27		-
		142,000	124,000	39	15	32		-
Stopper 1026	DFIQ + tempered at 1,400°F.	77,000	46,900	66	34	-	148-150BHN	7.5
		76,000	46,300	65	32	-		-
		77,500	47,800	61	30	-		-
		76,500	47,900	68	33	-		-
		77,500	48,400	62	33	-		-
Gland[1] 15B37 (railroad part)	DFIQ + tempered at 825°F	135,000	114,000	30	10	-	33RC	2.0
		125,000	103,000	35	12	-	37RC	1.5
	DFIQ + tempered at 900°F	126,000	107,000	33	12	-	33RC	2.5
		128,000	108,000	36	14	-	34RC	1.5
Yoke 5130	DFIQ + tempered at 1,150°F	130,000	116,000	30	12	-	30RC	2.0
		132,000	119,000	24	9	-		2.5
		131,000	117,000	15	7.5	-		1.5
		129,000	116,000	21	9.5	-		2.0
Clamp 4130	DFIQ + tempered at 1,150°F	129,000	115,000	61	18	-	32RC	2.5
		128,000	113,000	65	18	-		4.5
		128,000	112,000	67	19	-		3.0
		125,000	110,000	67	18	-		2.5
Drum support 4150	DFIQ + tempered at 1,150°F	139,000	120,000	40	14	-	30RC	4.0
		134,000	115,000	51	16	-		2.5
		139,000	121,000	37	12	-		4.0
		136,000	125,000	46	15	-		3.0

Note: [1] Tensile specimens were taken at the same depth from the surface as that for the railroad parts.

Appendix 4 – Pintle adapters and lugs microstructure.



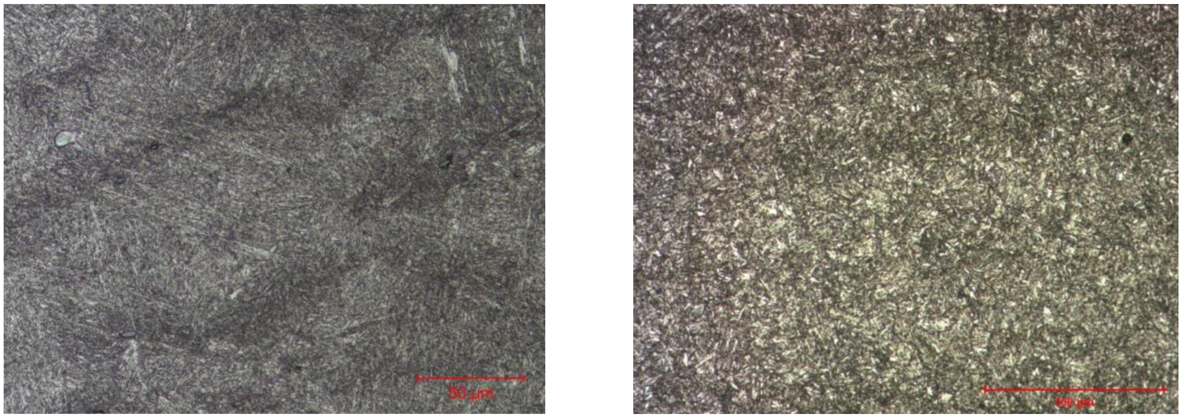
Standard (normalize, cycle anneal, quench and temper)



DFIQ, cycle anneal, quench in oil and tempered

DFIQ and tempered

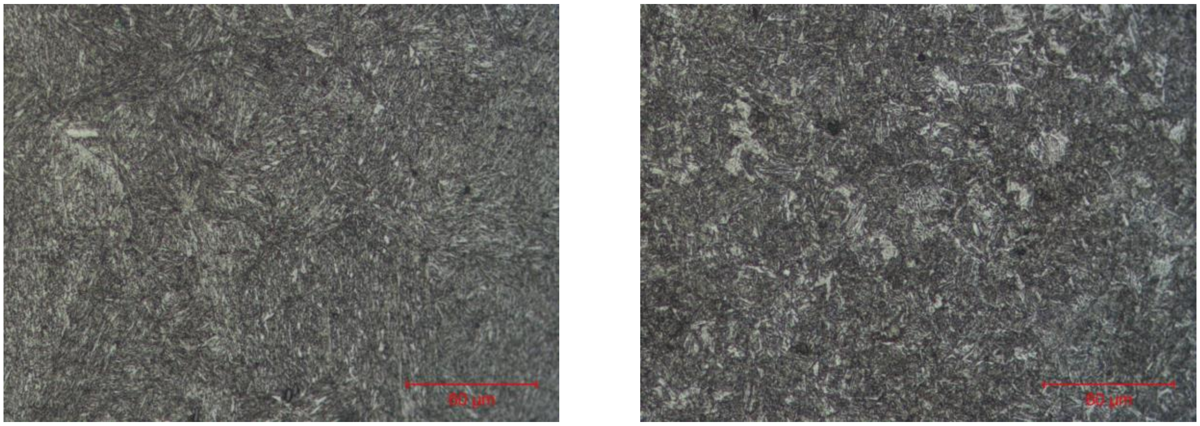
Figure A5 Microstructure of 4340 steel pintle adapters



DFIQ and temper

DFIQ, normalized, IQ and temper

Figure A6 Microstructure of 4140 steel pintle adapters

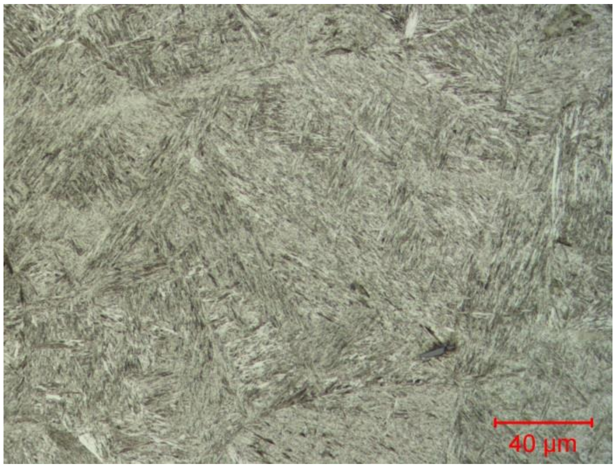


DFIQ and temper

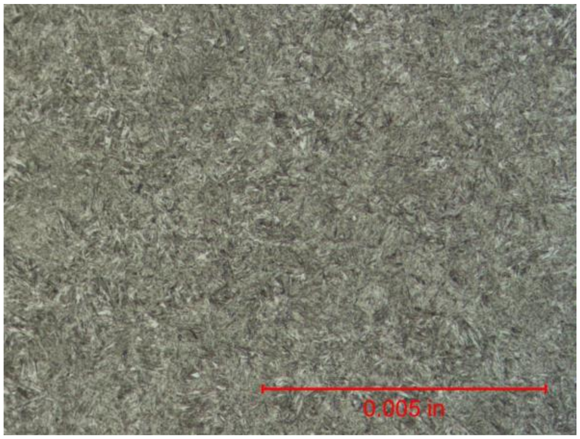
Standard (normalized, oil quench and temper

Figure A7 Microstructure of 8637 steel lugs

Appendix 5 – Microstructure of tines.

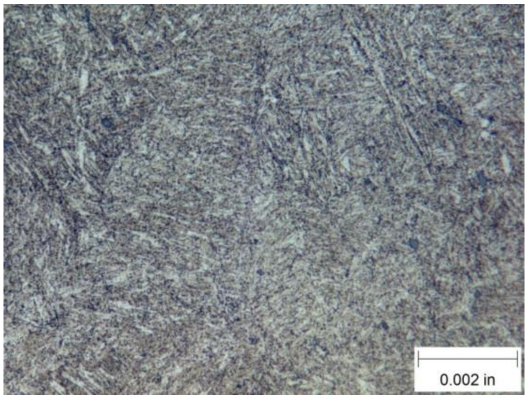


After DFIQ and temper, x500



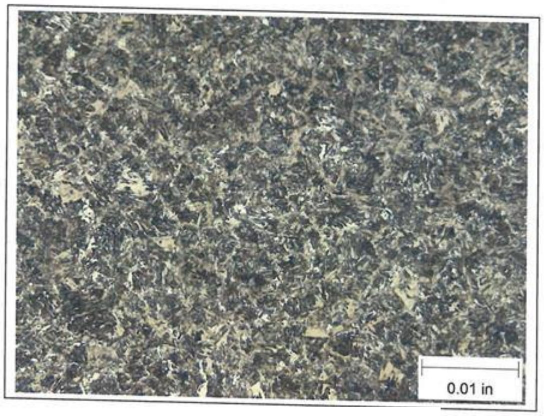
After standard post-forging heat treatment, x500

Appendix 6 – Microstructure of Clifford-Jacobs forgings.

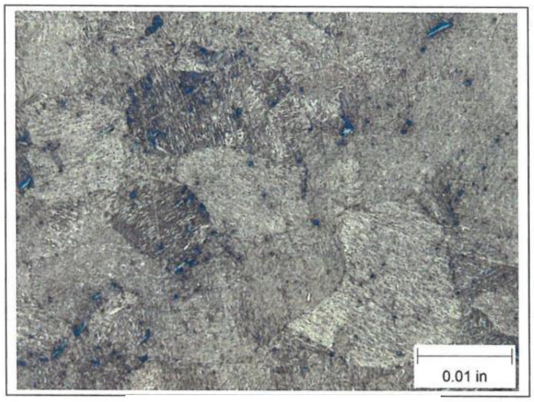


Disk, x100
ASTM grain size 5.0

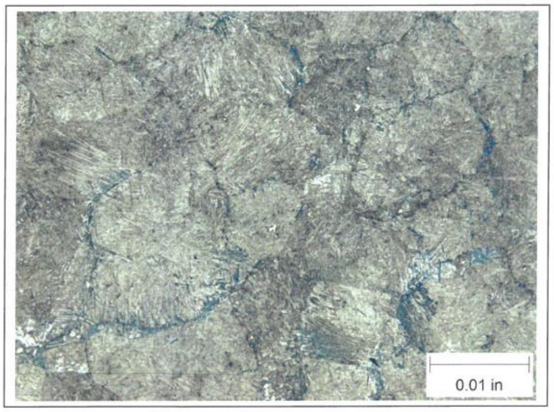
Hub, x100
ASTM grain size 2.5



Stopper, x100
ASTM grain size 7.0



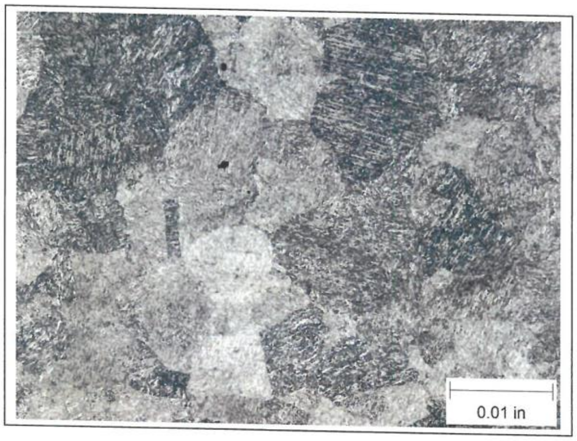
Gland #1, x100
ASTM grain size 2.0



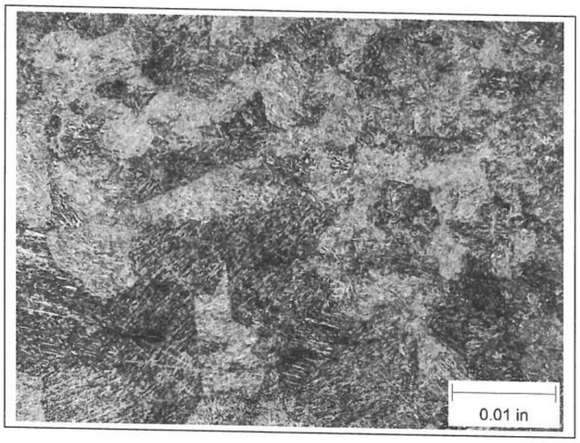
Gland #2, x100
ASTM grain size 1.5

Yoke #1, x100
ASTM grain size 2.0

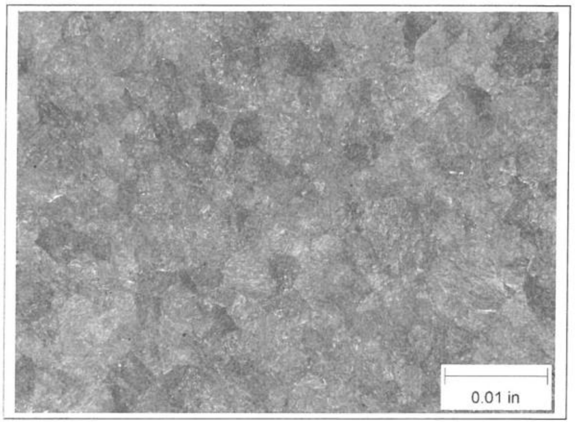
Yoke #2, x100
ASTM grain size 2.5



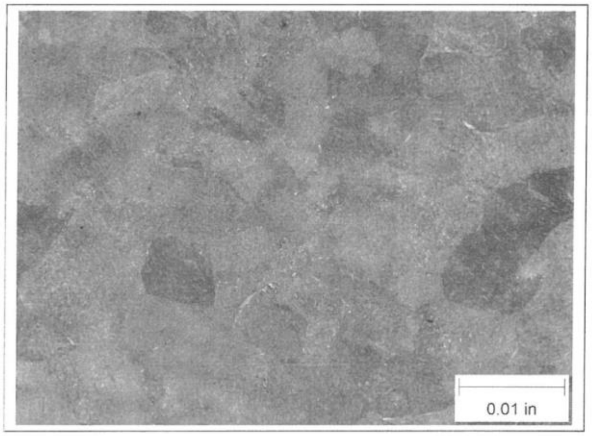
Yoke #3, x100
ASTM grain size 1.5



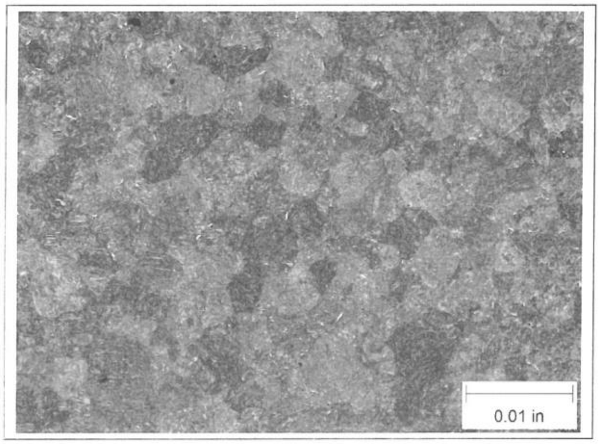
Yoke #4, x100
ASTM grain size 2.0



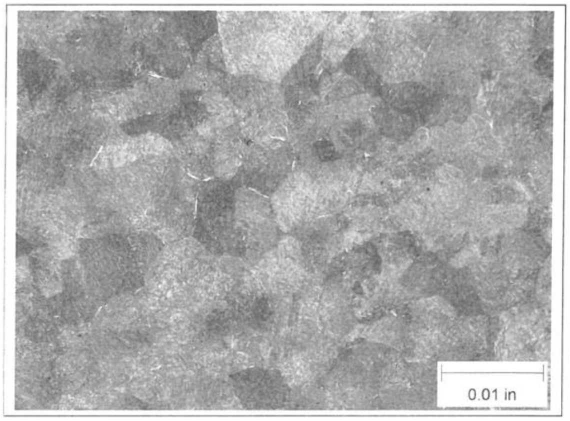
Drum support #1, x100
ASTM grain size 4.0



Drum support #2, x100
ASTM grain size 2.5

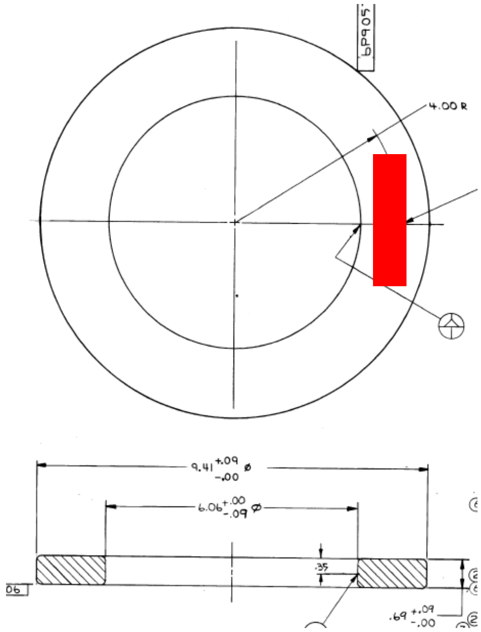


Drum support #3, x100
ASTM grain size 4.0

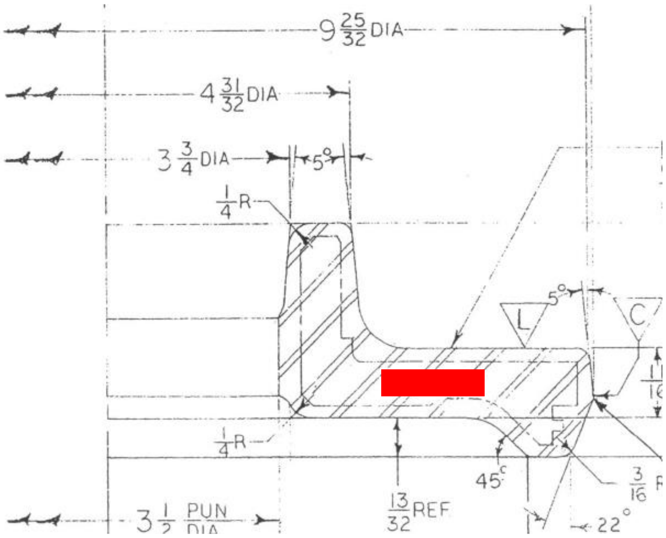


Drum support #4, x100
ASTM grain size 3.0

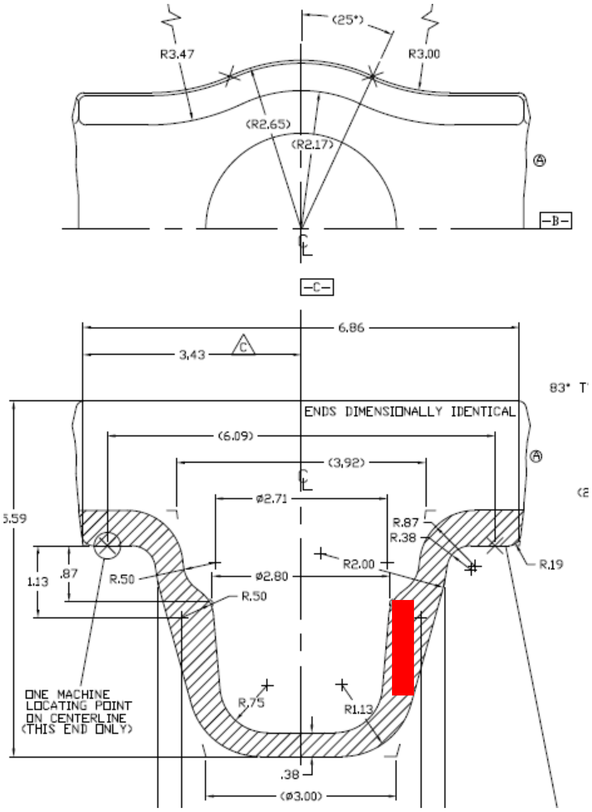
Appendix 7 – Clifford-Jacobs Forgings Tensile Specimens Location.



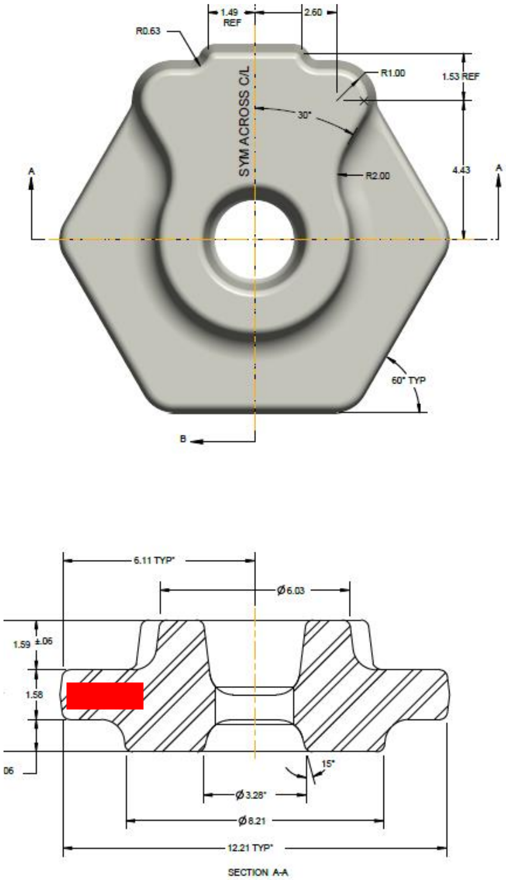
Disk



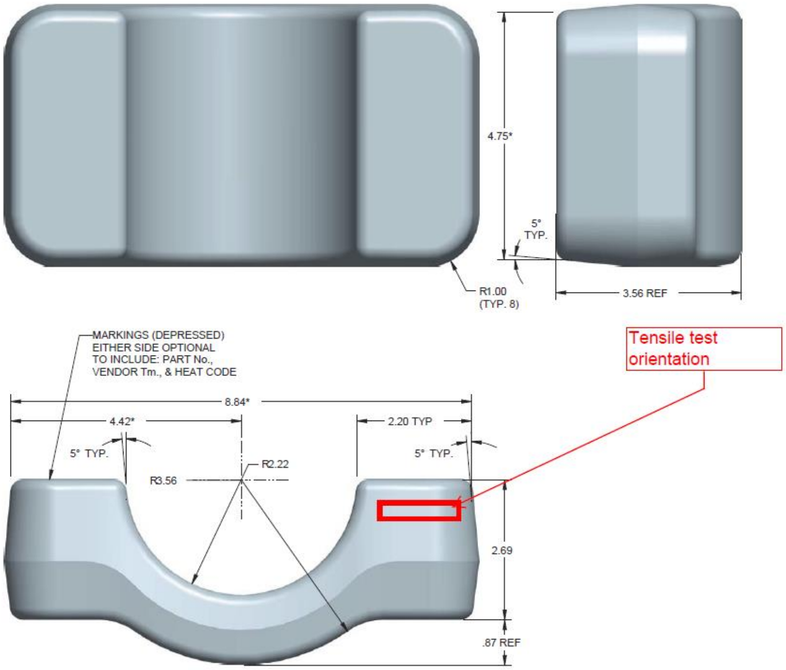
Hub



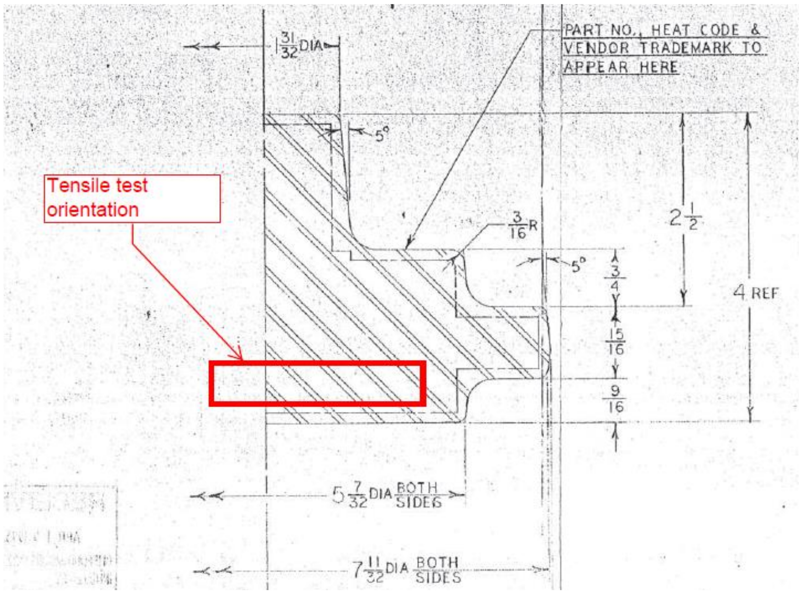
Stopper



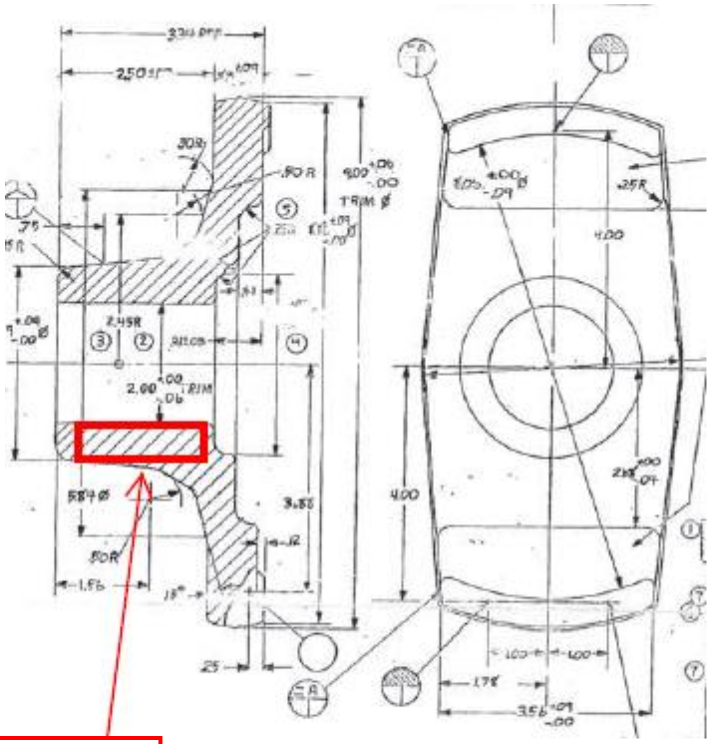
Gland



Clamp



Drum support

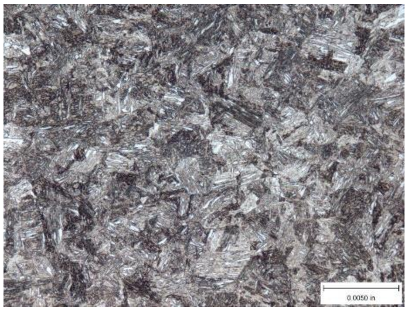


Tensile test orientation

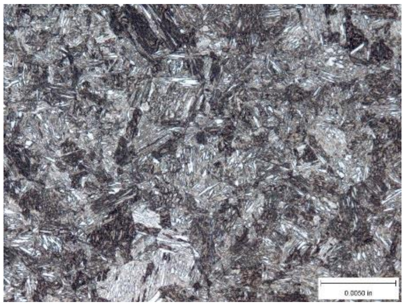
Yoke

Appendix 8 – Microstructure of Pyrowear-53 gear blanks forged from 2,100^{o}F

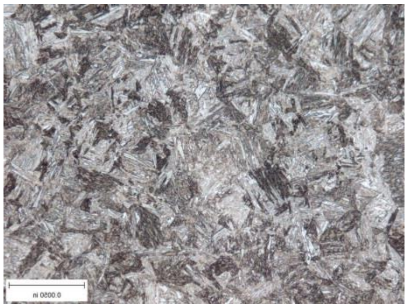
DFIQ gear blank located at furnace front



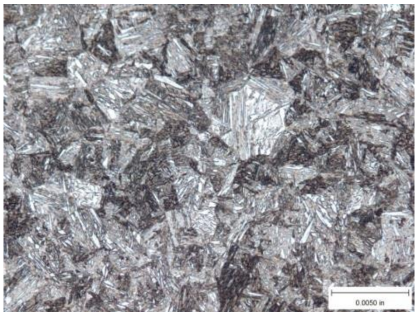
#1, x200, ASTM 6.0



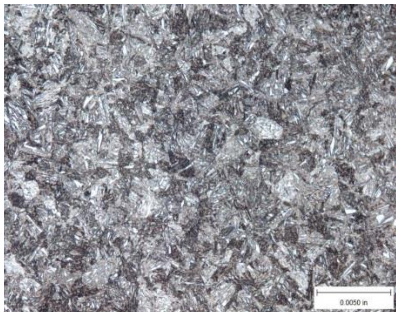
#2, x200, ASTM 6.0



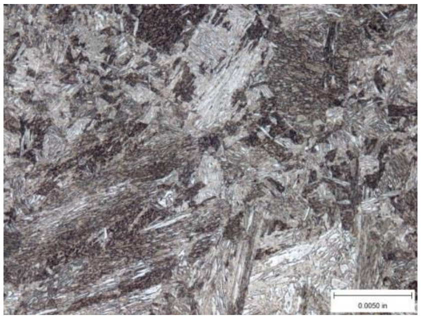
#3, x200, ASTM 6.0



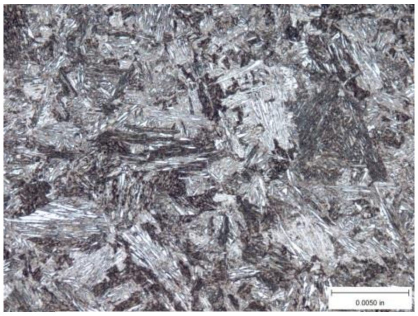
#4, x200, ASTM 6.0



#5, x200, ASTM 6.0

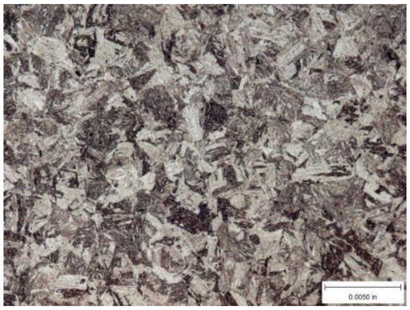


#6, x200, ASTM 5.5

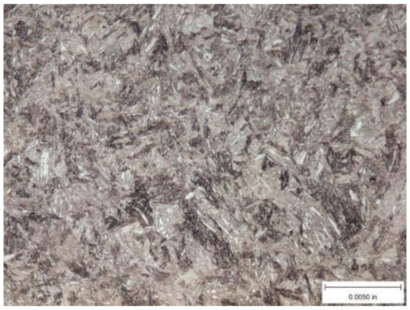


#7, x200, ASTM 5.5

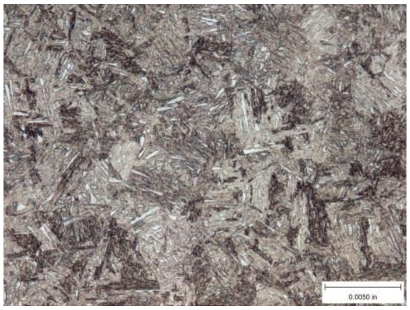
DFIQ gear blank located at furnace middle



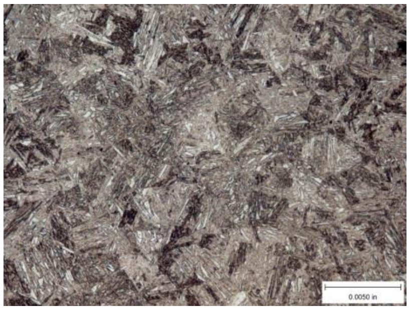
#1, x200, ASTM 6.6



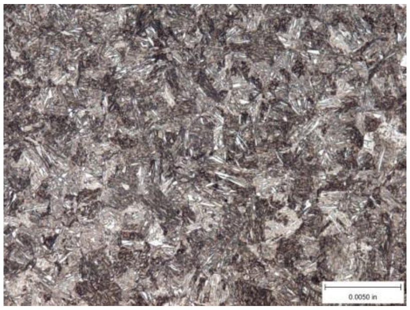
#2, x200, ASTM 7.0



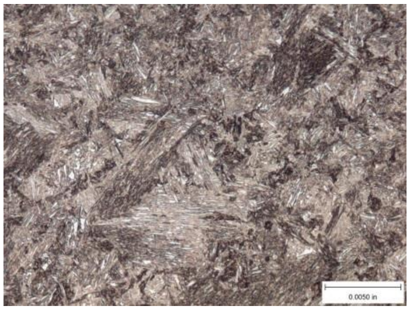
#3, x200, ASTM 6.6



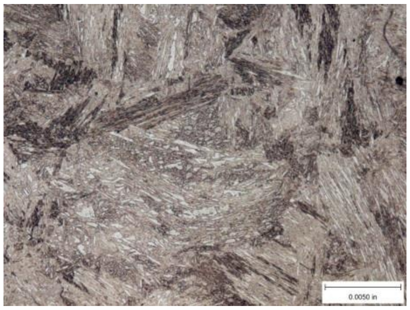
#4, x200, ASTM 7.0



#5, x200, ASTM 6.6

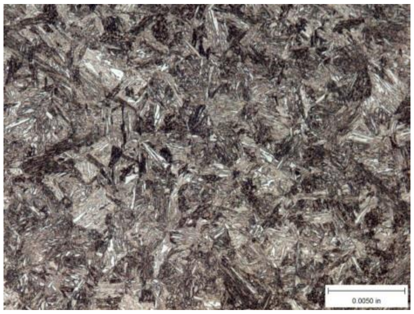


#6, x200, ASTM 7.0

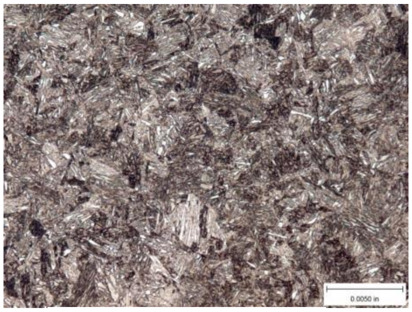


#7, x200, ASTM 6.5

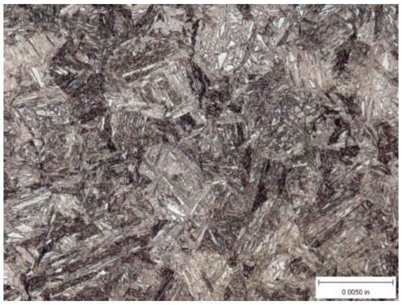
DFIQ gear blank located at furnace back



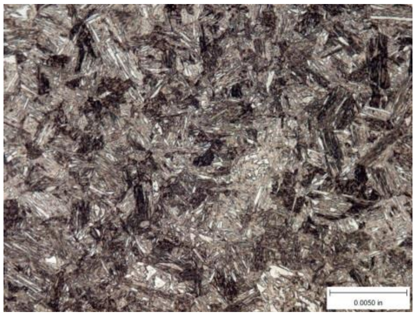
#1, x200, ASTM 7.0



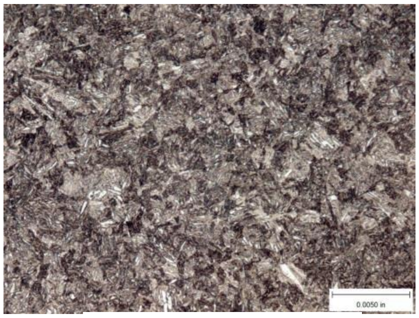
#2, x200, ASTM 7.0



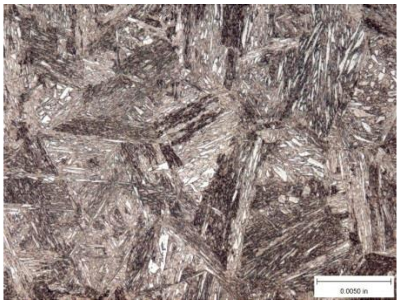
#3, x200, ASTM 6.6



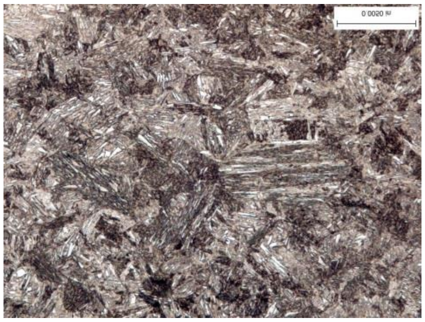
#4, x200, ASTM 7.0



#5, x200, ASTM 7.5



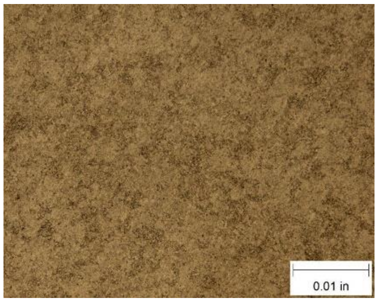
#6, x200, ASTM 5.5



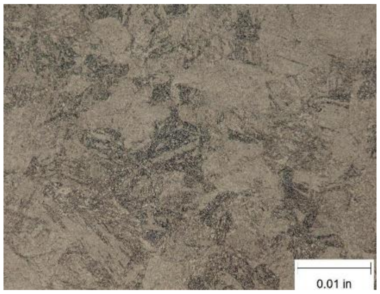
#7, x200, ASTM 6.5

Standard gear blank (location in the furnace is unknown)

#1, x100, ASTM 7.5

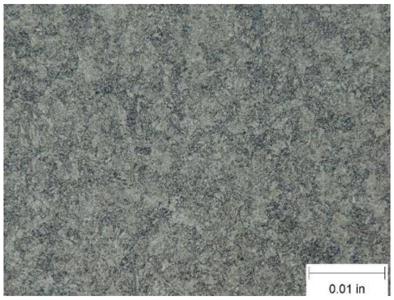


#2, x100, ASTM 7.5



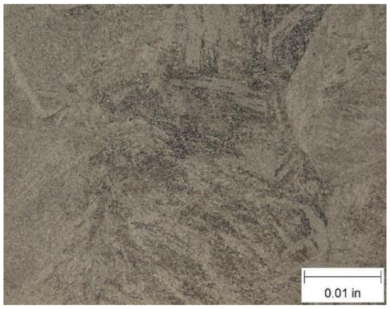
#3, x100, ASTM 5.5

#4, x100, ASTM 7.0



#5, x100, ASTM 6.0

#6, x100, ASTM 4.0



#7, x100, ASTM 1.0