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Analysis of Metallurgical Characterization of DFIQ Process

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IQ Technologies, Inc. has developed equipment, known as Direct from Forge Intensive Quenching (DFIQ), for quenching hot forgings directly as they come from the forging press. The purpose of the equipment is to investigate the possibility eliminating normalizing or austenitization heating steps after air cooling forgings by taking advantage of the residual heat in the hot forging and immediately using DFIQ and tempering. This report is a review of metallurgical characterization results, including hardness data, tensile data, Charpy V-Notch impact data, grain size measurements, and microstructure comparisons that have already been determined for the parent project.

Dr. Michael Aronov of IQ Technologies, Inc. prepared reports containing tension test results, hardness data, Charpy impact data, grain size measurements, and selected photomicrographs of conventionally processed parts and DFIQ + temper processed parts. These results are contained in references 1 through 3.

Steel Grades and Forgings

The three forging companies that participated in trials using the DFIQ unit are Bula Forge & Machine, Welland Forge and Clifford-Jacobs Forging. The typical forging preheat temperatures used at these companies, as reported to Dr. Aronov of IQT, are shown in Table 1.

Table 1. Typical Forging Temperatures.

Company	Forging Temperature
Bula Forge & Machine	2150 °F (furnace)
Welland Forge	2250 °F (induction)
Clifford-Jacobs Forging	2350 °F (furnace)

The alloys forged by these companies for the components that were used in the DFIQ trials are listed in Table 2. Table 3 lists typical forging temperatures for carbon and alloy steels. [4] Table 4 gives maximum safe forging temperatures for carbon and alloy steels for different carbon levels.[4]

Table 2. Steel Grades Forged for the DFIQ Trials.

Steel	Bula Forge & Machine	Welland Forge	Clifford-Jacobs Forging
1026			X
1045	X		
15B37			X
4140	X	X	X
4150			X
4340	X		
5130			X
8637	X	X	X
8640	X		
8650		X	
P53			X

Table 3. Typical Forging Temperatures for Various Carbon and Alloy Steels.*

Steel	Major Alloying Elements	Typical Forging Temperature, °F
1020		2350
1030		2350
1040		2300
1050		2300
1060		2160
4130	Cr, Mo	2200
4140	Cr, Mo	2250
4340	Ni, Cr, Mo	2350
5160	Cr	2200
8620	Ni, Cr, Mo	2250
P53	Ni, Cr, Mo, Si, V	

* page 242 of [4]

Table 4. Maximum Safe Forging Temperatures for Carbon and Alloy Steels of Various Carbon Contents.*

Carbon Content, w/o	Maximum Safe Forging Temperature, °F	
	Carbon Steels	Alloy Steels
0.10	2350	2300
0.20	2325	2275
0.30	2300	2250
0.40	2275	2250
0.50	2250	2250
0.60	2200	2200
0.70	2175	2150
0.90	2100	-

* page 242 of [4]

From inspection of Tables 1 through 4, 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 from Table 4, 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. My opinion is that overheating should not be an issue as long as temperature never exceeds 2450° F and that quality bar stock such as SBQ 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 2250 F, the temperature gradient in the billet prior to forging should be known.

Comments on Conventional Processing

The current procedure is to air cool the hot forgings in bins, and then heat treat them. Most parts are austenitized, quenched in oil, and then tempered. Some, such as the lug forged by Bula Forge & Machine from 8637 steel, are normalized after air cooling and then austenitized, quenched and tempered. As mentioned, the objective is to use the DFIQ unit to quench directly after hot forging and eliminate the energy waste of cooling in air and having to austentize before quenching. Several different versions of this scenario were used.

<u>Bula Forge & Machine, Inc.</u>
Table BULA-1 shows photographs of the parts that were forged at Bula Forge & Machine and the processing that was done after hot forging.

Table BULA-1. Processes investigated at Bula Forge & Machine.

Part	Type of steel	Heat treating process applied after forging	Notes
 Key	1045	Conventional: Cool in the air + oil quench & temper.	Baseline data on material microstructure and mechanical properties were obtained. Tensile and Charpy specimens were taken from part mid radius.
	4140		
	8640		
	4340		
	1045	DFIQ + self-tempering.	Material microstructure and mechanical properties were compared to the baseline data.
	4140		
	8640		
	4340		
 Pintle adapter	4340 (currently used)	Currently used process: Cool in the air + normalize + cycle anneal + quench in oil & temper at 1,180°F.	Baseline data on material microstructure and mechanical properties were obtained. Tensile and Charpy specimens were taken from mid radius of part round section.
	4340	DFIQ + cycle anneal + quench in oil & temper at 1,180°F.	A possibility of eliminating of the normalizing process was evaluated.
	4340	DFIQ + temper at 1,180°F.	A possibility of eliminating of all three post-forging heat treating processes was evaluated.
	4140	DFIQ + normalize + IQ & temper at 1,180°F.	A possibility of the substitution of high alloy 4340 steel with less alloy 4140 steel was evaluated.
	4140	DFIQ + temper at 1,180°F.	
 Lug	8637 (currently used)	Currently used process: Cool in the air + normalize + quench in oil & temper at 1,100°F.	Baseline data on material microstructure and mechanical properties were obtained. Tensile and Charpy specimens were taken from the core of part thin sections.
	8637	DFIQ + temper at 1,100°F.	A possibility of eliminating of the normalizing process followed by quenching in oil was evaluated.

<u>Pintle Adapter</u>
Mechanical properties for the pintle adapter forging after heat treatment are given in Table BULA-2. The specified minimum tensile strength and minimum elongation are 130,000 psi and 19.7%, respectively. The strength is met for all tests, but two tests fall below the minimum elongation value. These two tests both were DFIQ processed after forging, but one was then annealed, oil quenched

and tempered, and the other was normalized, intensively quenched and tempered. While the reported elongation values are in question, the reduction of area and CVN data are in line with good ductility and toughness for the strength level.

Table BULA-2. Pintle Adapter Mechanical Properties for Different Heat Treating Processes.

Heat treatment process applied after forging		Mechanical properties					Grain Size
		Tensile psi	Yield psi	RA %	Elong. %	Impact ft·lb	
Currently used process: normalize + cycle anneal + quench in oil & temper at 1,180ºF.	4340 Steel	141,000	125,000	59	24	69	
		141,000	126,000	62	23	66	
		139,000	123,000	60	22	69	
	Average	140,300	124,667	60.3	23	68	8.0
DFIQ + cycle anneal + quench in oil & temper at 1,180ºF (no normalizing process).	4340 Steel	143,000	123,000	47	17	66	
		141,000	120,000	56	24	63	
		142,000	121,000	53	21	69	
	Average	142,000	121,333	52	20.7	66	
DFIQ + temper at 1,180ºF (no normalizing, cycle annealing and quenching in oil processes.	4340 Steel	135,600	112,100	54	23	63	
		135,000	110,000	59	24	68	
		137,000	114,000	51	21	58	
	Average	135,667	112,033	54.7	22.7	63	7.5
DFIQ + normalize + IQ & temper at 1,180ºF.	4140 Steel	145,000	126,000	63	17	110	
		148,000	131,000	62	20	55	
	Average	146,500	128,500	62.5	18.5	82.5	-
DFIQ + temper at 1,180ºF (no normalizing and second IQ processes).	4140 Steel	133,500	113,400	-	18	76	
		132,000	112,000	56	20	63	
		135,000	113,000	52	22	51	
	Average	133,500	112,800	54	20	63.3	-
Specification		130,000	-	-	19.7	-	-

Figure BULA-1 shows the microstructure for a pintle processed with the conventional heat treatment. For 4340 steel this is a well tempered martensite microstructure. Figure BULA-2 shows the microstructure of a 4340 steel pintle that was processed using the DFIQ route, including tempering at 1180 F. This microstructure is similar to that of the conventionally processed pintle. As Table BULA-2 shows, the mechanical properties are similar.

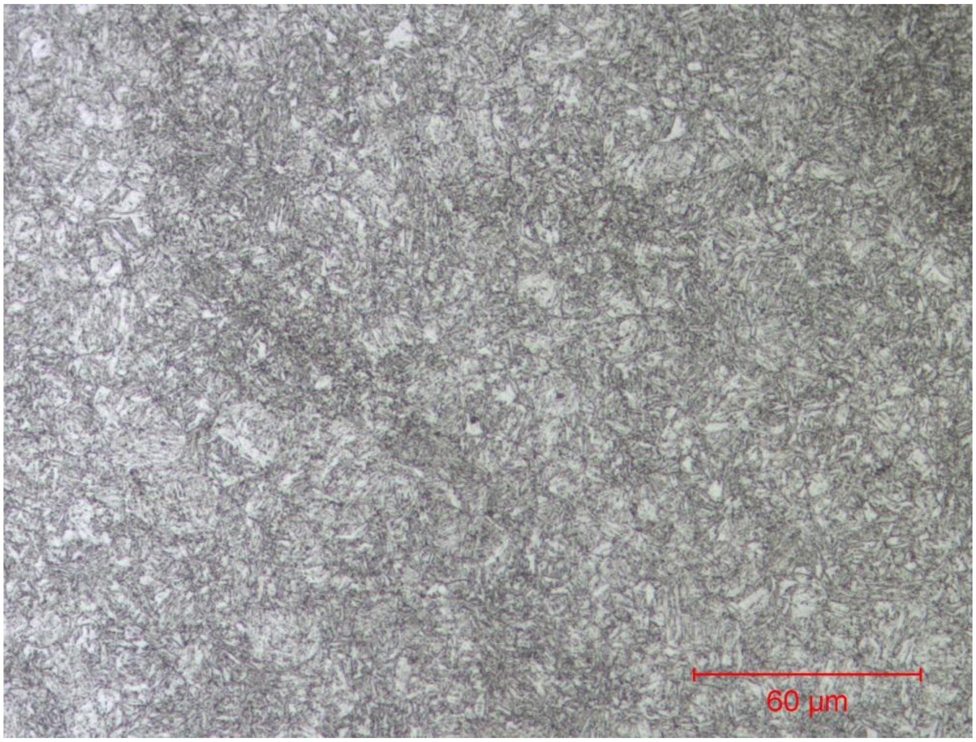


Figure BULA-1. Microstructure of 4340 steel pintle for conventional process route of normalize, cycle anneal, quench in oil, and temper at 1,180°F. 500X, Nital etch.

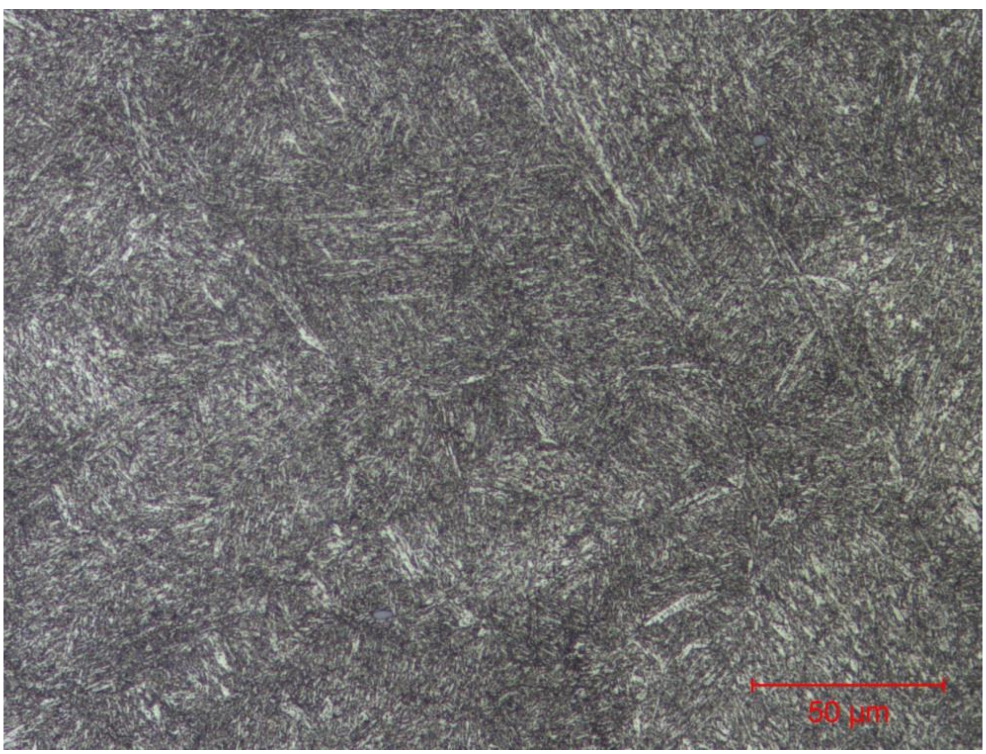


Figure BULA-2. Microstructure of 4340 steel pintle for sample 13 that was DFIQ'ed and tempered at 1,180°F. 500X, Nital etch.

Lug

Mechanical properties for forged lugs that were then heat treated are given in Table BULA-3. No required property levels were supplied. In comparing the conventional heat treatment and DFIQ processed lug forgings, the DFIQ processed parts had slightly lower strength, slightly higher ductility, and similar toughness. Both processes produced fine grained product with DFIQ grain size being ASTM 7 and the conventional process with the extra normalize having a grain size of ASTM 8. Without knowing the required properties, this comparison is not significant, meaning the DFIQ parts are most likely perfectly acceptable.

Table BULA-3. Lugs Mechanical Properties of Lug for Different Heat Treating Processes.

Heat treatment process applied after forging		Mechanical properties					
		Tensile psi	Yield psi	RA %	Elong. %	Impact ft·lb	Grain Size
Currently used process: normalize + quench in oil & temper at 1,100°F.	8637 Steel	145,000	120,000	34	14	20	
		166,000	150,000	30	19	20	
		163,000	146,000	39	16	15	
	Average	158,000	138,667	34.3	16.3	18.3	8.0
DFIQ + temper at 1,100°F (both the normalizing process and quench in oil processes were eliminated).	8637 Steel	154,000	135,000	44	20	18	
		148,000	123,000	44	19	20	
		146,000	122,000	46	16	17	
	Average	149,333	126,667	44.7	18.3	18.3	7.0

Key

Table BULA-4 contains mechanical property data for heat treated keys. Three steel grades were forged, as indicated. From Table BULA-4, the DFIQ processed keys have higher strength and hardness than the conventionally heat treated forgings. The higher strength and hardness is reflected in somewhat lower ductility for the DFIQ + self temper keys. For both the conventionally processed keys and the DFIQ+ self temper keys there was scatter in the data, especially in the ductility values. By adding a second tempering step to the DFIQ+ self temper route, the hardness and strength were dropped slightly and the ductility values were more consistent for all three alloys. Room temperature impact strength was also consistent.

Again, the part specifications are not known. The expectation is that the DFIQ processed forged keys should perform at least the same as the conventionally heat treated parts, especially with the additional tempering step.

Table BULA-4. Raw and Average Mechanical Properties for
Heat Treating Processes after Forging the Key.

<table>
<tr><th>Heat treatment process applied after forging</th><th>Steel</th><th>Tensile psi</th><th>Yield psi</th><th>RA %</th><th>Elong. %</th><th>Impact ft·lb</th><th>Hardness at ¼ thickness RC</th></tr>
<tr><td rowspan="12">Conventional: cooling in the air followed by quenching in oil and tempering at 600°F for 2 hours.</td><td rowspan="3">4140</td><td>254,000</td><td>216,000</td><td>32</td><td>9</td><td>5</td><td>50</td></tr>
<tr><td>252,000</td><td>230,000</td><td>11</td><td>8</td><td>5</td><td>48</td></tr>
<tr><td>249,000</td><td>214,000</td><td>34</td><td>13</td><td>5</td><td>50</td></tr>
<tr><td>Average</td><td>252,000</td><td>220,000</td><td>26</td><td>10</td><td>5</td><td>49</td></tr>
<tr><td rowspan="3">4340</td><td>264,000</td><td>224,000</td><td>38</td><td>12</td><td>7</td><td>52</td></tr>
<tr><td>264,000</td><td>223,000</td><td>40</td><td>17</td><td>7</td><td>51</td></tr>
<tr><td>258,000</td><td>254,000</td><td>40</td><td>15</td><td>9</td><td>50</td></tr>
<tr><td>Average</td><td>262,000</td><td>234,000</td><td>39</td><td>14</td><td>8</td><td>51</td></tr>
<tr><td rowspan="3">8640</td><td>228,000</td><td>186,000</td><td>24</td><td>13</td><td>6</td><td>50</td></tr>
<tr><td>232,500</td><td>188,300</td><td>12</td><td>10</td><td>6</td><td>48</td></tr>
<tr><td>202,000</td><td>161,000</td><td>30</td><td>12</td><td>7</td><td>49</td></tr>
<tr><td>Average</td><td>221,000</td><td>178,000</td><td>22</td><td>12</td><td>6</td><td>49</td></tr>
<tr><td rowspan="12">DFIQ followed by self-tempering* process only.</td><td rowspan="3">4140</td><td>285,000</td><td>169,000</td><td>22</td><td>11</td><td>14</td><td>52</td></tr>
<tr><td>285,000</td><td>164,000</td><td>39</td><td>14</td><td>16</td><td>51</td></tr>
<tr><td>291,000</td><td>172,000</td><td>18</td><td>18</td><td>13</td><td>54</td></tr>
<tr><td>Average</td><td>287,000</td><td>168,000</td><td>26</td><td>14</td><td>14</td><td>52</td></tr>
<tr><td rowspan="3">4340</td><td>323,000</td><td>186,000</td><td>11</td><td>14</td><td>11</td><td>55</td></tr>
<tr><td>278,000</td><td>180,000</td><td>17</td><td>8</td><td>15</td><td>54</td></tr>
<tr><td>258,000</td><td>186,000</td><td>0</td><td>4</td><td>12</td><td>56</td></tr>
<tr><td>Average</td><td>286,000</td><td>184,000</td><td>9</td><td>7</td><td>13</td><td>55</td></tr>
<tr><td rowspan="3">8640</td><td>289,000</td><td>170,000</td><td>15</td><td>12</td><td>13</td><td>52</td></tr>
<tr><td>291,000</td><td>195,000</td><td>6</td><td>7</td><td>12</td><td>52</td></tr>
<tr><td>304,000</td><td>167,000</td><td>1</td><td>8</td><td>17</td><td>52</td></tr>
<tr><td>Average</td><td>295,000</td><td>177,000</td><td>7</td><td>9</td><td>14</td><td>52</td></tr>
<tr><td rowspan="14">DFIQ followed by self-tempering* and additional tempering at 570°F for 2 hours.</td><td rowspan="4">4140</td><td>273,000</td><td>247000</td><td>37</td><td>9.5</td><td>11</td><td>50</td></tr>
<tr><td>271,000</td><td>236000</td><td>39</td><td>10</td><td>11</td><td>49</td></tr>
<tr><td>264,000</td><td>232000</td><td>41</td><td>9.5</td><td>9</td><td>50</td></tr>
<tr><td>254,000</td><td>223000</td><td>43</td><td>11</td><td>14</td><td>48</td></tr>
<tr><td>Average</td><td>266,000</td><td>235,000</td><td>40</td><td>10</td><td>11</td><td>49</td></tr>
<tr><td rowspan="3">4340</td><td>286,000</td><td>255,000</td><td>35</td><td>9</td><td>10</td><td>53</td></tr>
<tr><td>276,000</td><td>234,000</td><td>33</td><td>8</td><td>9</td><td>52</td></tr>
<tr><td>253,000</td><td>219,000</td><td>36</td><td>8</td><td>8</td><td>49</td></tr>
<tr><td>Average</td><td>272,000</td><td>236,000</td><td>35</td><td>8</td><td>9</td><td>51</td></tr>
<tr><td rowspan="4">8640</td><td>263,000</td><td>230,000</td><td>39</td><td>8.5</td><td>9</td><td>50</td></tr>
<tr><td>268,000</td><td>226,000</td><td>35</td><td>9</td><td>6</td><td>51</td></tr>
<tr><td>265,000</td><td>228,000</td><td>36</td><td>9.5</td><td>8</td><td>49</td></tr>
<tr><td>270,000</td><td>231,000</td><td>35</td><td>9</td><td>8</td><td>53</td></tr>
<tr><td>Average</td><td>267,000</td><td>229,000</td><td>36</td><td>9</td><td>8</td><td>51</td></tr>
</table>

*During the self-tempering process, the key temperature was between 500°F and 400°F for 25 minutes.

Welland Forge

The parts processed at Welland Forge were tines for agricultural equipment that were forged from 4140 or 8650 steel. Critical properties were hardness for wear resistance and toughness to withstand impacts. Product specification was a hardness of HRC 53-57. Dr. Aronov's report of March 13, 2017 summarizes the results of two forging trials.[2] Several problems were experienced in the first trial conducted in December of 2016.

- During DFIQ, several tines became tangled in the conveyor links. The conveyor was not used in the second trial, and all quenching during DFIQ was done with the tines held on the loading / unloading table. To increase the quenching rate, the tines were held in a vertical position, as shown in Figure W-1.
- The hardness after tempering the tines in the first trial was 2 to 3 HRC points lower than the specification hardness range (53 to 57 HRC). This was traced to an inaccurate furnace temperature (too high). The furnace was corrected in the second trial with the intent of producing correct hardness values.
- All 11 tines of 4140 steel in the first trial had cracks after tempering. No cracks were observed immediately after DFIQ, and the suspicion was a time delay issue between DFIQ and tempering. For the second trial, tines were tempered immediately after DFIQ.

In the first DFIQ run, the tines were laid on the loading tray grid and then automatically transferred to the conveyor; the water flow was across the top and bottom tine faces. The quench was interrupted after 8 seconds. In the second DFIQ trial, the forged tines were placed in a holder on the loading tray and the conveyor was not used. Figure W-1 shows a tine positioned on the DFIQ support. As the tine was lowered into the quench tank, the water jets impinged directly onto the broad faces of the tine, which should produce maximum cooling.

Figure W-1. Tine positioned on quench table showing the orientation of the part during the DFIQ process.

Table W1 summarizes the forging results for the second DFIQ trial. First, 3 tines each for 8650 steel and 4140 steel were forged and DFIQ treated. No cracks were observed on the tine surfaces after DFIQ, but 5 of the 6 tines were found to be cracked after tempering. Figure W-2 shows a photograph of quench cracks in a 4140 steel tine after dye penetrant inspection. Before the cracks were discovered, 25 tines of each steel grade were forged and DFIQ treated, and immediately tempered at 400° F after DFIQ. As Table W-1 shows, the surface temperature of the tines upon removal from the DFIQ tank was close to the tempering temperature. For 4140 steel, the Ms is ~640° F and the Mf is ~425° F, so the surface has transformed to martensite at this point. For 8650 steel, the Ms is ~590° F, and the Mf is ~200° F, so the surface has partially transformed to martensite. Because the interior is hotter, transformation will be continuing as the tine is removed from the DFIQ unit, either going into the tempering furnace, or waiting to be tempered. It seems that if the surface transformation is completed in the DFIQ unit for this part, it will crack as the core transforms. If the surface still has not fully transformed, there may be enough plasticity available in the untransformed patches to withstand surface stress generated as the core transforms to bainite. This is conjecture at this point. The tine thickness variation certainly complicates the issue. The higher Ms and Mf for 4140 steel make it more sensitive than 8650 to cracking in this case. The more severe quench for the vertically held tines accentuates the cracking problem for 8650 as more surface martensite would have formed in the DFIQ unit than for the flat orientation.

Table W-1. Summary of the second DFIQ trial for tines.

Steel	Run No.	No. of parts	Cooling time	Surface temperature at middle of tine after DFIQ	Surface hardness at middle of tine*		Notes
					After quench	After temper*	
8650	1	3	8sec	380-420ºF	56-58RC	55-57RC	_No cracks_ were observed after DFIQ in all six tines. The tines were put for tempering in about 1hour after DFIQ. _No cracks_ were observed after tempering in all three 8650 steel tines, while all three 4140 steel tines cracked.
4140	2	3	8sec	380-420ºF	54-55RC	55RC	
8650	3	25	8sec	380-420ºF	-	55-57RC	The tines were put into the tempering furnace *immediately* after DFIQ. Cracks were observed in 22 tines.
4140	4	25	8sec	380-420ºF	-	55RC	The tines were put into the tempering furnace *immediately* after DFIQ. Cracks were observed in all 25 tines.

*Hardness was measured at Welland Forge.
**All tines were tempered right after DFIQ at 400ºF for 1 hour in the portable continuous electric furnace installed in a close proximity from the DFIQ unit.

Mechanical properties were determined for the three 8650 steel tines from the first DFIQ trial; these tines had no cracks. Property values are reported in Table W-2. While hardness and strengths were similar for conventionally heat treated and DFIQ processed tines, the ductility and toughness of the DFIQ processes tines were significantly lower than for conventionally processed tines. Also, the grain size of the DFIQ tines was larger than that of the conventionally processed tines. This is another indication that DFIQ process as applied is not suited for this geometry.

Table W-2. Mechanical properties of 8650 steel tines from first DFIQ trial.

Heat treatment	Surface hardness, RC	Tensile strength, psi	Yield strength, psi	Elongation, %	Reduction in area, %	Impact strength, ft·lb	ASTM Grain Size
Conventional	56	297,000	226,300	12	30	10.7	8.0
DFIQ	55	303,300	222,300	6	5	6.8	5.0-6.0

Figure W-2. Photograph of 4140 steel tine showing quench cracks after dye penetrant inspection.

Clifford Jacobs Forge

Parts processed at Clifford Jacobs Forge are listed in Table CJ-1, along with the alloy and the heat treatment normally used, and the DFIQ treatment. Mechanical property testing was done at Tensile Testing Metallurgical Laboratory, and after DFIQ at Clifford Jacobs, the forgings (except for the Pyrowear 53 gear blanks) were snapped tempered at 400° F, shipped to Euclid Heat Treating, and then fully tempered prior to testing. Many of these parts are tempered at high temperatures, above 900° F.

Table CJ-1. Forgings processed at Clifford-Jacobs Forge

Forging name	Steel	Weight	Post-forging heat treatment		Number of forgings
			Currently used	Applied	
Disk (spur gear blank)	5130	9.6 lb	Forge – cool in air – quench in oil and temper at 1,135°F to hardness of 28-32RC.	DFIQ – temper at 1,200°F.	5
Hub	4140	21 lb	Forge – cool in air – quench in oil and temper at 1,050°F to hardness of 31-37RC.	DFIQ – temper at 1,150°F.	6
Stopper	1026	12 lb	Forge – cool in air – normalize. Hardness after normalizing: 137-187BH.	DFIQ – temper at 1,400°F.	5
Gland[1]	15B37	80 lb	Forge – cool in air – normalize - IQ and temper at 825°F to hardness of 32-39RC.	DFIQ – temper at 825°F or at 900°F.	5
Clamp	4140	23 lb	Forge – cool in air – quench in oil and temper at 1,050°F to hardness of 30-35RC.	DFIQ – temper at 1150°F.	4
Yoke	5130	10 lb	Forge – cool in air – quench in oil and temper at 1,125°F to hardness of 28-32RC.	DFIQ – temper at 1150°F.	4
Drum support	4150	20.5 lb	Forge – cool in air – quench in oil and temper at 1,075°F to hardness of 33-38RC.	DFIQ – temper at 1150°F.	4
Gear shaft	Pyrowear-53	21 lb	Forge – cool in air – normalize – carburize – quench in oil and temper.	DFIQ – temper at 400°F.	2

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 wheels that are made of 15B37 steel and have a similar thickness. The current post-forging heat treatment process for the standard railroad wheels 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 wheels.

Table CJ-2 gives the tensile properties, impact strength at room temperatures and hardness for forgings treated using DFIQ followed by tempering. The property values show good consistency, indicating that the DFIQ process is behaving in a consistent manner. This is important since variations in quenching can cause drastic mechanical behavior differences.

Table CJ-2. Mechanical property data for forgings processed by DFIQ and tempering at Clifford-Jacobs Forge.

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
Disk 5130	DFIQ + tempered at 1,200°F.	123,000	109,000	55	17	24	30-32RC	5.0
		119,000	105,000	57	14	22		
		121,000	107,000	49	15	19		
		121,000	106,000	51	17	22		
		123,000	108,000	47	14	17		
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		
		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* 15B37 (railroad wheel)	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	
		128,000	113,000	65	18	-		
		128,000	112,000	67	19	-		
		125,000	110,000	67	18	-		
Drum support 4150	DFIQ + tempered at 1,150°F	139,000	120,000	40	14	-	30RC	
		134,000	115,000	51	16	-		
		139,000	121,000	37	12	-		
		136,000	125,000	46	15	-		
Gear shaft Pyrowear-53	DFIQ + tempered at 400°F	-	-	-	-	-	-	5.5 to 7.5

Note: Tensile specimens were taken at the same depth from the surface as that for the railroad wheels.

Table CJ-3 compares average mechanical property values and grain size for the DFIQ plus tempered parts with the conventionally processed forgings. Specifications are also included in this table. The standard processed forgings and the DFIQ forgings have similar properties, in general. In three cases, the DFIQ treated forgings have elongations that fall just slightly short of the specification value, but the difference is less than 1%. For the 4140 steel hub, both the standard processed and the DFIQ processed forgings had hardnesses just above the specified maximum. The standard processed clamp forging fell short of the minimum yield strength, while exceeding the other requirements. Except for the 1026 steel stopper, these forgings were coarse grained, but grain size was not specified for any of the parts.

Table CJ-3. Average mechanical properties for DFIQ forgings and standard forgings from Clifford Jacobs Forge.

Part name Steel	Heat treatment	Tensile psi	Yield psi	RA %	Elong. %	Impact at 70°F ft·lb	Part hardness RC	ASTM grain size
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	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 wheel)	Standard[1]	132,500	110,000	50	14.5	-	33	-
	DFIQ[3]	127,000	107,500	34.5	13	-	33.5	1.5-2.5
	Specs[2]	-	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	2.0
	Specs	-	-	-	-	-	25	-
Clamp 4130	Standard	127,000	101,000	55	18	-	31	-
	DFIQ	127,500	112,500	65	18.3	-	32	3.0
	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	3.5
	Specs	125,000	105.000	35	15	-	28-33	-

Notes: [1] Standard heat treatment for railroad wheels made of 15B37 steel: normalize + IQ + temper at 825°F.
[2] Specs for railroad wheels.
[3] DFIQ glands were tempered at 900°F.

The gland forging was sued in these trials as a representation of a railroad wheel because it had similar thickness and would respond to DFIQ in a similar manner to a railroad wheel. Grade 15B37 was used because this is the grade used in railroad wheels. For this part, the DFIQ process of quench after forging and then temper omitted the normalize step that the conventional heat treat process uses. The elimination of normalization is thought to be the reason for the large grain size after DFIQ+temper route.

Pyrowear 53 Gear Blank

Figure CJ-1 shows a cross section of a Pyrowear 53 (P53) gear blank and the locations used for grain size determination after air cooling of the forging. The aim is to achieve an ASTM grain size of 6 or higher after forging at all locations. Table CJ-3 lists the grain size values for three gear blanks that were placed at the indicated location in the 2100 F furnace for forging. Note that this temperature is not the typical heating temperature of 2350 F for forging at Clifford Jacobs Forge, which reportedly results in grain sizes of ASTM 3 to 6 for this steel. The purpose of the lower forging temperature is to produce a finer and more uniform grain structure after forging. The hardness difference for furnace location shows that the furnace temperature is not uniform in the chamber. Observations at Clifford Jacobs Forge are that subsequent normalizing does not refine the grain size in these forgings and sometimes results in larger grains in some areas of the cross section.

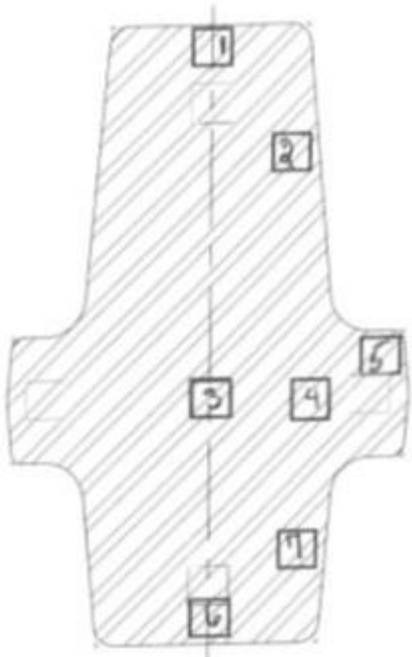
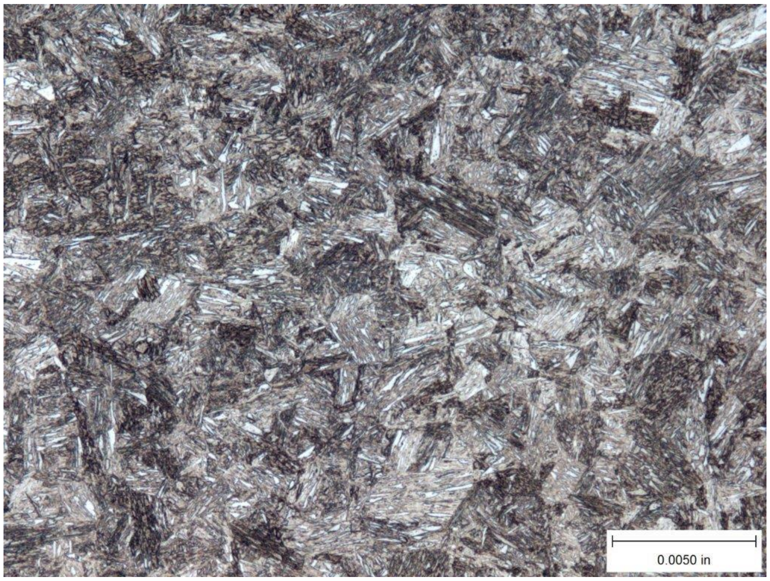


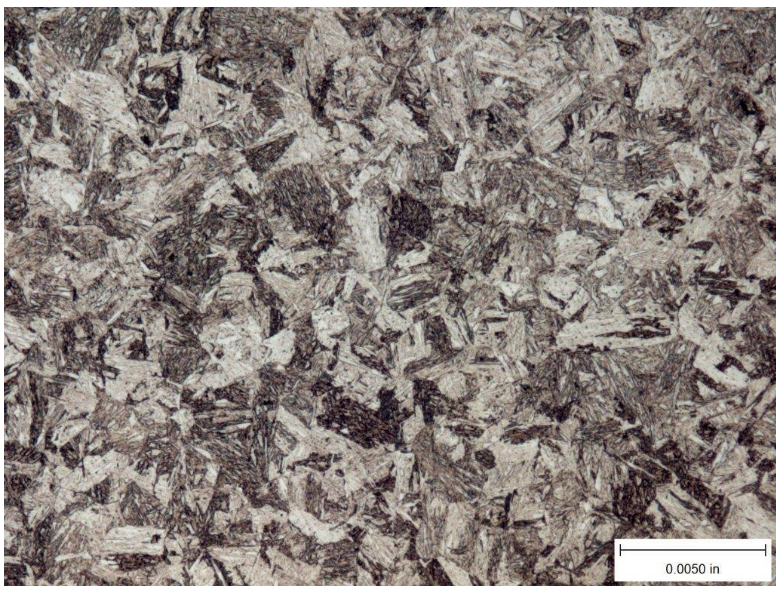
Figure CJ-1. Pyrowear 53 gear blank showing locations used to measure grain size after heat treatment.

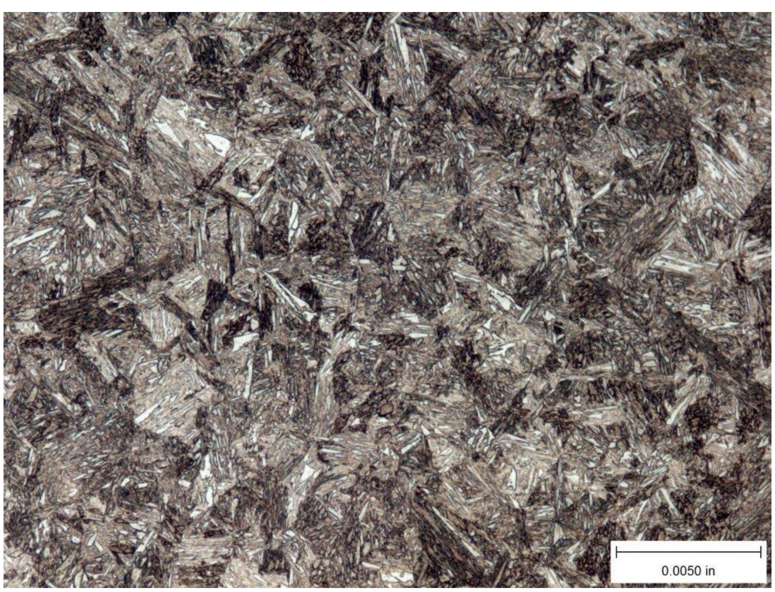
Table CJ-3. Grain Size Values for Three Gear Blank Forgings Heated at 2100 F Prior to Forging.

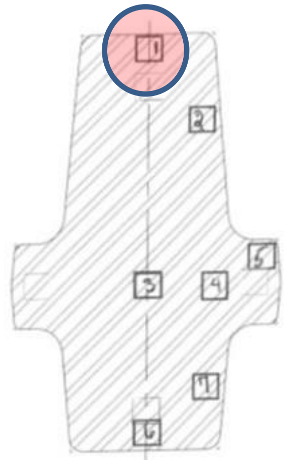
Gear blank No.	Gear blank location in furnace	Sample / Location Number							Average grain size
		1	2	3	4	5	6	7	
3	Front	6.0	6.0	6.0	6.0	6.0	5.5	5.5	5.9
6	Middle	6.5	7.0	6.5	7.0	6.5	7.0	6.5	6.7
9	Back	7.0	7.0	6.5	7.0	7.5	5.5	6.5	6.7

Microstructures for these forgings are shown in Figures CJ-2 to CJ-8. Because of the high hardenability of Pyrowear 53 steel, the gear blanks are martensitic with a high amount of retained austenite. The purpose of these photomicrographs is to simply compare the microstructure. Ideally, the dislocation density should be determined to investigate the effect of cooling rate on microstructure, but this determination is beyond the scope of this project.







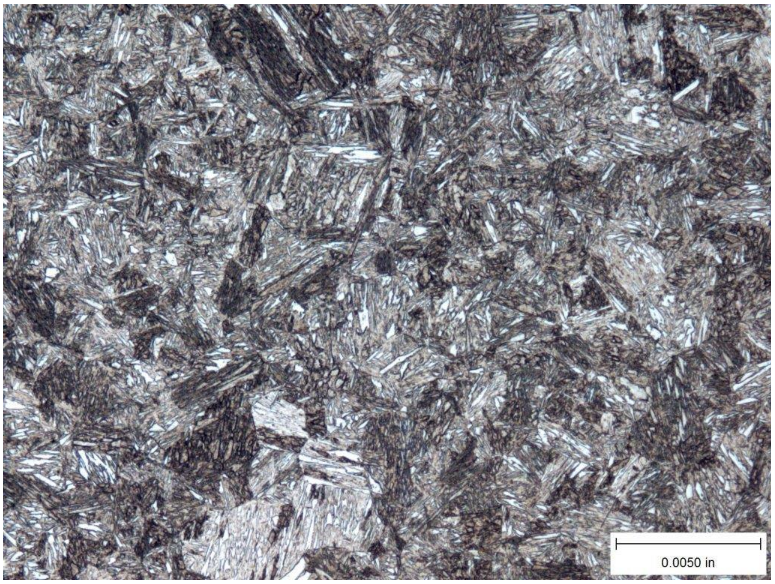


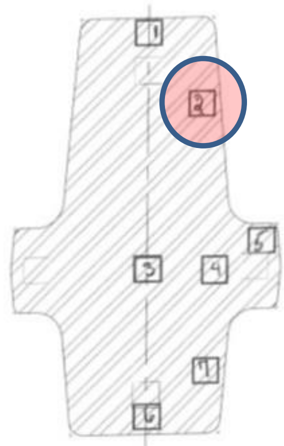
Position 1:
Front: 6.0

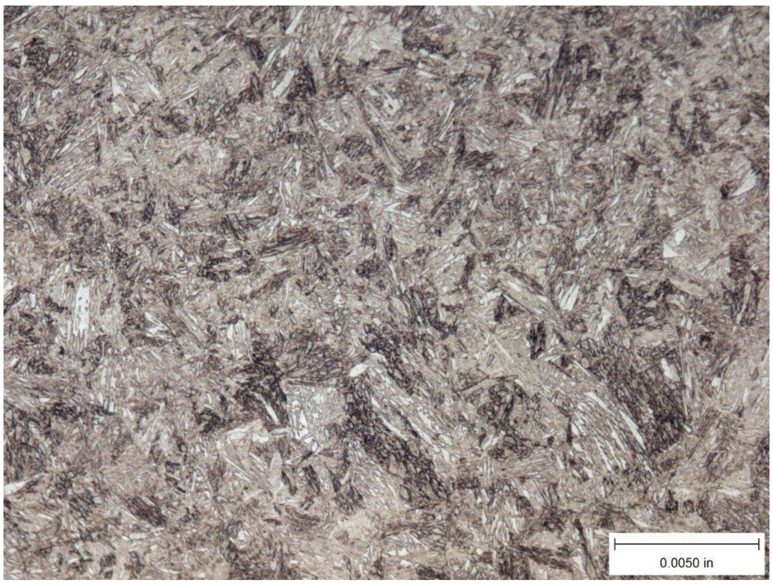
Middle: 6.5

Back: 7.0

Figure CJ-2. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 1.







Position 2:
Front: 6.0

Middle: 7.0

Back: 7.0

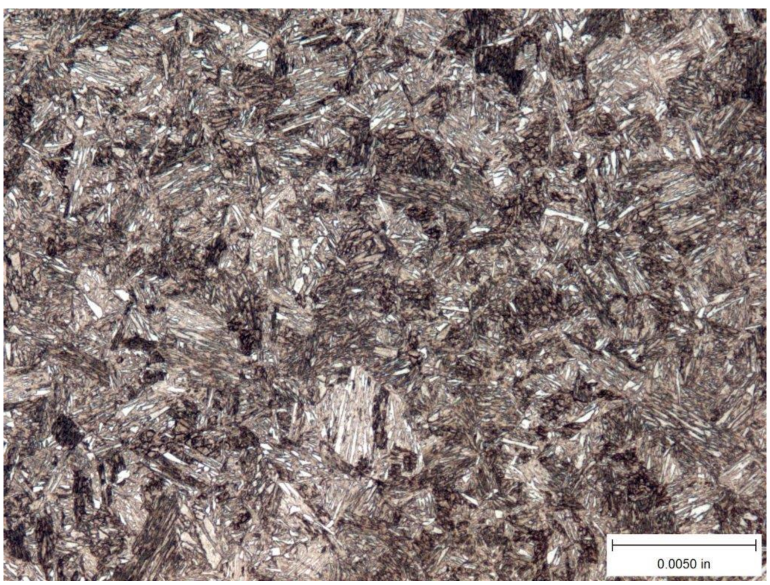
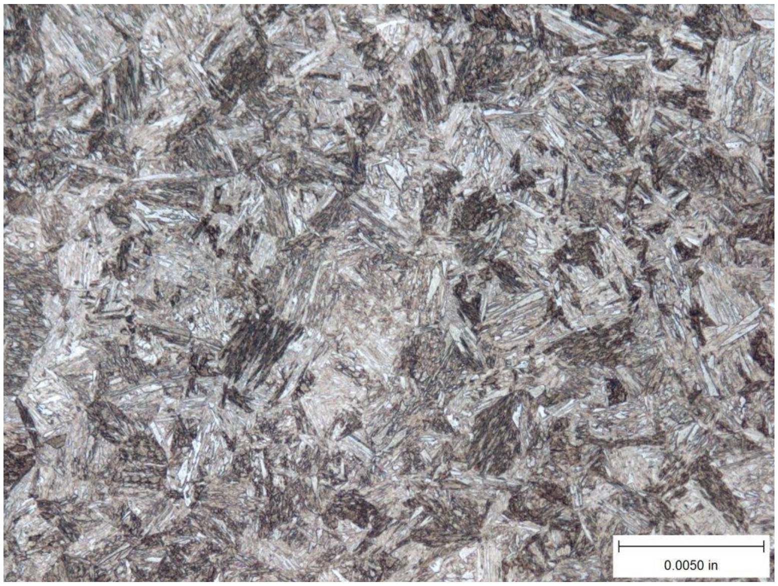
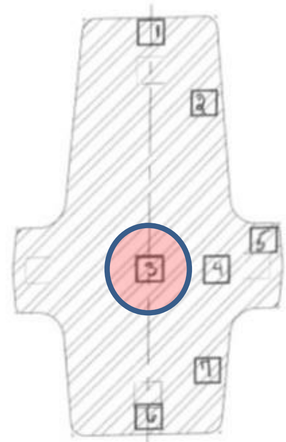


Figure CJ-3. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 2.

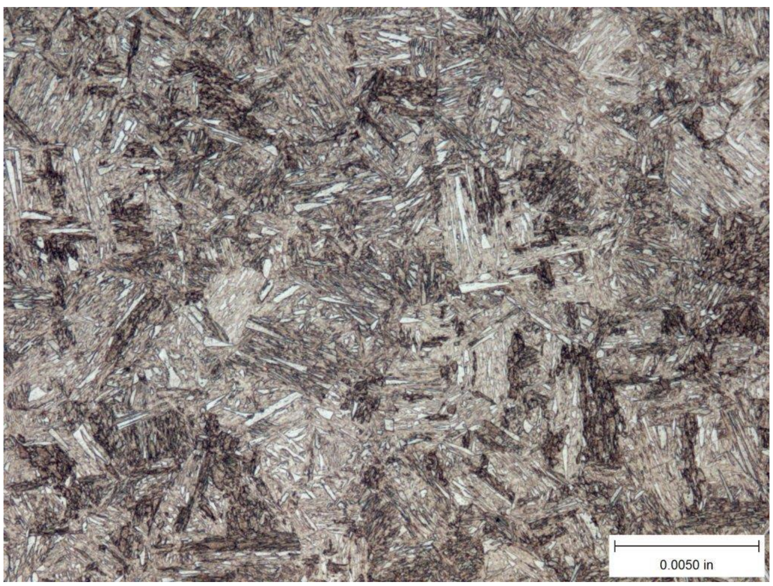




Position 3:
Front: 6.0

Middle: 6.5

Back: 6.5



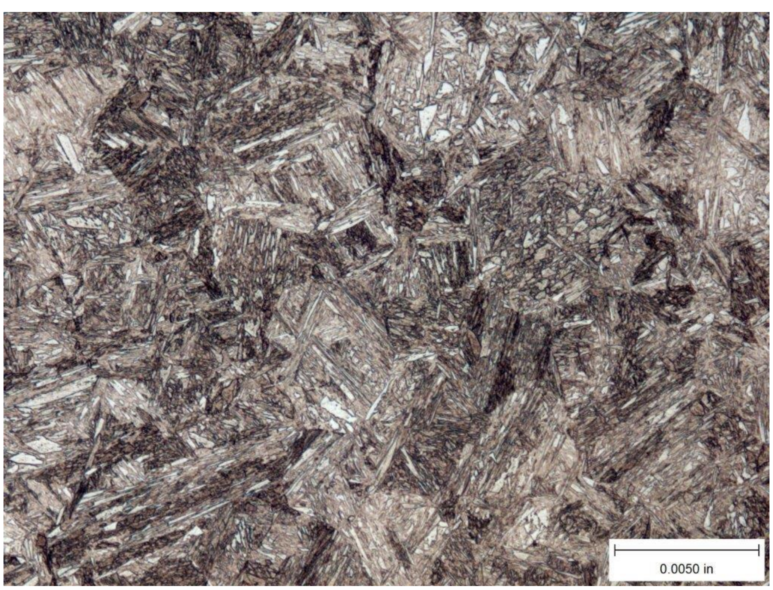
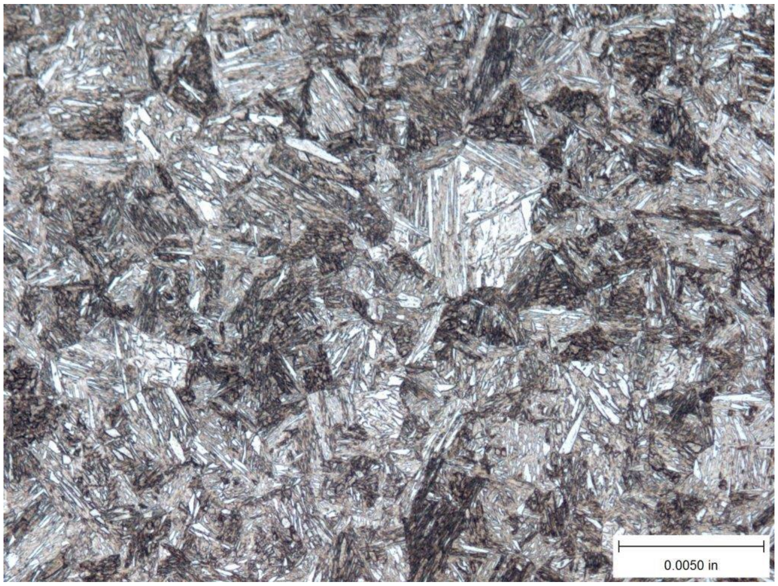
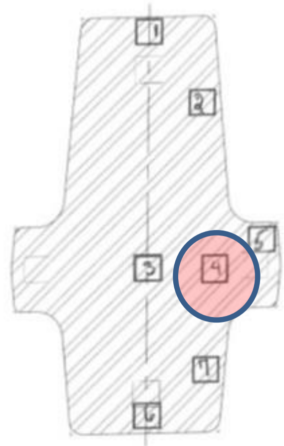


Figure CJ-4. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 3.

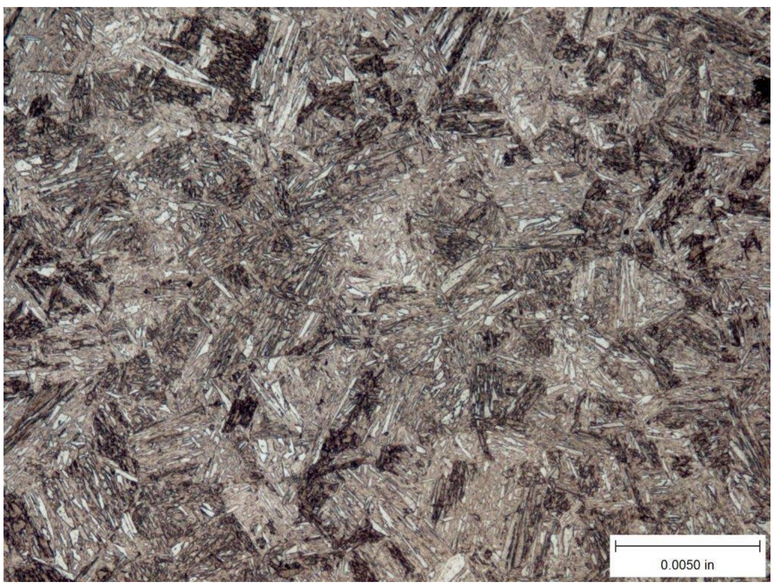




Position 4:
Front: 6.0

Middle: 7.0

Back: 7.0



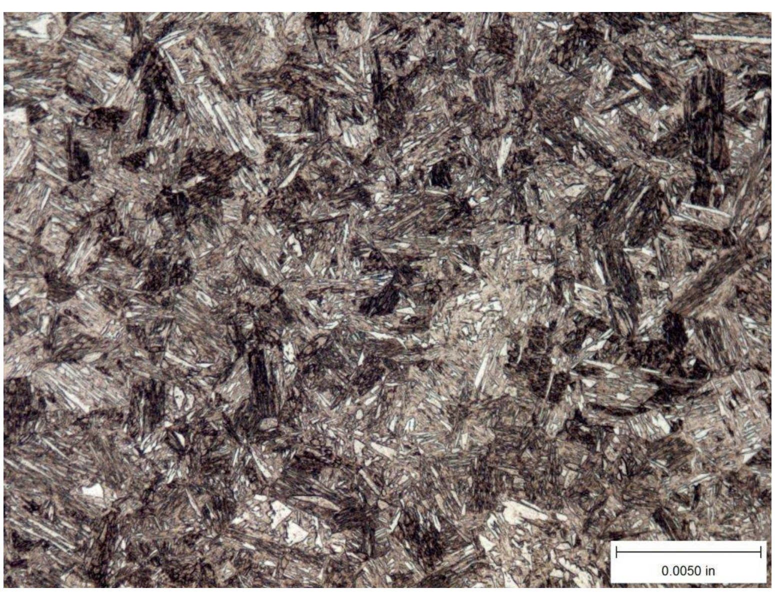
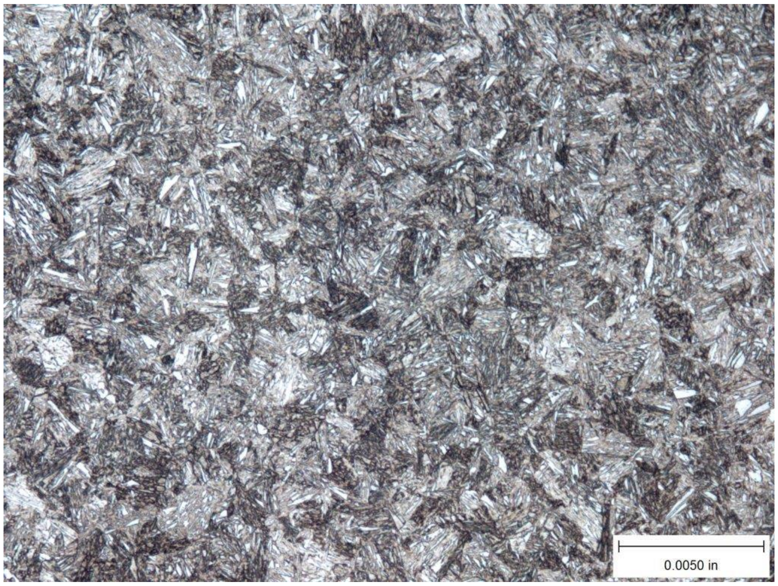
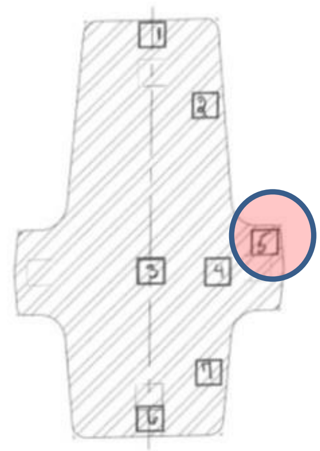


Figure CJ-5. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 4.

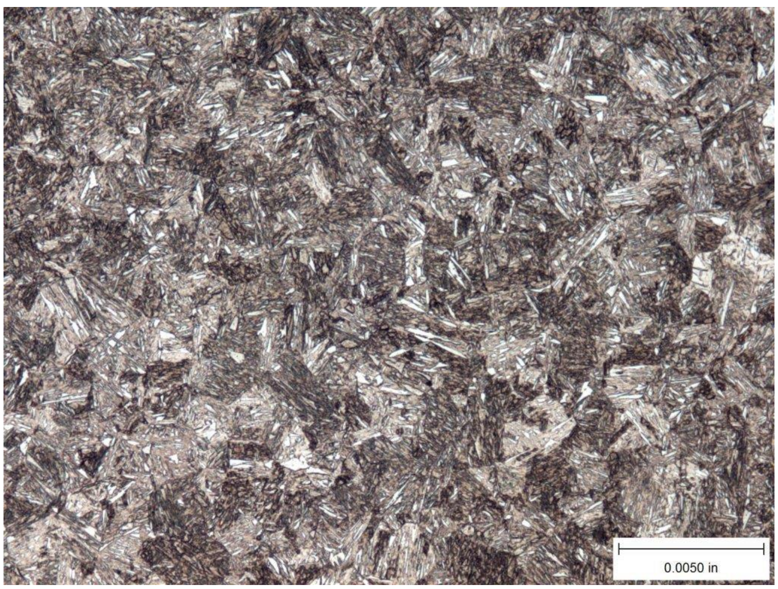




Position 5:
Front: 6.0

Middle: 7.5

Back: 7.5



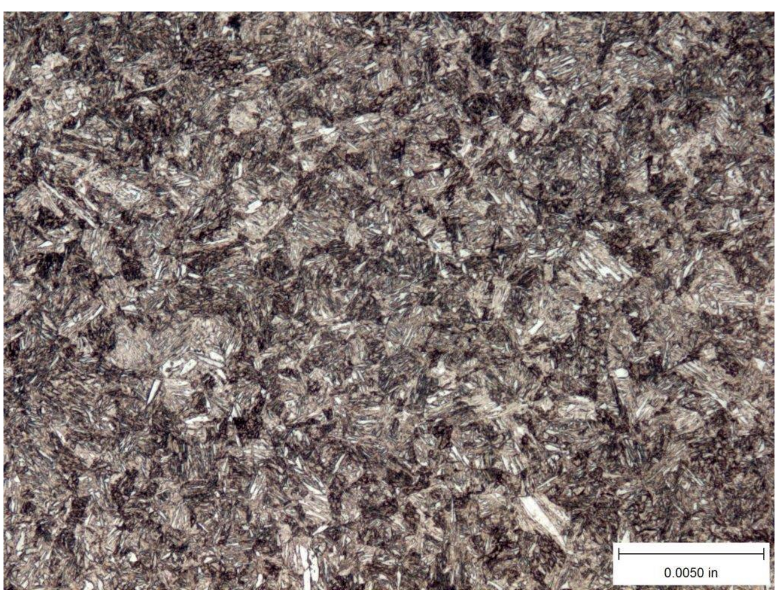
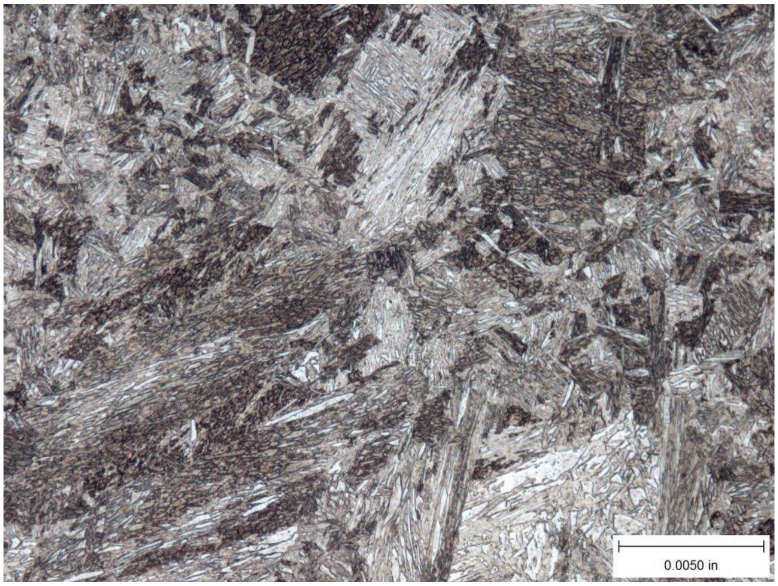
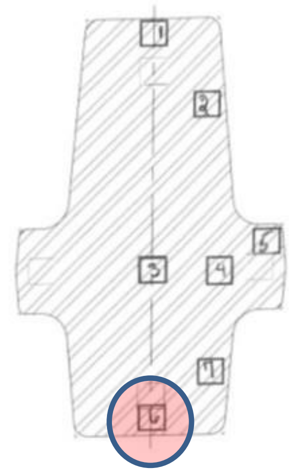


Figure CJ-6. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 5.

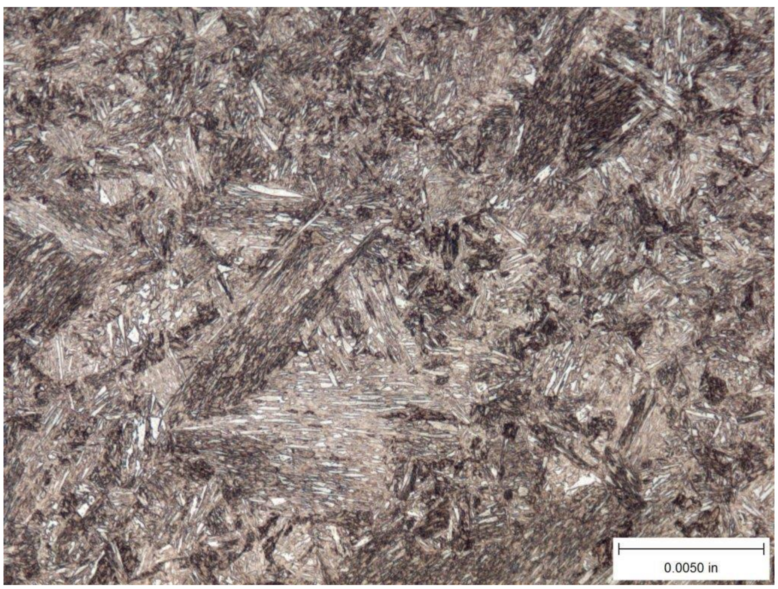




Position 6:
Front: 5.5

Middle: 7.0

Back: 5.5



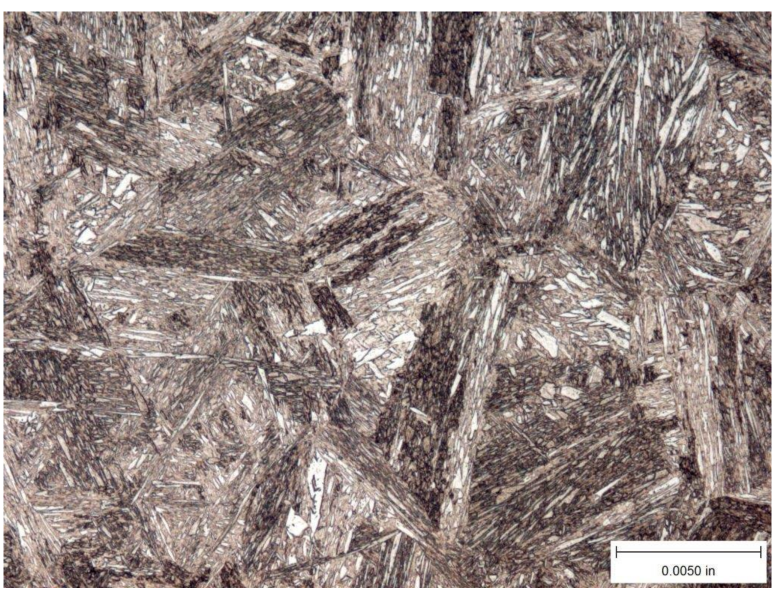
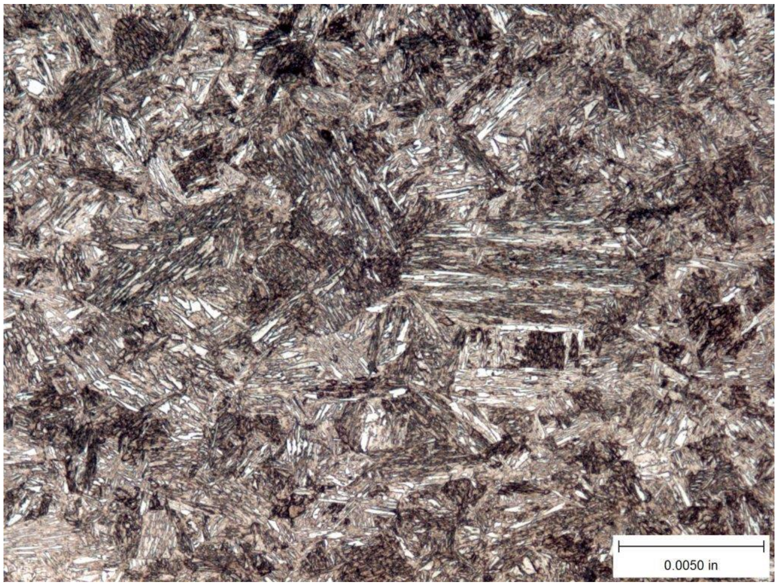
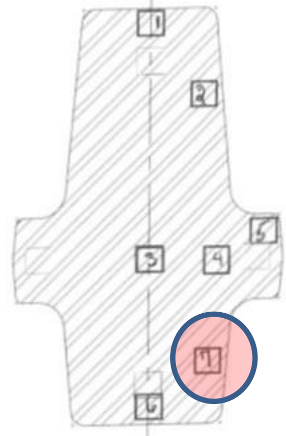
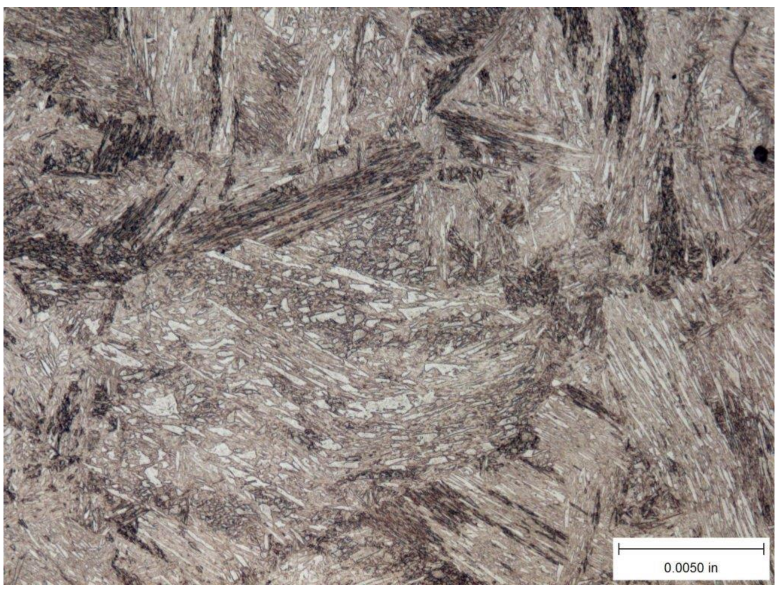


Figure CJ-7. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 6.







Position 7:
Front: 5.5

Middle: 6.5

Back: 6.5

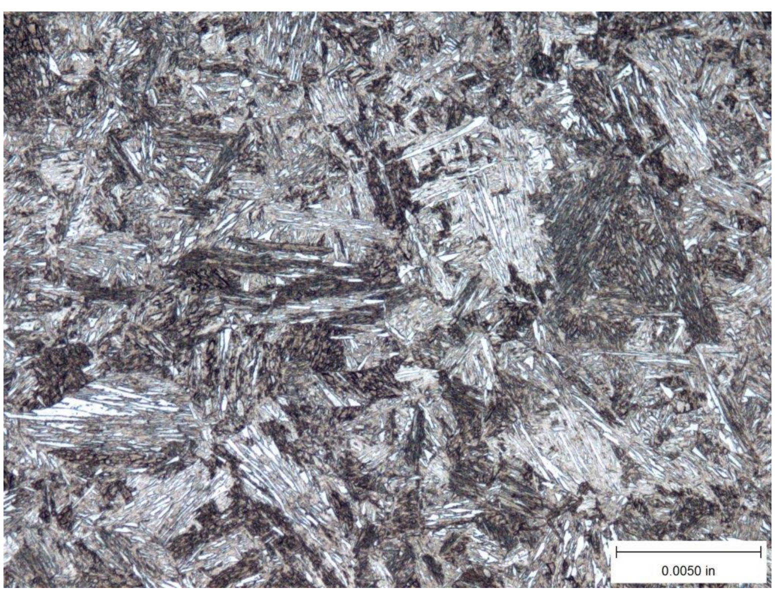


Figure CJ-8. Microstructure of Pyrowear 53 hot forged and air cooled gear blanks. Sections were taken from Position 7.

Summary

The Direct from Forge Intensive Quench (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. It is a compact, portable unit that can be used in a forge shop environment with little interference of existing facilities. Its applicability is subject to the hardenability of the steel being used, part geometry, and more importantly to the manufacturing steps that follow the hot forging operation.

The forgings that were processed by DFIQ covered a wide range of relatively complex geometries, i.e. thin and thick sections. The main cracking issue was for the tines forged from 8650 and 4140 steel at Welland Forge. The issue here was the interruption time of the DFIQ process relative to the amount of martensite transformed and its location. A change in cooling rate could correct this issue and avoid cracking. A probe has been prepared to measure the cooling rate of the DFIQ unit, and experiments are planned for the near future.

Dr. Nikolai Kobasko, a principal inventor of the intensive quenching family of processes, has proposed that intensive quenching results in super strengthening of the microstructure because the high cooling rate increases the dislocation density of the austenite prior to transformation to martensite, resulting in a finer martensitic structure. This cannot be proven by the measured mechanical property data or the grain sizes of the DFIQ treated forgings. The 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. Strengths and hardness values were acceptable in almost all cases. The strength properties tended to be higher for DFIQ treated forgings, most likely due to a higher cooling rate, but they were not appreciably different from the conventionally processed forgings. The main benefit is that the heat from hot forging can be used with DFIQ to eliminate the need for a second or even third reheat.

If the 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 the purpose of the thermal treatment immediately after forging is to condition the microstructure for subsequent machining operations and a final hardening step will be relied on to achieve the required properties, then DFIQ loses it benefit. At that point, a controlled air cooling step most likely should be favored, as it will eliminate a tempering step that the DFIQ route will require.

A final consideration concerns carburization. If a forging will be machined and finally carburized, grain size is important. During carburization, grain boundaries provide the easiest carbon diffusion path into the part. A coarse grain structure will build up higher levels of carbon and is more likely to form carbide networks than a fine grain structure because it has less grain boundary volume for diffusion. For this reason, minimum grain sizes of ASTM 5 or even 6 are usually specified for carburized parts. Here, cooling rate after forging can be a benefit for DFIQ.

References

1. Michael Aronov, Pintle Micros&Properties.pptx

2. Michael Aronov, “Preliminary Technical Report on Second DFIQ Trial Conducted for Tines at Welland Forge on March 13, 2017.”
3. Michael Aronov, “Preliminary Report of Metallurgical Evaluation of Forgings Processed at Clifford-Jacobs Forge (as of March 4, 2018).”
4. ASM Handbook volume 14A, Metalworking: Bulk Forming, ASM International, Materials Park, OH, 2005.