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High-Energy Rate Forgings of Wedges: Characterization of Processing Conditions

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High-Energy Rate Forging: Characterization of Processing Conditions for Wedge Forging

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Abstract

The wedge geometry is a simple geometry for establishing a relatively constant gradient of strain in a forged part. The geometry is used to establish gradients in microstructure and strength as a function of strain, forging temperature, and quenching time after forging. This geometry has previously been used to benchmark predictions of strength and recrystallization using Sandia's materials model for type 304L austenitic stainless steel. In this report, the processing conditions, in particular the times to forge and quench the forged parts, are summarized based on information recorded during forging on June 18, 2013 of the so-called wedge geometry from type 316L and 21Cr-6Ni-9Mn austenitic stainless steels.

ACKNOWLEDGMENTS

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1 DESCRIPTION OF THE WEDGE FORGING

A simple wedge geometry was previously developed for studying the combined effects of strain, forging temperature and time on the microstructure and mechanical properties of high-energy rate forged austenitic stainless steel. In previous work on type 304L austenitic stainless steel [1], two wedge-shape geometries were considered. This study only considered one geometry (Figure 1), equivalent to geometry A from previous work. Additionally, this study seeks to evaluate the forging process parameters on type 316L and 21Cr-6Ni-9Mn (also called Nitronic 40 or simply 21-6-9) austenitic stainless steels. Modeling and simulation work by Arthur Brown (SNL/CA) has shown that the forged properties of type 304L are very sensitive to the time between forging and quenching in water. Therefore, during forging of type 316L and 21-6-9, additional efforts were taken to measure the characteristic times for the forging steps, as well as to vary the time for these steps. This report summarizes the processing and forging times for the wedge forgings of type 316L and 21-6-9. It is anticipated that subsequent reports will summarize the resulting forged microstructures, mechanical properties, and forging simulations.

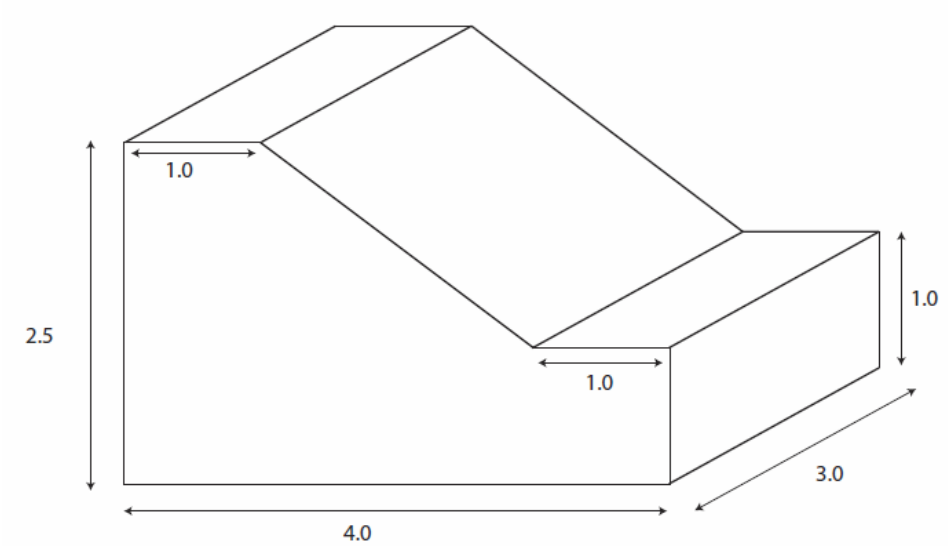

Figure 1. The wedge-shape geometry (in inches) prior to forging.

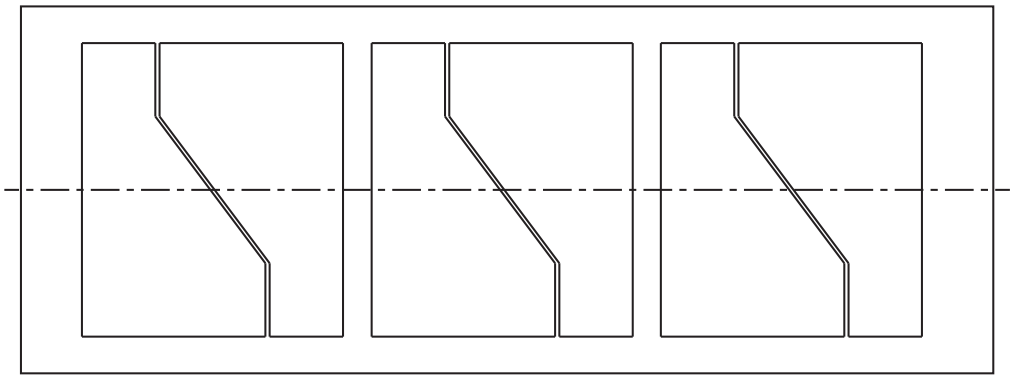

Figure 2. Orientation of the forging preform in annealed bar (5-inch diameter).

2 EXPERIMENTAL METHODOLOGY

2.1 Materials and forging schedule

The materials from which the wedge preforms were machined are summarized in Table 1. The manufacturer obtained the 316L material from a commercial distributor as 5-inch diameter round bar in the annealed condition meeting materials specification ASTM A276. The 21-6-9 material was provided by Honeywell FM&T (material control number 115545, also 5-inch diameter, meeting SNL specification 9855212). The forging preforms were machined to the geometry shown in Figure 1 and were extracted from the bar as shown in Figure 2; the axis of the bar was oriented in the height direction of the wedge (i.e., forging direction). The cut preforms were annealed by the manufacturer at 1750 ± 25˚F for 3 ± 1 hr prior to forging.

Forging was accomplished in a single step using DOE-owned high-energy rate hammers operated by the single-source vendor for high-energy rate forging (HERF). All forging was completed on June 18th, 2013; in attendance were representatives, including the authors, from Sandia National Laboratories California and Honeywell Federal Manufacturing and Technologies (Honeywell FM&T, also commonly referred to as Kansas City Plant, KCP). The list of nominal forging conditions is provided in Table 2; three forgings were produced for each condition and labeled A, B and C. All forging conducted by HERF to reduce the height of the wedge to ~1 inch. Forging was done at four different initial temperatures: 1500°F, 1600°F, 1700°F, and 1800°F. After forging was complete, the bulk of the work pieces were either quenched directly (rapid quench condition) or the forged parts were held for 30 seconds in air (quench delay condition) prior to quenching. The transfer times and the temperature of the wedges' surface were measured for each forging operation. Two sets of samples (numbers 5-A,B,C and 12-A,B,C) were held for 10 seconds in air prior to forging.

2.2 Transfer times

The transfer times were independently measured by Sandia National Labs (SNL) and the manufacturer. The process is idealized as consisting of four time segments:

1) the time the work piece left the furnace until it was stationary on the forge die;
2) the time the work piece is stationary on the die until it is initially struck by the ram;
3) the time after the initial strike until the work piece begins to be lifted off of the die;
4) the time from when the work piece is lifted from the die until it enters the quench bath.

The time of each step or segment was determined from video recorded using a digital camera with a frame rate of 30 frames/second. The transfer times for each segment of the forging process were determined visually to the nearest 0.1 second. The manufacturer recorded times live during the forging operation using a stopwatch; however, only two time segments were recorded, segment 1+2 (the "pre-strike" time: the time prior to work piece being struck) and segment 3+4 (the "post-strike" time: the time after the work piece has been struck and prior to quenching). It is not clear the exact midpoint of the manufacturer's measurements – whether the press time itself was included in segments 1+2 or segments 3+4. SNL only measured the times for 316L and 21-6-9 samples that were initially held at 1500°F and 1600°F, while the manufacturer measured the times for all samples.

For the SNL measurements, while the video worked very well to calculate the transfer times, in some cases the viewing angle made it difficult to determine exactly when the work piece was removed from the furnace, or when it was placed in the quench bath. As a result, in those cases the start and end times were inferred since they could not be measured directly. In future runs, having the video camera at an angle where the start and end could be observed directly could improve the accuracy of the measurements. For the manufacturer measurements, the observer had a direct view of the oven and the quench bath, allowing him to accurately measure the start and finish times of the forging run. However, the cutoff time that separated segments 1+2 and segments 3+4 was not clearly defined, and for future runs it would be advantageous to explicitly define the segments to be timed in the scope of work prior to the forging run.

Table 1. Composition of austenitic stainless steels used in this study.

material	Fe	Cr	Ni	Mn	Mo	N	C	Si	S	P
21-6-9 MCN 115545	Bal	19.2	7.1	9.7	nr	0.26	0.034	0.47	0.0001	0.021
Type 316L	Bal	16.6	10.5	1.4	2.0	0.034	0.020	0.29	0.03	0.028

nr = not reported

Table 2. Conditions of forging processes and specimen identifications.

ID	Material	Temp	Time to Press	Time to Quench
1A-C	316L	**1500**	Rapid	Rapid
2A-C	316L	**1500**	Rapid	+30s
3A-C	316L	**1600**	Rapid	Rapid
4A-C	316L	**1700**	Rapid	Rapid
5A-C	316L	**1700**	+10s	+30s
6A-C	21-6-9	**1500**	Rapid	Rapid
7A-C	21-6-9	**1500**	Rapid	+30s
8A-C	21-6-9	**1600**	Rapid	Rapid
9A-C	21-6-9	**1600**	Rapid	+30s
10A-C	21-6-9	**1700**	Rapid	Rapid
11A-C	21-6-9	**1700**	Rapid	+30s
12A-C	21-6-9	**1700**	+10s	Rapid
13A-C	21-6-9	**1800**	Rapid	Rapid

2.3 Temperature measurement

To measure the surface temperature of the work pieces during the forging process, a Mikron M90-H1 infrared pyrometer with a temperature range of 300 – 1000°C and a spectral range of 0.78 – 1.06 µm was used. Temperature measurements were made of all pieces that were forged at 1500°F and 1600°F; no measurements were made for the samples at 1700°F or 1800°F.

For accurate temperature readings, the emissivity value of the work piece must be manually entered into the pyrometer. A brief literature search prior to the forging runs revealed that the emissivity of stainless steel is strongly dependent on the surface finish, the temperature, and the measured wavelength; in the literature values ranging from 0.2 – 0.8 have been reported. Since there was not an opportunity to calibrate the emissivity of the specific stainless steel work pieces prior to the forging runs, an emissivity of 1 was used for all measurements. This was expected to affect the accuracy of the temperature measurements, but also allow the measurements to be consistent with one another, allowing for self-comparisons to be made.

Another variable that impacts the temperature measurements is the working distance from the sample. The temperature was taken a distance of ~15 feet from the die and a height of ~8 feet from the floor, except where otherwise noted (see Appendix III). The die itself was at a height ~3 feet from the floor. The sample was placed into a ~4 inch recession into the forge die, which obscured the direct line of sight for the pyrometer, affecting the temperature readings. The recorded value is the maximum value seen on the pyrometer as the work piece was placed into this recession, and was often not the same value that was observed once the piece was stationary in the die.

3 RESULTS

3.1 Transfer times

From SNL measurements (Table 3), it was observed that the time the work piece was removed from the furnace until quench was consistent for the rapid-quench condition and for the quench-delay condition, respectively. For the rapid quench (10 specimens), the total time was 15.8 ± 0.6 s, while for the delayed quench (8 specimens) the total time was 37.6 ± 0.6 s. Video was not available for the entire forging process for the remaining 3 specimens. In both the rapid quench and the quench-delay conditions, the difference between the longest and shortest total times was < 2 s.

The standard deviation was also relatively small (<10% of measured time) for shorter time segments. For the rapid-quench and quench-delay conditions combined, the time from when the piece was removed from the furnace until it was first contacted by the forge die (segments 1+2) was 6.5 ± 0.4 s, with a minimum transfer time of 5.5 s and a maximum transfer time of 7.1 s. The time from initial contact with the forge die until quenching (segments 3+4) was 9.5 ± 0.4 s for the rapid-quench specimens, and 31.0 ± 0.3 s for the quench-delay specimens. This includes the time that the sample was in the die while the die was closed, which was measured at 0.9 s for all specimens. The average times are further broken down in Table 3. The times (determined from the video records) for all runs measured by SNL are presented in Appendix I.

When comparing the total forging times measured by SNL and the vendor (Table 4), they are in close agreement, usually within a standard deviation of one another for both the rapid-quench and quench-delay conditions. For the rapid-quench condition, the SNL average time was 15.8 ± 0.6 s, while the vendor average time was 16.1 ± 0.5 s. For the quench-delay condition, the SNL time was 37.6 ± 0.6 s while for the vendor the total forge time was 37.3 ± 0.7 s. For all samples in the rapid-quench condition, including those that were not measured by SNL, the average forging times of the vendor were 16.1 ± 0.7 s for the rapid-quench condition (21 samples), and 37.4 ± 0.8 s for the quench-delay condition (12 samples). In this study, the total forging time is indicative of the process and time delay after forging. In general, however, the total forging time does *not* indicate a bias in the process. The total forging time includes: (i) the time prior to the forging strike (longer "pre-strike" times tend to increase the strength because the forging temperature is decreasing), and (ii) the time after forging but prior to quenching (longer "post-strike" times tend to reduce strength because more time is allowed for recrystallization prior to quenching). Therefore, total time for forging should be used with caution in relation the anticipated properties.

When examining the individual transfer-time segments, the times between SNL and vendor were consistent as well. For segments 1+2 ("pre-strike" time): SNL had an average time of 6.5 ± 0.4 s (19 samples) while the vendor's average time was 6.6 ± 0.5 s (33 samples). For segments 3+4 ("post-strike" time), for the rapid-quench condition, SNL time was 9.5 ± 0.4 s (10 samples) and the vendor time was 9.4 ± 0.7 s (24 samples), while for the quench-delay condition, SNL average time was 31.0 ± 0.3 s (8 samples) and the vendor time was 30.7 ± 0.3 s (15 samples). Thus, the overall times for both the rapid-quench and quench-delay conditions were consistent throughout the forging runs. The data also suggests that the midpoint of the vendor measurements, splitting segments 1+2 from 3+4, was the initial strike of the ram, as with the

SNL measurements. This is because the times taken by SNL and vendor agree closely with one another. However, it is possible that other explanations are valid. For example, the vendor measurements for segments 1+2 may have begun earlier – such as when the part was initially touched – and that the vendor did not measure the time that the part was pressed.

Table 3. Transfer time by segment for wedge forgings (SNL measurements), in seconds.

Segment	1	2	1+2	3	Quench condition	4	3 + 4
Average	3.2	3.3	6.5	7.1	Rapid quench	2.5	9.5
					Quench delay	23.7	31
SD	0.3	0.2	0.4	0.5	—	0.5	0.4

Table 4. Total forging time, in seconds: segments 1+2+3+4.

Condition	SNL measurements	Manufacturer measurements	Average of all measurements
Rapid quench	15.8 ± 0.6	16.1 ± 0.5	16.1 ± 0.7
30s delay prior to quench	37.6 ± 0.6	37.3 ± 0.7	37.4 ± 0.8

3.2 Temperature measurements

For the work pieces forged with a furnace set temperature of 1500°F, the pyrometer registered the temperature inside the furnace to be 1504°F, and at a furnace set temperature of 1600°F, the pyrometer measured the furnace temperature to be 1616°F. The temperature of each work piece was measured as they were placed into the forge die, prior to forging (Table 5). The temperature of the forge die itself was not measured as it was below the temperature range of the pyrometer. Typically, forging dies are initially heated to 300 – 400°F using blow torch heaters. For a furnace set temperature of 1500°F, the measured temperature of the work pieces when placed in the die was 1299 ± 2°F for the 316L (3 samples), and 1339 ± 11°F for the 21-6-9 (6 samples). For a furnace set temperature of 1600°F, the measured temperature was 1447 ± 28°F for the 316L (3 samples), and 1467 ± 15°F for the 21-6-9 (6 samples).

For the quench-delay condition, the temperature was also measured as the work piece was held in air prior to quenching. The maximum and minimum temperatures observed were recorded. Since the air hold occurred while the work pieces were physically held over the quench bath, the orientation of the part and the working distance to the pyrometer was not consistent from sample to sample. As a result, there was variation in the measured temperature from sample to sample. Table 6 summarizes the results of the temperature measurement during the quench delay. Full results are given in Appendix II.

There are several ways in which the accuracy and repeatability of the temperature measurements could be improved. The first is to attempt to calibrate the emissivity of the work piece prior to forging. A brief attempt was made in this case; a single sample of the 316L was

removed from the 1600°F furnace and placed on a table for 3 seconds while measuring the temperature with the pyrometer with an emissivity setting of 1. The temperature was measured at 1535°F for that time period. However, in the future, adjusting the emissivity such that the sample temperature matched that of the furnace temperature would lead to more accurate measurements for the forging process.

A second method to improve the temperature measurements would be to establish fixed distances and orientations between the pyrometer and work pieces that have unobstructed lines of sight. Setting up a remote pyrometer closer to the forge die that could see into the recession would improve temperature readings prior to forging, and having a fixed position and orientation for all air holds would improve the measurements during the air hold period.

Table 5. Measured temperature (˚F) of forgings in the die prior to forging.

Furnace	316L	21-6-9
1500	1299 ± 2	1339 ± 11
1600	1447 ± 28	1467 ± 15

Table 6. Measured temperature (˚F) of forgings during 30-second quench delay.

Furnace temperature	316L		21-6-9	
	max	min	max	min
1500	1427 ± 16	1364 ± 0	1454 ± 12	1383 ± 10
1600	N/A	N/A	1491 ± 40	1456 ± 0

4 SUMMARY

1) Video footage was taken of the forging process by Sandia to determine transfer time variation. The times were also recorded in person by the manufacturer using a stopwatch.
2) Temperature measurements of the work pieces were made using an infrared pyrometer at two locations: in the forge die prior to the hit, and prior to quenching for samples that were held in air.
3) For the samples measured by Sandia, the total time from the removal from the furnace until quench was 15.8 ± 0.6 s for samples that were immediately quenched, and 37.6 ± 0.6 s for samples that were held in air for 30 s between the hit and the quench. For the same specimens, as measured by the manufacturer, the times were 16.1 ± 0.5 s and 37.3 ± 0.7 s, respectively. There is reasonable agreement between manufacturer-reported transfer times and those observed in the video, although the manufacturer reported times for only two of the four process divisions desired for subsequent simulation and analysis.
4) The accuracy and precision of the temperature measurements suffered due to a number of variables. The emissivity of the stainless steel was unknown, and the measurement distance and effective cross-sectional area were not consistent from hit to hit. For future pyrometer measurement, an emissivity calibration step prior to the forging process would improve the accuracy of the measured temperature values, while standardization of the working distance and viewing angle are expected to decrease the variance of the measured temperature.

5 REFERENCES

[1] AA Brown, TD Kostka, BR Antoun, ML Chiesa, DJ Bammann, SA Pitts, SB Margolis, DT O'connor, NYC Yang. "Validation Of Thermal-Mechanical Modeling Of Stainless Steel Forgings", Eds. E Onate, DRJ Owen, D Peric, et al., Computational Plasticity XI: Fundamentals and Applications (2011) pp. 1153-64.

APPENDIX I: SNL MEASURED TRANSFER TIMES FOR WEDGE FORGINGS.

Table A I-1. Measured transfer times: 316L – 1500°F.

Hit #	Furnace to Die (s)	Die Prior to Hit (s)	Die Post Hit* (s)	Transfer to Quench (s)	Total Time (s)
1-A	no video	-	-	-	-
1-B	3.3	3.5	7	2.2	16
1-C	2.8	3	7	1.8	14.6
2-A	2.9	3.2	6.9	24.3	37.3
2-B	3.6	3.4	7	24.2	38.2
2-C	3.3	3.3	7.2	23.2	37.0

Table A I-2. Measured transfer times: 316L – 1600˚F.

Hit #	Furnace to Die (s)	Die Prior to Hit (s)	Die Post Hit* (s)	Transfer to Quench (s)	Total Time (s)
3-A	3.3	3.3	6.5	3.1	16.2
3-B	3.1	3.1	6.4	3.1	15.7
3-C	3.2	3.3	6.5	3.3	16.3

Table A I-3. Measured transfer times: 21-6-9 – 1500˚F.

Hit #	Furnace to Die (s)	Die Prior to Hit (s)	Die Post Hit* (s)	Transfer to Quench (s)	Total Time (s)
6-A	2.9	3.4	7.6	2.3	16.2
6-B	2.5	3	7.9	2.3	15.7
6-C	3.1	no video	-	-	-
7-A	3.4	2.9	7.2	23.5	37.0
7-B	3.6	3.2	no video	-	-
7-C	3.2	3.2	6.6	24.2	37.2

Table A I-4. Measured transfer times: 21-6-9 – 1600˚F.

Hit #	Furnace to Die (s)	Die Prior to Hit (s)	Die Post Hit* (s)	Transfer to Quench (s)	Total Time (s)
8-A	2.8	3.3	6.6	2.3	15.0
8-B	3.3	3.7	7.2	2.2	16.4
8-C	3	3.6	7.2	2.3	16.1
9-A	3.6	3.5	8.1	23.1	38.3
9-B	3.8	3.1	7.8	23.4	38.1
9-C	3.6	3.1	7.8	23.4	37.9

* The time that the die remains closed on the sample, 0.9 s, is included in this value.

APPENDIX II: COMPARISON OF SNL AND VENDOR MEASURED TRANSFER TIMES

Table A II-1. Comparison of transfer times: 316L – 1500˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. time (s)	SNL time (s)	manuf. time (s)
1-A	-	7.6	-	9
1-B	6.8	6.8	9.2	9.1
1-C	5.8	7.5	8.8	9.1
2-A	6.1	5.9	31.2	30
2-B	7	7	31.2	30.8
2-C	6.6	6.6	30.4	30.7

Table A II-2. Comparison of transfer times: 316L – 1600˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. time (s)	SNL time (s)	manuf. time (s)
3-A	6.6	7	9.6	9.5
3-B	6.2	6.2	9.5	9.3
3-C	6.5	6.7	9.8	10.1

Table A II-3. Comparison of transfer times: 316L – 1700˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. time (s)	SNL time (s)	manuf. time (s)
4-A	-	6.7	-	10
4-B	-	6.8	-	9.1
4-C	-	7.5	-	9.7
5-A	-	15.8	-	30.6
5-B	-	16	-	30.6
5-C	-	16.4	-	30.4

APPENDIX II: (CONT)

Table A II-4. Comparison of transfer times: 21-6-9 – 1500˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. time (s)	SNL time (s)	manuf. time (s)
6-A	6.3	6.3	9.9	10.2
6-B	5.5	5.4	10.2	10.2
6-C	-	6.3	-	9.3
7-A	6.3	6.2	30.7	30.5
7-B	6.8	6.8	-	30.5
7-C	6.4	6.5	30.8	30.6

Table A II-5. Comparison of transfer times: 21-6-9 – 1600˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. time (s)	SNL time (s)	manuf. time (s)
8-A	6.1	6.1	8.9	9.6
8-B	7	7	9.4	9.6
8-C	6.6	6.2	9.5	9.5
9-A	7.1	7.2	31.2	31
9-B	6.9	6.8	31.2	31.1
9-C	6.7	6.8	31.2	30.6

Table A II-6. Comparison of transfer times: 21-6-9 - 1700˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. time (s)	SNL time (s)	manuf. time (s)
10-A	-	6.1	-	10
10-B	-	6.3	-	8
10-C	-	6.4	-	8.3
11-A	-	5.9	-	30.7
11-B	-	6.6	-	30.8
11-C	-	7.7	-	31.2
12-A	-	16.2	-	8.9
12-B	-	15.5	-	8.4
12-C	-	15.1	-	8.1

APPENDIX II: (CONT)

Table A II-7. Comparison of transfer times: 21-6-9 – 1800˚F.

Hit #	pre-hit		hit + post-hit	
	SNL time (s)	manuf. Time (s)	SNL time (s)	manuf. time (s)
13-A	-	6	-	9.6
13-B	-	6.8	-	10
13-C	-	6.5	-	9.8

APPENDIX II: (CONT)

APPENDIX III: SURFACE TEMPERATURE OF WEDGE FORGINGS DURING PROCESSING

Table A III-1. In situ surface temperature measurements: 316L – 1500˚F. Pyrometer reference measurement: 1504˚F at furnace temperature of 1500˚F.

Hit #	T** (°F)	Hold Max T*** (°F)	Hold Min T (°F)	Filming Position
1-A	1033	N/A	-	low tripod
1-B	1269	N/A	-	high tripod
1-C	1267	N/A	-	standing
2-A	1297	1418	1364	chair
2-B	1301	1418	1364	chair
2-C	1299	1445	1364	chair

Table A III-2. In situ surface temperature measurements: 316L – 1600˚F. Pyrometer reference measurement: 1616˚F at furnace temperature of 1600˚F.

Hit #	T** (°F)	Hold Max T*** (°F)	Hold Min T (°F)	Filming Position
3-A	1418	N/A	-	chair
3-B	1450	N/A	-	chair
3-C	1474	N/A	-	chair

** Parts placed in depression in forge press. T measurement is max temperature recorded while being placed in press prior to hit. Did not have clean line of sight to depression (hidden by lip), so max temperature often while piece was moving/being placed in die.

*** 30 second holds after hit occurred. Measurements were made in last ~20-25 s while part was manually held over the quench bath prior to quench.

For 1500°F heat: During hold measurements, part was not held in a consistent orientation or distance from pyrometer

For 1600°F heat: During hold measurements, part was held so that largest surface area was facing the pyrometer.

APPENDIX III: (CONT)

Table A III-3. In situ surface temperature measurements: 21-6-9 – 1500˚F. Pyrometer reference measurement: 1504˚F at furnace temperature of 1500˚F.

Hit #	T** (°F)	Hold Max T*** (°F)	Hold Min T (°F)	Filming Position
6-A	1335	N/A	-	chair
6-B	1324	N/A	-	chair
6-C	1348	N/A	-	chair
7-A	1330	1467	1382	chair
7-B	1344	1443	1373	chair
7-C	1351	1452	1393	chair

Table A III-4. In situ surface temperature measurements: 21-6-9 – 1600˚F. Pyrometer reference measurement: 1616˚F at furnace temperature of 1600˚F.

Hit #	T** (°F)	Hold Max T*** (°F)	Hold Min T (°F)	Filming Position
8-A	1467	N/A	-	chair
8-B	1447	N/A	-	chair
8-C	1452	N/A	-	chair
9-A	1468	1537	missed	chair
9-B	1483	1470	1456	chair
9-C	1483	1465	1456	chair

Table A III-5. Reference filming locations.

Filming Positions	Height off Ground
low tripod	~4 ft
high tripod	~5 ft
standing	~6 ft
chair	~8 ft

** Parts placed in depression in forge press. T measurement is max temperature recorded while being placed in press prior to hit. Did not have clean line of sight to depression (hidden by lip), so max temperature often while piece was moving/being placed in die.

*** 30 second holds after hit occurred. Measurements were made in last ~20-25 s while part was manually held over the quench bath prior to quench.

For 1500°F heat: During hold measurements, part was not held in a consistent orientation or distance from pyrometer

For 1600°F heat: During hold measurements, part was held so that largest surface area was facing the pyrometer.

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