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Effect of forging strain rate and deformation temperature on the mechanical properties of warm-worked 304L stainless steel

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Stainless steel 304L forgings were produced with four different types of production forging equipment – hydraulic press, mechanical press, screw press, and high-energy rate forging (HERF). Each machine imparted a different nominal strain rate during the deformation. The final forgings were done at the warm working (low hot working) temperatures of 816 °C, 843 °C, and 871 °C. The objectives of the study were to characterize and understand the effect of industrial strain rates (i.e. processing equipment), and deformation temperature on the mechanical properties for the final component. Some of the components were produced with an anneal prior to the final forging while others were deformed without the anneal. The results indicate that lower strain rates produced lower strength and higher ductility components, but the lower strain rate processes were more sensitive to deformation temperature variation and resulted in more within-part property variation. The highest strain rate process, HERF, resulted in slightly lower yield strength due to internal heating. Lower processing temperatures increased strength, decreased ductility but decreased within-part property variation. The anneal prior to the final forging produced a decrease in strength, a small increase in ductility, and a small decrease of within-part property variation.

1. Introduction

During forging processes, dynamic and interconnected variables, such as strain, strain rate, strain distribution, temperature, and cooling rate control how the microstructure evolves. Altan et al. (1973) indicated the importance of deformation temperature by stating that above the recrystallization temperature of a formed metal, strain rate is the significant processing parameter, while below the recrystallization temperature, strain is the processing parameter of primary significance. Hertzberg (1996) defines metal deformation above the recrystallization temperature as hot working. McQueen (1977) revealed that for many metals there is also a transitional region of forming temperatures between hot working and cold working within which both strain, and strain rate as well as deformation temperature interact to affect the resulting microstructure and mechanical properties. This intermediate temperature range is often called the warm working range. The deformation temperatures for 304L stainless steel in the present study are in this range.

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1.1. Effects of temperature and strain rate

There have been previous studies on the deformation of 304L austenitic stainless steel in the warm working range but with a limited number of strain rates. Mataya et al. (1981) showed that for 21-6-9 and 304L deformed at high strain rate of approximately 800 s^{-1}, there is an increase in the warm/hot working transition temperature up to at least 60% of the absolute melting point of the alloy. They used high-energy rate forging (HERF) equipment to produce several complex geometries in temperatures ranging from 760 °C to 955 °C and found deformation temperature and geometry affect the final mechanical properties of the parts. Mataya et al. (1981) also observed large microstructural and hardness variations across parts forged in this temperature range.

Mataya et al. (1990) performed forward extrusion tests on cylindrical 304L specimens by HERF and press forming. In their experiments, HERF and press forming strain rates for the specific geometry were approximately 2000 s^{-1} and 2 s^{-1}, respectively. Contour maps were created for the estimated 0.2% offset yield strength as a function of forging temperatures from 600 °C to 1200 °C and percent reduction up to 80%. These contour plots, however, lacked the necessary detail to estimate yield strength for production forgings at intermediate strain rates and at common production forging temperatures.

Data from Barraclough and Sellars (1979) show that 304L should be deformed at or below about 950 °C to ensure that grain diameter remains within the common engineering limit of about 64 μm. Whereas, Raudebaugh (1990) indicated that 304L stainless steel should be forged above the sensitization range of 480 °C to 815 °C to prevent carbon diffusion to grain boundaries and chromium carbide formation. Adhering to both of these restrictions gives a narrow temperature range, which is in the warm working region for 304L.

1.2. Part-to-part variation

Variation is often the nemesis of forging process development, and two important types of variation are part-to-part variation and within-part variation. The Forging Industry Association (FIA) (2009) indicates that forging processes minimize part-to-part variation in comparison with other manufacturing processes, but FIA does not discuss the different levels of variation for different forging processes. There are many potential causes for part-to-part variation. For example, Altan and Shirgaokar (2005) recognized sources such as forging process type, machine variables, strain rate, die contact time, and work piece temperature. Mataya et al. (1990) showed that strain rate (i.e. HERF versus press forming) has significant influence on final properties of 304L. In the present work, part-to-part variation was examined by varying temperature and forging equipment and by adding in an intermediate anneal.

1.3. Within-part variation

After Mataya et al. (1981) observed gross variations in grain structure and hardness in complex forging geometries of 304L, Mataya and Carr (1984) provided an explanation of these variations due to processing variables and die shapes. They indicated that during deformation, the flow of soft bulk material may be constrained by “die locked”, “die chilled”, or “dead metal” zones. These constraints lead to velocity gradients within the forgings, subsequent strain rate and strain gradients, and ultimately mechanical property variation within the part. Mataya and Carr (1984) also pointed out that strain hardening may improve the uniformity of the mechanical properties, whereas flow softening due to internal heating may exacerbate variation due to inhomogeneous deformation. Mataya and Sackschewsky (1994) studied internal heating in 304L and observed some heating at strain rates of 0.01 s^{-1} and 0.1 s^{-1}, but significant heating at a strain rate of 1 s^{-1}. For a deformation temperature of 850 °C and strain rate of 1 s^{-1}, their data predict an internal temperature increase of about 20 °C at roughly 0.4 true plastic strain. Belyakov et al. (1999) stated that flow softening in 304L may be due to dynamic recrystallization, but Mataya et al. (1990) have proven that dynamic recrystallization will not occur at a strain rate of 1 s^{-1} or greater at deformation temperatures of 1150 °C or less for strain values of 1.0 or less.

In addition to within-part variation due to strain gradients and internal heating, variation may also arise from flow localization. Venugopal et al. (1996, 1997, 2002) have plotted microstructural development maps of 304L and cast 304 with respect to strain rate and temperature. Their results indicate inhomogeneous deformation due to flow localization affects the primary microstructural development at strain rates of about 1 s^{-1} and faster. They also showed that dynamic recrystallization occurs at strain rates of 1 s^{-1} or less and at temperatures above 1000 °C and dynamic strain aging takes place at strain rates of 0.1 s^{-1} and temperatures below 700 °C. Venugopal et al. (2002) suggest avoiding the “flow localization” regime during 304L deformation, but many production environments continue to use these ranges of temperatures and strain rates to arrest grain growth and prevent sensitization and because of the forging equipment within the plant. Complete characterization of localized strain and internal heating is outside of the scope of the present work, however, interaction between local hardness variation and processing equipment is presented and discussed, and internal heating and grain structure is considered as sources of within-part variation.

Table 1
Chemical composition (wt.%).

Fe	Cr	Ni	Mn	Si	Nb	C	N	P	S
67.9	19.48	10.69	1.63	0.52	0.06	0.029	0.03	0.028	0.0064

1.4. Objective of study

The present investigation characterizes the effect of temperature and production strain rates in producing a forged 304L component with a relatively simple geometry under industrial conditions. The temperature variation was over a realistic forging temperature range from 816 °C to 871 °C using four different forging processes with nominal strain rates ranging from about 1 s^{-1} to 100 s^{-1}. The common practice of water quenching immediately after forging was used to prevent slow cooling through the sensitization range as well as prevent static recrystallization. Data from McQueen et al. (1995) indicated that static recrystallization would not occur in 304L as long as it is water quenched within at least 10 s of deformation.

The four forging processes utilized in the present work are common in industry and include hydraulic press, mechanical press, screw press, and high-energy rate forging (HERF). Room temperature tensile tests and hardness surveys were used to evaluate the effects of temperature and strain rate, as well as the effects of multistage processing and annealing, prior to the final forging, on the mechanical properties of forged 304L.

2. Experimental methods

The experimental material was argon oxygen decarburized (AOD) 304L stainless steel, which was vacuum arc remelted (VAR), cast into ingots, and homogenized at 1232 °C. The cast ingots were hot rolled, solution annealed at 954 °C for 4.5 × 10^3 s (1.25 h), water quenched, cold finished, and peeled. Table 1 shows the composition of the two bars that were received as 102 mm rounds, 4 m in length.

Three deformation stages – two extrusions and a final upset forging – produced the final shape on production equipment. After each deformation stage, the 304L material was water quenched within 10 s to prevent static recrystallization as recommended by Barraclough and Sellars (1979) and confirmed by McQueen et al. (1995). Fig. 1 shows the experimental flow chart where the extrusions during deformation stages one and two were identical for all samples. After the second extrusion the processing diverged into two paths. For the first sequence there was no anneal before the final forging, whereas for the second sequence the metal was annealed before final forging. Fig. 2 shows the thermo-mechanical processing for both paths. The dies for all deformations were preheated to 220 ± 100 °C before the extrusion or forging.

2.1. Stage one: first hydraulic extrusion

In preparation for the initial extrusion, the bars were sawed into the appropriate length and turned down from 102 mm to 95 mm. This turning operation was used to produce the proper billet diameter so that it would fit into the die and would have sufficient

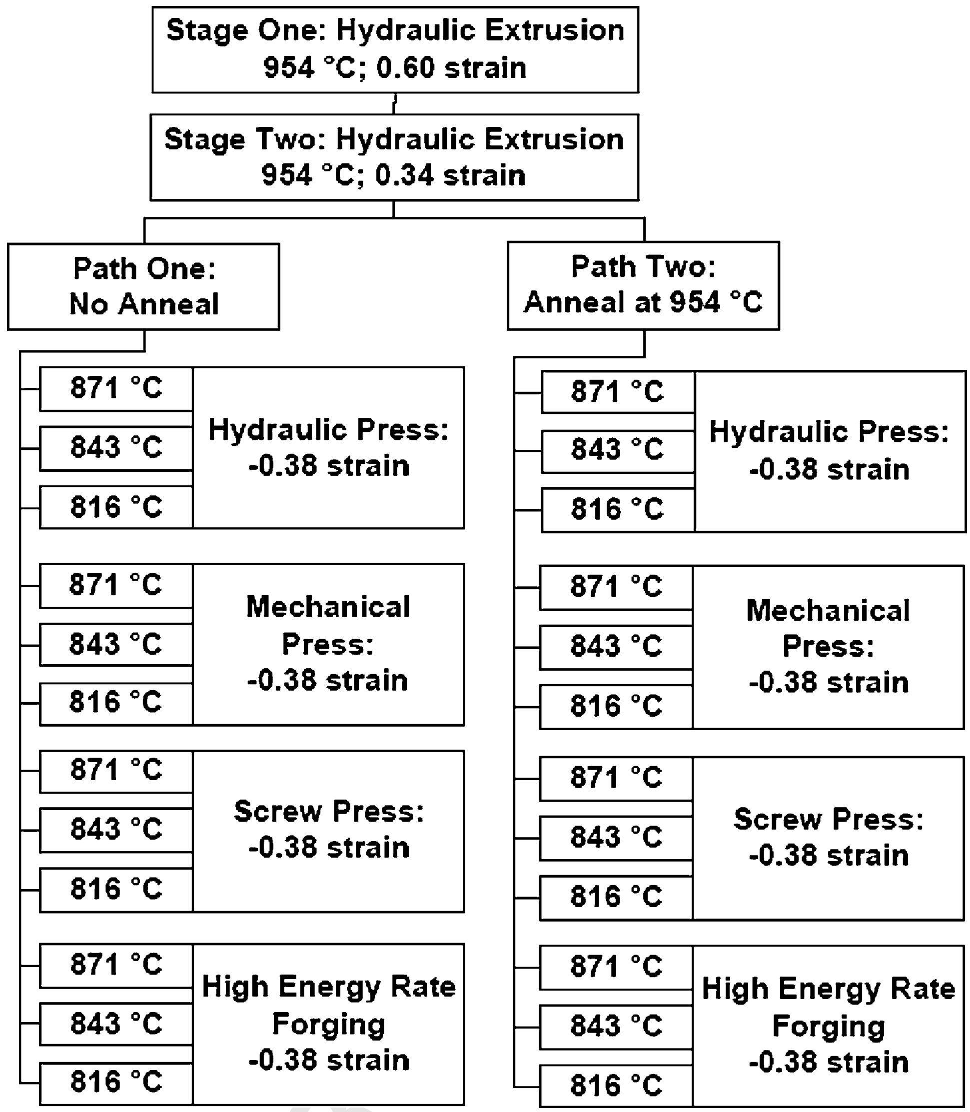

Fig. 1. Flowchart matrix for 304L stainless steel processing experiments.

volume so that complete fill of the final die cavity would occur. Fig. 3a shows the sawn billet. The billets were lubricated, heated to 954 °C in an electric rotary furnace, and held for about 10^4 s (2.5 h). They were manually transferred and extruded on a hydraulic press to a true strain of 0.60. A Clearing H-800-48 hydraulic press was used for both extrusion steps. The extrusion created a 70 mm diameter part with a 102 mm diameter lip on the end in contact with the punch. After the lip was machined off, steel grit blasting was used to clean the lubricant residue, and the volume was fine-tuned by machining to length in preparation for the second extrusion. Fig. 3b shows the product produced after the first extrusion.

2.2. Stage two: second hydraulic extrusion

The material from the first extrusion was machined then soaked at 954 °C for 8×10^3 s (2 h). The second extrusion was again with the hydraulic press producing 59 mm diameter product. The parts were steel grit blasted and machined to the precise volume in preparation for the final forging. At this point, one-half of the extruded specimens were annealed for 7×10^3 s (2 h) at 954 °C prior to final forging. Fig. 3c shows the resultant product from the second extrusion.

2.3. Stage three (final stage): forging by four processes

For the final forging step the specimens were presoaked in either an electric rotary furnace (for hydraulic press, mechanical press, or screw press) or a gas-fired box furnace (for HERF) at one of three different temperatures, 816 °C, 843 °C, and 871 °C, for 10^4 s (2.5 h), and upset to a true strain of 0.38 in a closed die using one of four forging processes – hydraulic press, mechanical press, screw press, or HERF. These steps in conjunction with the anneal/no anneal prior to final forging resulted in twenty-four unique processing paths for the experimental matrix. The purpose of annealing was to ensure complete recrystallization and uniform grain structure within the pieces before final forging. Three replicate specimens were produced via each of these twenty-four paths. The final shape was a 71 mm diameter "puck". Fig. 3d shows the product after the final forging.

The same Clearing press that was used for the initial two extrusions was also used for hydraulic press final forging. The mechanical press for the final forging step was a Version No. 1500-SI-48T. The screw press was a Weingarten PSS 530 with direct electric drive. High-energy rate forging (HERF) was performed with a Dynapak 1220. The HERF machine used high-pressure nitrogen gas to drive the upper die downward to deform the work piece.

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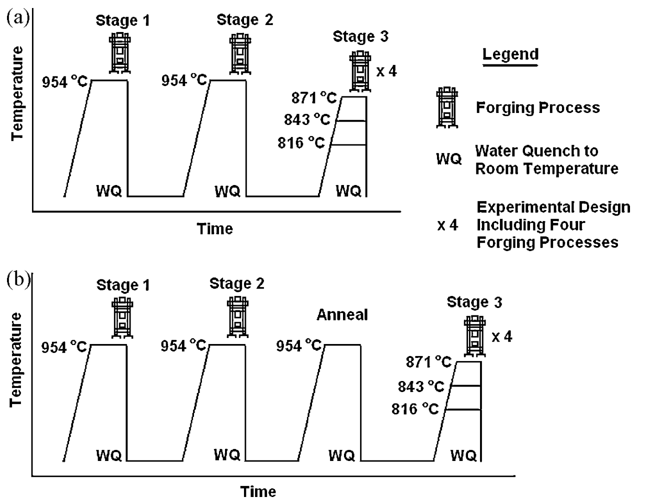

Fig. 2. Thermo-mechanical processing history diagram for the two processing sequences for 304L stainless steel forgings. (a) Path one processing sequence and (b) path two processing sequence. For both paths, two extrusions in stage one and stage two were completed using a hydraulic press. An annealing stage was added in path two. The forging (stage three) utilized the four types of forging equipment (hydraulic press, mechanical press, screw press, and HERF) at three temperatures.

2.4. The strain rate of each forging process

Table 2 presents a calculation of the nominal strain rate used to final forge the material on the four types of equipment. The data for these calculations comes from both the literature and experimental measurements. For the four processes listed in Table 2, the strain rate range covers two orders of magnitude. Although the mechanical press and screw press show similar strain rates, the mechanical press slows to a strain rate of zero at the end of its stroke; whereas, the screw press maintains a high strain rate throughout most of its stroke. Since the strain rates were similar between the mechanical press and screw press used in the present work, differences in the results for these two processes were interpreted by considering the relative strain rate near the end of the stroke.

Table 2
Nominal strain rates for each of the four forging processes.

Final forging process	Approximate forging die contact velocity (mm/s)	Deformation time[a] (s)	Engineering strain rate[b] (s^{-1})
Hydraulic press[c]	60	0.4	1
Mechanical press, estimated[c]	300	0.08	5
Weingarten screw press, calculated using operational information	500	0.05	8
Weingarten screw press	575	0.04	10
Dynapak HERF	5600	0.005	80
Dynapak HERF, calculated[d]	6500–7500	0.003–0.004	100–125

[a] Assumptions included in these calculations include: (1) the velocity measurements of various processes have not changed notably since they were measured prior to the present work, and (2) the velocity is constant from contact to completion of the forging stroke.
[b] Calculations are based on a 60 mm diameter work piece upset forged to 72 mm diameter, resulting in a true strain of −0.38.
[c] Data from Altan et al. (1973).
[d] Calculated using data from Marlow et al. (1988).

2.5. Mechanical testing

After the final forging step room temperature tensile tests hardness tests, and hardness maps were performed to compare the effects of processing on the strength, ductility, and within-part variation of 304L stainless steel. Fig. 4 shows the positions from which samples were extracted from the final forged component for tensile testing, hardness measurements, and hardness mapping. Tensile testing was done with a 5.1 mm extensometer. Rockwell B hardness measurements were made along a diametrical cross-section of the final forging on the intersections of a 10 mm spaced grid pattern.

3. Results and discussion

3.1. Effect of multistage processing on mechanical properties

Fig. 5 shows the room temperature yield strength versus the percent elongation for the three processing stages. This plot indicates that forging can be used to increase the strength of 304L while maintaining good ductility. The yield strength increases from

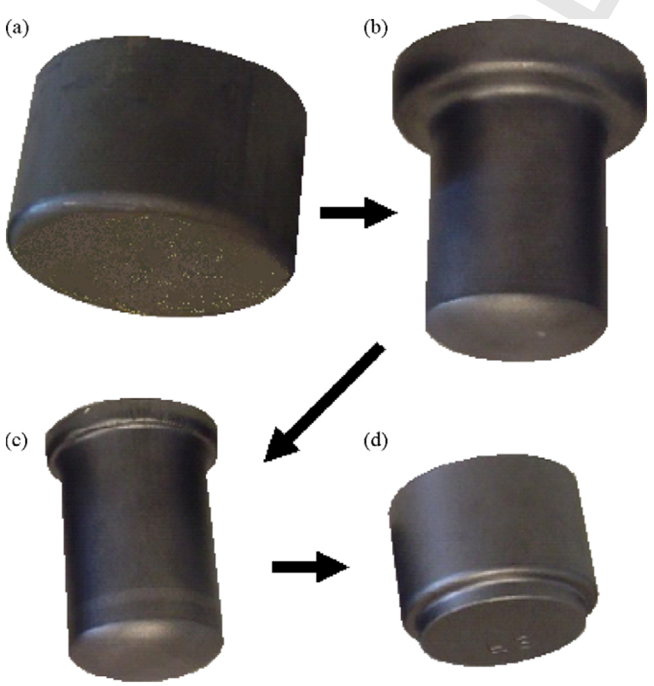

Fig. 3. Product of each step for 304L stainless steel: (a) billet prepared for first extrusion, (b) after first extrusion, (c) after second extrusion, and (d) after final forging.

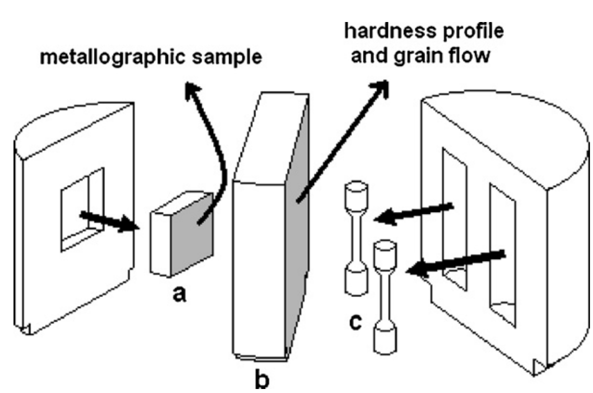

Fig. 4. Exploded view of final forging shape, showing the locations of each test sample: (a) metallographic imaging sample, (b) hardness mapping sample, and (c) tensile test samples.

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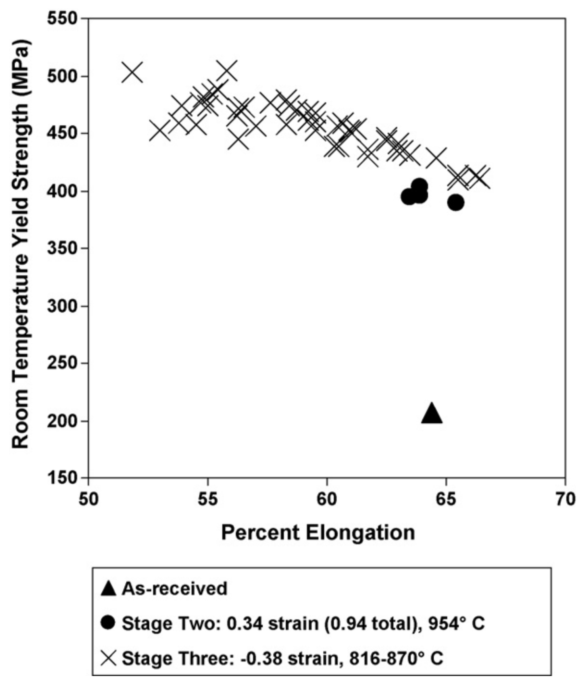

Fig. 5. Yield strength and percent elongation data from tensile tests showing the effects of warm working on 304L stainless steel.

208 MPa for as-received material to 400 MPa after the two extrusions, which occurred at 954 °C. This strength increase is due to microstructural developments during processing, including grain refinement as shown by Mataya et al. (1990), who refined grains to 29 µm by forging at 900 °C. The average grain size for the as-received material in the present work was 64 µm and the average grain size for the material after the second extrusion was about 27 µm. Similarly, Mataya et al. (1994) refined 250 µm grain diameter as-received 304L to a final grain diameter of 27 µm after a four-pass deformation to a total strain of 0.56 at 950 °C.

The final upset forging increased the strength further from 400 MPa to a range between 425 MPa and 500 MPa, although no grain size difference was detected (the grain size was approximately 29 µm in diameter after forging). Differences in strength and ductility for the material after the second extrusion as compared to the final forging cannot be attributed to grain size, and the strength increase is likely due to the dislocation density, the extent of recovery, and the strain accumulation. Similar strength increases, not related to grain refinement, have been shown by Belyakov et al. (1999). Venugopal et al. (2002) also show strength increases in 304L due to strain localization.

3.2. Effect of anneal prior to final forging on mechanical properties

Table 3 presents data that demonstrate the effect of annealing at 954 °C prior to the final forging on the mechanical properties of 304L stainless steel. Components with no annealing prior to forging had a slightly higher room temperature yield strength, tensile strength, and hardness, but exhibited a slightly lower elongation and reduction in area. Elongation and reduction in area were higher for most of the samples that had been annealed prior to the forging. The softening effect from the annealing step is due to recrystallization. In 304L deformed to a strain of 0.25, Barraclough and Sellars (1979) showed complete recrystallization and a decrease in hardness from 190 HV to 140 HV after annealing for at least 10^3 s at 950 °C. In the present study, the strain free material (i.e. annealed material) subsequently resulted in slightly lower yield strength after the final forging.

3.3. Effect of strain rate (i.e. processing equipment) and deformation temperature on mechanical properties

Table 4 gives the room temperature mechanical property data for material without an anneal prior to the final forging for all four processes at all deformation temperatures. Table 5 gives the room temperature mechanical property data for material, which had been annealed prior to the final forging. The screw press pro-

Table 3
Q1 Effect of anneal prior to final forging on the mechanical properties of final forged 304L stainless steel.[a]

	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction in area (%)	Average hardness (HRB)[b]
No prior anneal	409–505	613–659	52–66	82–90	93.5–98.2
Prior anneal	401–488	603–646	53–68	83–90	93.2–95.3
Design spec.	379–517	586 min	35 min	40 min	n/a

[a] Data based on tests from forgings produced using varying processing equipment at varying deformation temperatures.
[b] Average of all of the hardness values taken from center cross-section of forging.

Table 4
Effect of forging equipment on the mechanical properties of 304L stainless steel (without prior anneal).[a]

	Deformation temperature (°C)	Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)	Reduction in area (%)	Hardness (HRB)[b]
Hydraulic press	816	458 ± 10	641 ± 8	59 ± 4	85 ± 1	98 ± 4
	843	433 ± 7	625 ± 4	63 ± 2	88 ± 3	
	871	412 ± 4	617 ± 7	66 ± 1	88 ± 1	94 ± 7
Mechanical press	816	476 ± 5	649 ± 5	57 ± 3	84 ± 2	96 ± 5
	843	457 ± 7	639 ± 7	59 ± 4	86 ± 1	
	871	436 ± 8	628 ± 9	61 ± 3	88 ± 1	95 ± 5
Screw press	816	495 ± 20	656 ± 7	55 ± 4	85 ± 4	97 ± 5
	843	475 ± 9	634 ± 11	58 ± 5	85 ± 2	
	871	461 ± 20	631 ± 12	60 ± 2	87 ± 3	94 ± 5
HERF	816	470 ± 15	651 ± 3	55 ± 2	84 ± 1	95 ± 4
	843	459 ± 13	643 ± 5	57 ± 7	85 ± 2	
	871	444 ± 4	637 ± 8	61 ± 6	87 ± 1	94 ± 5

[a] Average and uncertainty for a 95% confidence interval are shown.
[b] Hardness values taken from center cross-section of forgings.

Table 5
Effect of forging equipment on the mechanical properties of 304L stainless steel (with prior anneal).[a]

	Deformation temperature (°C)	Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)	Reduction in area (%)	Hardness (HRB)[b]
Hydraulic press	816	448 ± 3	624 ± 5	60 ± 2	87 ± 1	94 ± 5
	843	423 ± 5	615 ± 2	63 ± 3	88 ± 1	
	871	403 ± 3	605 ± 3	67 ± 3	88 ± 3	93 ± 6
Mechanical press	816	461 ± 8	632 ± 3	60 ± 2	85 ± 3	95 ± 4
	843	444 ± 3	626 ± 4	62 ± 5	86 ± 1	
	871	427 ± 4	621 ± 5	64 ± 3	88 ± 1	94 ± 4
Screw press	816	483 ± 9	642 ± 5	57 ± 5	85 ± 2	95 ± 4
	843	466 ± 14	631 ± 4	59 ± 3	85 ± 3	
	871	453 ± 10	627 ± 5	60 ± 4	87 ± 2	94 ± 3
HERF	816	458 ± 9	639 ± 5	56 ± 6	85 ± 1	94 ± 5
	843	449 ± 11	632 ± 5	58 ± 1	87 ± 5	
	871	433 ± 6	629 ± 5	59 ± 5	88 ± 4	93 ± 4

[a] Average and uncertainty for a 95% confidence interval are shown.
[b] Hardness values taken from center cross-section of forgings.

duced forgings with the highest yield strength, followed by HERF, the mechanical press, and the hydraulic press. The same trend is seen for tensile strength. Although the strain rates of the mechanical press and screw press are similar, the higher strength for the screw press components is thought to be due to the high strain rate being maintained throughout the deformation cycle.

Figs. 6 and 7 compare the resultant room temperature properties from the forgings in terms of yield strength and elongation. Fig. 6 is for material without a prior anneal and Fig. 7 is for material with an anneal prior to the final forging. Figs. 6 and 7 show that as ductility increases, strength decreases, as would be expected. The lower deformation temperature data points are located in the upper left of each group, and data points translate downward and to the right as deformation temperature increases. Figs. 6 and 7 have two important implications. First, the screw press produces the highest yield strength forgings for any given deformation temperature. Second, the data from the hydraulic press, the mechanical press, and the screw press form a nearly straight line, with the data for the forging made by HERF fall below this line. One would expect HERF components to exhibit higher yield strength than screw press due to the higher strain rate. However, the forgings produced by HERF showed lower yield strength with approximately the same ductility as forgings from the screw press. The lower yield strength of forgings from HERF versus the screw press is due to the internal heating, which has been identified and quantified by Mataya and Sackschewsky (1994). They calculated that internal heating at a true strain of 0.4 increases the temperature in the work piece about 5 °C when deformed at a strain rate of 0.01 s^{-1} and about 22 °C at strain rates of 1 s^{-1}. For the even higher strain rates of 10 s^{-1} (screw press) and 100 s^{-1} (HERF) the internal heating could be somewhat greater. The high-speed deformation and subsequent internal heating in HERF would increase the amount of recovery and cause the observed decrease in strength.

Figs. 8 and 9 show the tensile strength versus elongation for 304L without an anneal prior to final forging (Fig. 8) and with an anneal (Fig. 9). Again, HERF, although the highest strain rate process, results in the second highest tensile strength due to internal heating and recovery. Unlike Figs. 6 and 7, the HERF data in Figs. 8 and 9 do not fall below the trend line of the data from the other three presses. This means that for HERF processed 304L, the yield strength is slightly lower than for other processes, yet the tensile strength is consistent with the other processes.

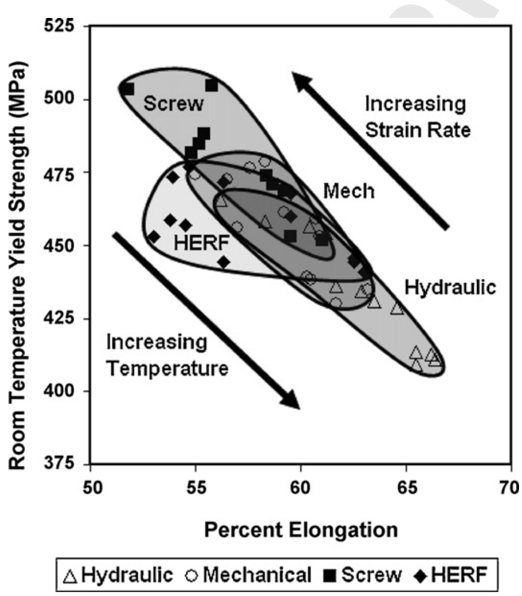

Fig. 6. Yield strength and total plastic elongation data from tensile tests showing the effects of forging equipment on 304L stainless steel without a prior anneal. In general, the higher strain rate processes result in higher strength and lower ductility.

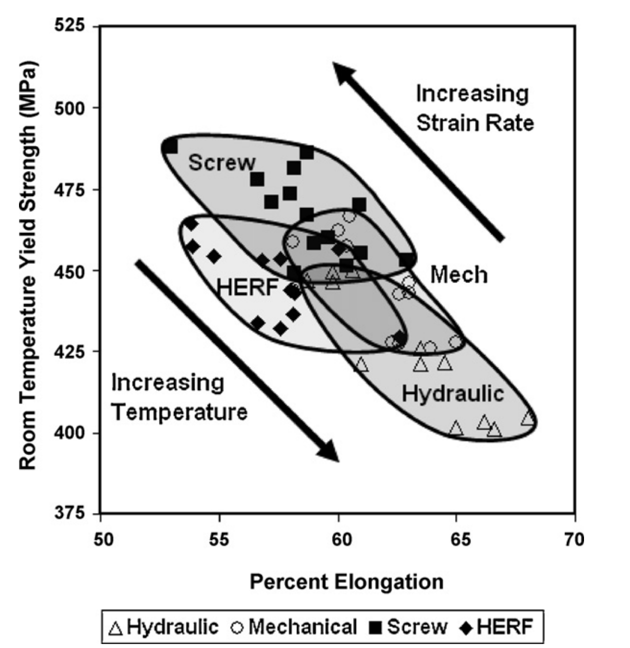

Fig. 7. Yield strength and total plastic elongation data from tensile tests showing the effects of forging equipment on 304L stainless steel with a prior anneal.

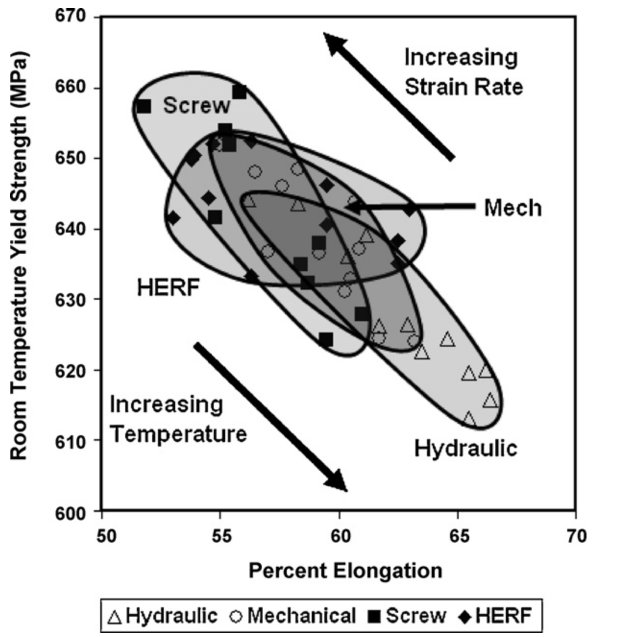

Fig. 8. Room temperature tensile strength and total plastic elongation data from tensile tests showing the effects forging equipment on 304L stainless steel without a prior anneal.

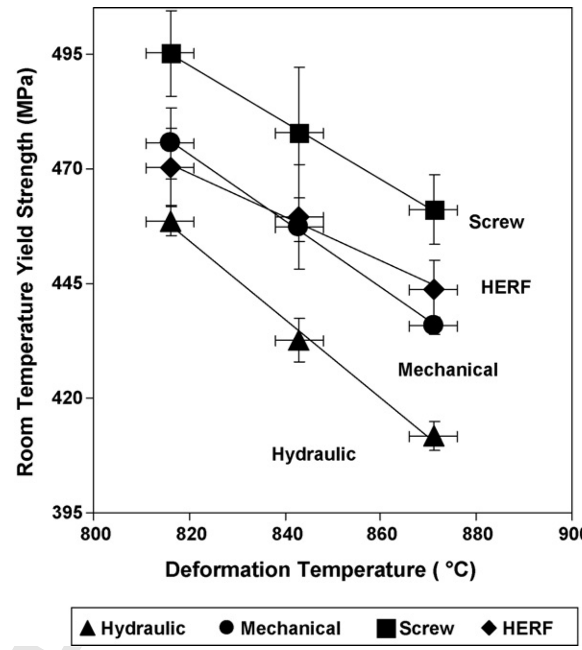

Fig. 10. Room temperature yield strength versus deformation temperature for forging 304L stainless steel without an anneal prior to final deformation. As deformation temperature increases, room temperature yield strength decreases.

Figs. 10 and 11 show the dependence of room temperature yield strength upon deformation temperature for material without and with an anneal prior to final forging. As deformation temperature increases, the room temperature yield strength decreases; but the effect is not equal for all processes.

Fig. 12 shows a plot of the temperature sensitivity of yield strength (i.e. the slope of the yield strength versus deformation temperature) with respect to strain rate. Fig. 12 indicates that the sensitivity of room temperature yield strength to deformation temperature decreases with increasing strain rate. In other words, the room temperature yield strength produced by higher strain rate processes, such as screw press forging and HERF, is relatively insensitive to deformation temperature variation. Mataya et al. (1990) found that the yield strength of 304L processed by HERF at 800 °C was insensitive to strain within the range 0.2–0.5, however, deformation at 900 °C caused the yield strength to drop significantly when the amount of strain increase from 0.2 to 0.5. They also showed that for press forming (strain rate of 2 s^{-1}) yield strength increased with increasing deformation at both temperatures. Combining the present work with that of Mataya et al. (1990), 304L material processing is most robust with respect to yield strength when performed by HERF or screw press at about 800–850 °C in

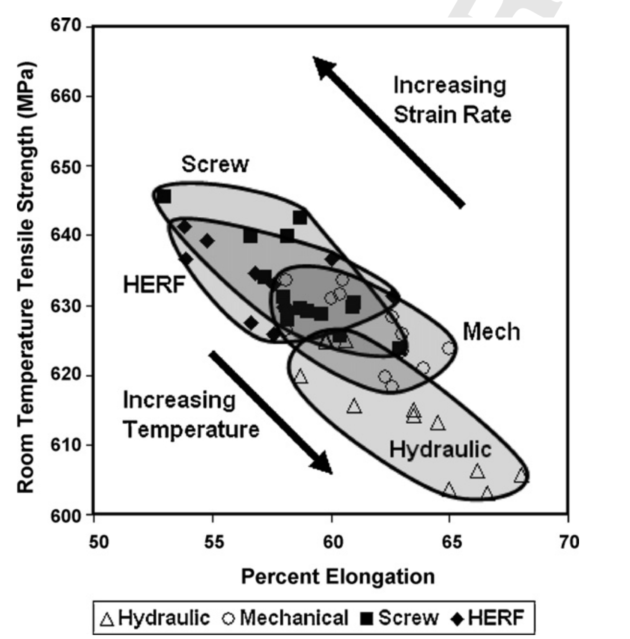

Fig. 9. Room temperature tensile strength and total plastic elongation data from tensile tests showing the effects forging equipment on 304L stainless steel with a prior anneal.

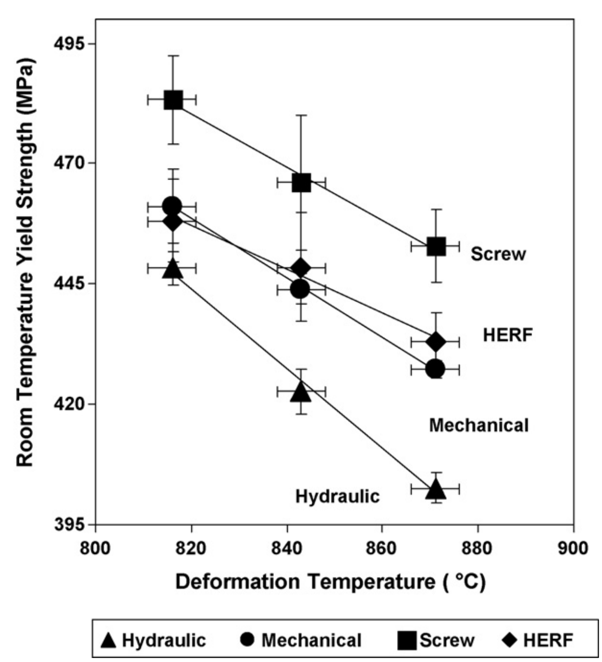

Fig. 11. Room temperature yield strength versus deformation temperature for forging 304L stainless steel with an anneal prior to final deformation.

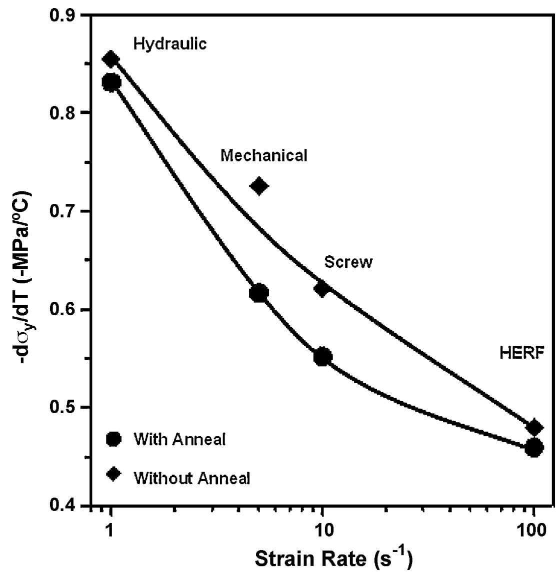

Fig. 12. The sensitivity of 304L yield strength to deformation temperature showing that as strain rate increases, the room temperature yield strength becomes less sensitive to deformation temperature.

the strain range of 0.2–0.5. However, as deformation temperature increases to about 900 °C or higher, the lower strain rate processes become more robust and less susceptible to variation due to the amount of strain imparted.

3.4. Hardness mapping and within-part hardness variation

As indicated by Mataya and Carr (1984), the flow strength of 304L varies with respect to temperature and microstructure, which leads to complex material flow and gradients in the resulting microstructure and mechanical properties of the forged shape. For the present study, Fig. 13 shows the hardness map for a half section after the second extrusion. The contour lines are iso-hardness values. The orientation of the hardness map is shown using the schematic of extrusion shape. The zones are labeled: dead zone, circumferential zone, and upper die zone. As expected the dead zone has the lowest hardness due to lack of deformation, and higher hardness is observed in the circumferential and upper die zones due to localized flow and rapid cooling. The anneal prior to final forging has little effect on the dead zone. Dead zone hardness measurements were excluded from the reported results and averages. There is a great deal of hardness variation after the second extrusion. This large variation is caused by the work piece at

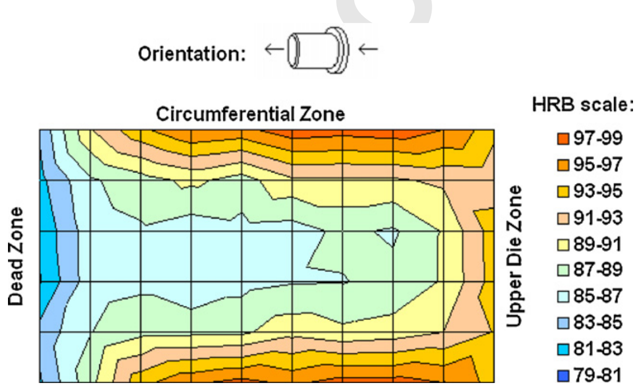

Fig. 13. Hardness (HRB) map for warm-worked 304L stainless steel after the second extrusion on a hydraulic press at 954 °C (1750 °F). The spacing between grid lines is 10 mm.

Table 6
Average hardness and within-part hardness variation.[a]

	Average hardness (HRB)	Variation (HRB)
After second extrusion (hydraulic)	91.3	8.2
After final forging (all processes)	95.6	4.2
After final forging: no prior anneal (all processes)	96.2	3.1
After final forging: prior anneal (all processes)	95.0	2.8
Final forging at 816 °C (all processes)	96.5	2.5
Final forging at 871 °C (all processes)	94.6	3.5

[a] Variation for a 95% confidence interval calculated as two times the standard deviation of all hardness measurements on part excluding the dead zone.

954 °C being placed on the cooler extrusion die causing the surface of the billet to cool, while the center remains at the higher temperature.

Table 6 shows the average hardness, as well as the 95% confidence interval after the second extrusion and after the final forging. For the extruded material the circumferential zone of the part is in contact with the lower die throughout the extrusion process. Similarly for the final forging within-part hardness variation occurs due to localized flow and rapid cooling of the outer circumference. The final forging step is an upset process, which has less contact time between the die and the work piece, resulting in lower within-part hardness variation than after the second extrusion. The components after the final forging had a higher average hardness than after the second extrusion due to the lower deformation temperatures used in the final forging. The factors that caused a decrease in hardness of the final forging are the prior anneal and high deformation temperature. For components with the annealing step prior to forging, softening takes place during the anneal, which also decreases the variation of properties across the component. The effect of the annealing step prior to the final forging is roughly a 10% decrease of the within-part hardness variation. An increase in deformation temperature caused a decrease in hardness but an increase in hardness variation across the forged part.

Mataya et al. (1990) measured hardness as a function of radial position in HERF and press formed 304L processed at temperatures ranging from 600 °C to 1200 °C. They found that as temperature increased, hardness variation increased, with less variation observed after HERF than after press forming. For the present study Table 7 shows the average hardness and 95% confidence interval for parts after final forging using the different processing equipment and different temperatures. The processing equipment appears to have had no definitive effect on average hardness, but the processing equipment does have an effect on the within-part hardness variation. Fig. 14 shows a plot of variation for the 95% confidence interval versus the strain rate of the processing equipment. Fig. 14 illustrates that within-part hardness variation decreases as strain rate increases, which is consistent with the results from Mataya et al. (1990). The within-part hardness variation in the present study was not due to recrystallization. The strain in the final stage forging process was ~0.38, which is too low for significant recrystallization. Furthermore, metallographic samples were examined to confirm that recrystallization did not occur. The higher within-part variation in the lower strain rate processes is likely due to the longer time for heat loss to the air and die prior to and during the deformation.

Table 7
Effect of forging equipment on average hardness and within-part hardness variation.[a]

	No prior anneal				Prior anneal			
	816 °C[b]		871 °C[b]		816 °C[b]		871 °C[b]	
	Average hardness (HRB)	Variation	Average hardness (HRB)	Variation	Average hardness (HRB)	Variation	Average hardness (HRB)	Variation
Hydraulic press	98.9	2.9	94.4	6.1	95.2	4.0	93.7	5.9
Mechanical press	97.0	2.8	95.3	3.5	96.2	2.1	94.5	3.2
Screw press	98.1	1.8	94.9	2.9	95.5	2.3	95.2	1.9
HERF	96.2	2.0	94.6	2.7	95.0	1.7	94.2	1.6

[a] Variation for a 95% confidence interval calculated as two times the standard deviation of all hardness measurements on part excluding the dead zone.
[b] Deformation temperature.

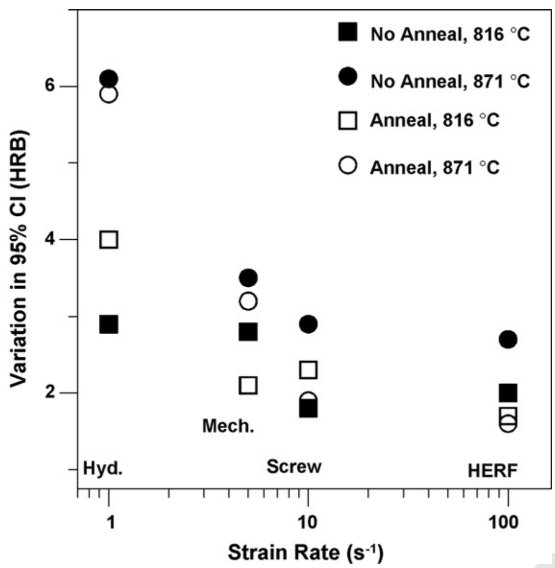

Fig. 14. Within-part hardness variation (95% confidence interval) as a function of deformation strain rate for warm-worked 304L forging. Data from the dead zone are excluded.

4. Summary

The primary objective of this study was to evaluate the effects of multistage processing, annealing prior to the final forging, strain rate during forging using different production equipment, and deformation temperature on the mechanical properties of 304L stainless steel.

- Multistage processing of 304L stainless steel results in an increase in room temperature yield strength with little loss of ductility.
- 304L that was annealed prior to the final forging exhibited slightly lower strength and slightly higher ductility as compared to material that was not annealed prior to the final forging, due to the softening prior to the forging deformation. Annealing prior to final forging results in lower hardness and slightly lower within-part hardness variation. Lower hardness and less hardness variation is due to the recrystallization, which takes place during annealing.
- Less strengthening occurs in lower strain rate processes due to longer deformation times. Although high-energy rate forging (HERF) is a higher strain rate process than screw press forging, the resulting yield strength after HERF is lower possibly due to internal heating. An increase in strain rate reduces the within-part hardness variation. Additionally, the yield strength of material forged with higher strain rate equipment is less sensitive to temperature variations.
- Processing at higher deformation temperatures results in material with lower yield strength. An increase in deformation temperature causes a decrease in average hardness but an increase in within-part hardness variation.

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