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STAINLESS STEEL EXTRUSIONS AND PRODUCT PROPERTIES FOR HIGH PRESSURE - HIGH TEMPERATURE (HPHT) APPLICATIONS

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ABSTRACT

Extrusion process produces semi-finished product that provides significant savings in machining and fabrication of the finished components. Plymouth Engineered Shapes (PES) employs forward extrusion techniques to produce products up to 40 feet long that are utilized in power generation, nuclear, and petrochemical applications where it is critical to meet or exceed ASME piping, boiler and pressure vessels code specifications. The extrusion process has been successfully employed to manufacture components such as various types of valve bodies, manifolds, adapters and more that are targeted for elevated temperature applications up to 1200°F and under high pressures up to 10,000 PSIG. Critical product characteristics include flatness, straightness, twist, angularity, surface quality and dimensions over the full length. This paper presents an overview of the carbon steel and stainless steel extrusion process, the room temperature and elevated temperature mechanical properties, metallographic characterization, testing requirements and the applications of such products. Properties are also be compared to those produced by the conventional hot rolling and forging operations.

INTRODUCTION

Extrusion is a metal forming process in which the work piece, typically a round billet of certain length and cross section is forced to flow through a die of a smaller cross sectional area, thus forming the product of a desired shape. Figure 1 depicts the direct or forward extrusion process at PES, where the die and the ram are in the opposite ends and the billet travels in the same direction as the ram. The extrusion process is capable of creating a tremendous amount of deformation in the material. Several factors such as the type of material, size of the original billet, cross sectional area of the extruded product, billet temperature and strain rate during extrusion, must be taken into consideration for effective design and analysis of the extrusion operation. Many of the extruded sections typically require a straightening operation after the completion of the extrusion process.

Figure 1. Forward extrusion process at PES, where the ram 'pushes' the hot metal through the die.

The size of the cross section of the work billet may be much larger than the size of the cross section of the extruded part. To relate the cross section of the work piece to that of the extruded product, a value commonly termed as "extrusion ratio" was established. It is the ratio of the area of the original billet cross section (A_o) to that of the extruded product (A_f). The extrusion ratio, or reduction ratio, can be expressed as (A_o/A_f). Depending on the geometry of the part, different products will be extruded in wide range of extrusion ratios. Stainless steel extrusions provide high strength, outstanding durability and excellent versatility. One of the major advantages of the extruded products includes the amount of savings realized in terms of machining time and cost required to produce the final product from a shape that is much closer to the actual profile of the part compared to hot rolled or a forged bar/plate. An example of various extruded shapes is shown in Figure 2.

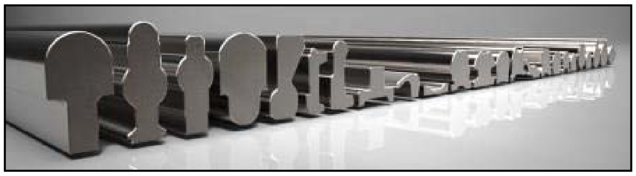

Figure 2. Wide possibility of shapes extruded using stainless steel billets.

MATERIALS AND PROCESSING

Different grades of stainless steel products can be produced by the extrusion process for various applications that include elevator sills & door tracks, marine parts & products, decorative & functional architectural components, surgical instruments, firearms, pump & valve fittings and many more. However, the focus for this paper is limited particularly to the products extruded using stainless steel grade 316/316L and related characteristics. Two different billet diameters (6” and 7”) of stainless steel 316/316L were employed to produce the extrusions to be utilized as valve bodies for high pressure-high temperature applications. Nominal chemical composition of these billets is shown in Table 1.

Table 1. Chemical composition of the raw material used for extrusions, wt%

Dia, in	C	Si	Mn	Cr	Mo	Ni	S
6.0”	0.013	0.61	1.8	16.7	2.06	10.3	0.02
7.0”	0.016	0.38	1.9	16.7	2.02	10.4	0.02

Billets are extruded using a carefully designed process to provide the best surface quality on the product. The dies used for the extrusion process are manufactured in-house using modified tool steel. An extrusion die with the profile of the shape to be extruded is shown in Figure 3. Stainless steel billets are loaded into the vertical induction furnaces where they are subjected to heat treatment to a set “recipe” (temperature/time), which is a proprietary value. Infra-red pyrometers are utilized to monitor the billet temperature while in the furnace and before the actual extrusion to ensure uniformity in temperature through the length of the billet.

The extrusion temperature and pressure are selected based on the alloy type, chemistry and the extrusion ratio. A typical extrusion is ~30-40ft depending on the initial dimensions of the billet. The extruded products are then subjected to straightening operations to achieve the required key characteristics such as flatness across the width of the part, straightness (bow/camber) and twist (or angularity) along the full length of the extrusion. The full length extrusions are eventually cut into the smaller sections, machined and installed depending on the temperature-pressure requirements of the final application. Examples of different sections extruded specifically for valve body applications are shown in Figure 4.

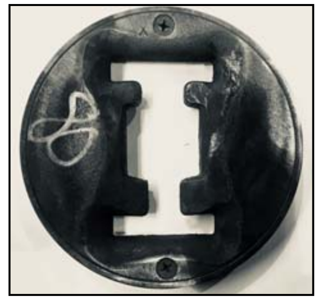

Figure 3. Modified tool steel die, manufactured in-house, used for stainless steel extrusion process.

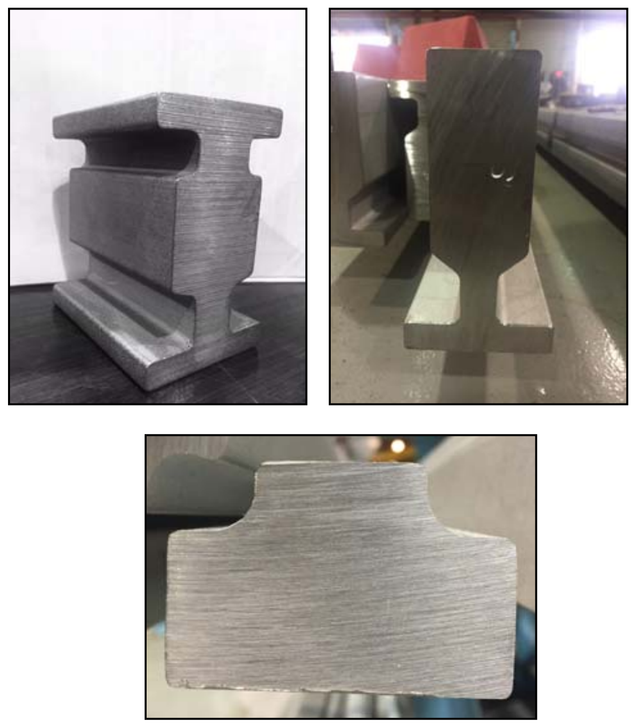

Figure 4. Extruded and straightened sections of SS316 used for valve bodies utilized for a variety of industrial applications.

The basic 300 series stainless materials like 304/L and 316/L have an austenitic microstructure and are non-magnetic. In the annealed condition, these stainless steels are essentially free of ferrite, which is a magnetic phase. Cast products of these alloys typically have some presence of ferrite. These alloys also form some ferrite when they are cold worked or work hardened. In both cases stainless steel products will show a magnetic tendency. It is well known that ferrite can be detrimental to corrosion resistance in some environments. In order to avoid ferrite formation and maintain homogeneous austenitic microstructure in the extruded products, the entire extrusion process is completed above the solvus temperature of austenite phase. Thus, the extruded parts do not show any magnetic tendency and the products are tested for intergranular corrosion as per ASTM A262 Method E to ensure that the corrosion resistance of the products has not been compromised due to ferrite formation or carbide precipitation during the extrusion process.

Extruded product is visually inspected throughout the manufacturing process for any surface defects. Post straightening operation, the parts are subjected to dye-pen and ultrasonic inspections to ensure acceptable overall condition.

APPLICATIONS AND KEY CHARACTERISTICS

As mentioned in the previous section, SS316/316L extruded products are used in various industrial applications. The SS316 parts presented in this paper are particularly used for critical applications that comply with the ASME boiler and pressure vessel code requirements. Examples of such applications include boilers, pressure vessels and piping for power generation, oil & gas, petrochemical applications and nuclear components such as valve bodies, manifolds, adapters and more. Figure 5 shows a machined valve body from an extruded product (left) and a fully functional manifold (right)[1]. These manifolds are rated and utilized for applications that require service temperatures and pressures up to 1200°F and 10,000 PSIG respectively. Significant savings in terms of machining costs and time is realized when utilizing the extruded sections rather than a bar or a plate, due to the profile of the extruded part being very near to the final finished part. Machining these parts from a bar or a plate would result in generating excessive scrap, increase in machining time and related tooling costs. The total savings achieved in terms of material, processing and machining time, are better illustrated in the following example –

To produce a valve body, consider two different forms of input stock such as an extruded part and bar stock as shown in Figure 6. The initial weight of the bar stock, assuming the size as indicated in the figure is approximately 36.4 lbs/ft. On the other hand, the weight of an extruded part is about 22.6 lbs/ft that is used to produce the valve body, ~21.0lbs/ft. As noticed, extrusion process produces a near-to-net shape product with minimal machining scrap which approximates to ~40% in material savings. Also, assuming the standard feed rates (12-24 ipm) and depth of cut (0.5d), it would require about 15~20 min of machining to produce ~1ft long valve body from the bar stock. Needless to say that feature based machining from an extrusion will result in enormous savings in material consumption, machining time and tool life compared to that of a bar stock.

The standard characteristics of PES extrusions include a bow/camber of 0.025" per ft., with a 3° max twist and a flatness of 0.010" per the width, along the full length of the extrusion. The extreme tight control on the dimensions and key characteristics provides a significant advantage to the end user as the extrusion is fed through the bar feeder and automatically cut into smaller sections at the required length.

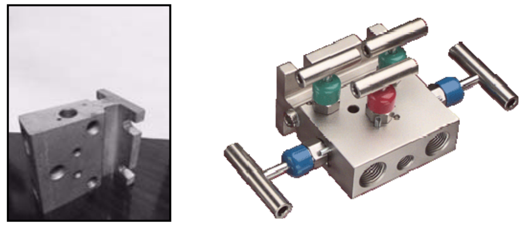

Figure 5. Machined valve body (left) and a fully functional service manifold from SS316 (right).

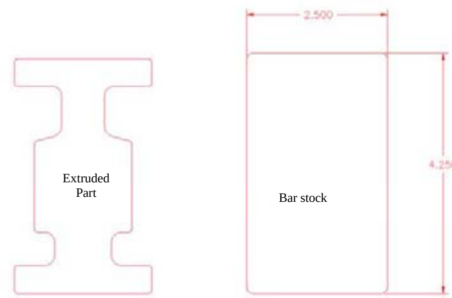

Figure 6. Illustration of an extruded part and a bar stock used to machine the finished valve body.

MECHANICAL TESTING

To illustrate that the SS316/316L extrusions are capable of adhering to the mechanical property requirements based on the maximum allowable stress criteria in ASME BPVC II D for time independent regime and ASME B31.1 for time dependent regime, the following mechanical tests were conducted –

- Room temperature tensile testing, in accordance to ASTM E8.
- Elevated temperature tensile testing, in accordance to ASTM E21.
- Creep testing in accordance to ASTM E139.

RESULTS AND DISCUSSION

Ambient and elevated temperature mechanical properties of extruded & straightened SS316/316L are shown in Table 2, which are also compared to a hot rolled and annealed product[2].

The minimum tensile and the yield strength requirements per the ASME BPVC II.D.C-2017[3], Table 1A for use in section I, (construction of power boilers), section III (nuclear) class 2 and 3 and section VIII (pressure vessel) Division 1 are noted as 70ksi and 25ksi respectively. Also, the maximum allowable stress values in the time-independent regime up to maximum temperature limits of 800°F from section III and 850°F in section I and VIII-1 are 12.9ksi and 12.7ksi respectively.

Table 2. Mechanical properties of extruded SS 316/316L compared to hot rolled and annealed condition.

Product Type	Test Temp, °F	YS, ksi	UTS, ksi	El, %	Hardness (Rockwell B)
Extrusion	RT	52	88	54	82
	300	43	70	45	
	500	37	65	40	
	800	35	70	41	
Hot Rolled & Annealed	RT	42	91	55	80
	400	35	81	51	
	600	31	78	48	
	800	28	76	47	

As observed in Table 2, the tensile and the yield strength of the extruded SS 316/316L products not only adheres to, but exceeds the requ irements specified per ASME BPVC II.D.C-2017 standards.

Yield strength and elongation of the hot rolled & annealed vs. the extruded product in comparison to the ASME BPVS standards are shown in Figures 7 and 8 respectively. It should be noted that yield strength at ambient and the elevated temperatures of the extrusions is higher than the hot rolled and annealed products, thus providing significant interest to employ the extrusions over the conventionally utilized hot rolled material for similar applications, besides considering the cost savings offered by the extrusions.

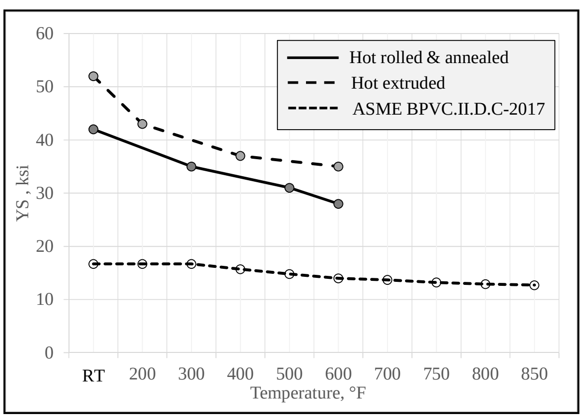

Figure 7. Yield strength of the hot rolled/annealed vs. extruded 316/316L stainless steel products in comparison to the ASME BPVC requirements.

It should be noted that the mechanical properties on the extruded products were evaluated in the hot extruded and straightened condition. No annealing treatments were performed on the extruded products which could explain the

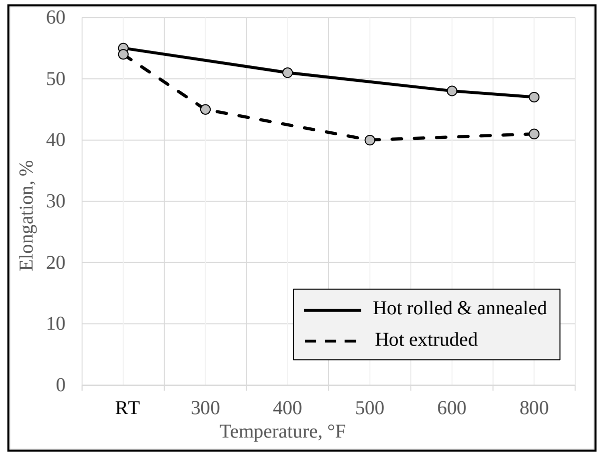

Figure 8. Elongation on the hot extrusions was noticed to be slightly lower than the hot rolled and annealed products.

higher yield strength and the slightly lower elongation values observed, compared to the hot rolled & annealed products.

In order to better understand the behavior of the hot extruded 316/316L stainless steel in the time dependent regime for deformation, creep tests were performed for 100hours at 800°F/13ksi, 1000°F/12ksi and 1200°F/6.5ksi. The creep test conditions were selected based on the data, as indicated in ASME B31.1-2016[4)] Table A3.

No significant creep was recorded on the test samples from the extruded material after 100hours at any test condition. Applied stress was then doubled and the tests were continued for another 50 hours with no indication of creep strain. Thereafter, the creep test at 800°F was discontinued and the maximum allowable stress applied to the remaining two samples was quadrupled.

After an additional 140hours and 4 times the initial test loads, the tests at 1000°F/48ksi and 1200°F/26 ksi resulted in 0.44% and 1.49% total creep strains respectively. Due to the insignificant creep strain observed after additional load and the extended time, the test at 1000°F/48ksi was terminated. However, after continuing the test for 260 hours, the sample at 1200°F/26ksi indicated a total creep strain of 2.2% (Figure 9). The extruded 316/316L stainless steel behaves as expected in the primary creep region when compared to an earlier analysis (Figure 10)[5)]. Table 3 summarizes the data obtained from the creep testing of the extruded products.

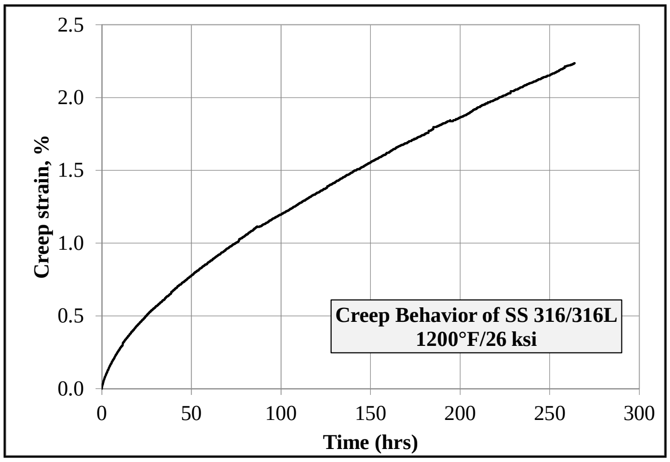

Figure 9. Creep curve of hot extruded 316/316L stainless steel at 1200F/26ksi/260hours.

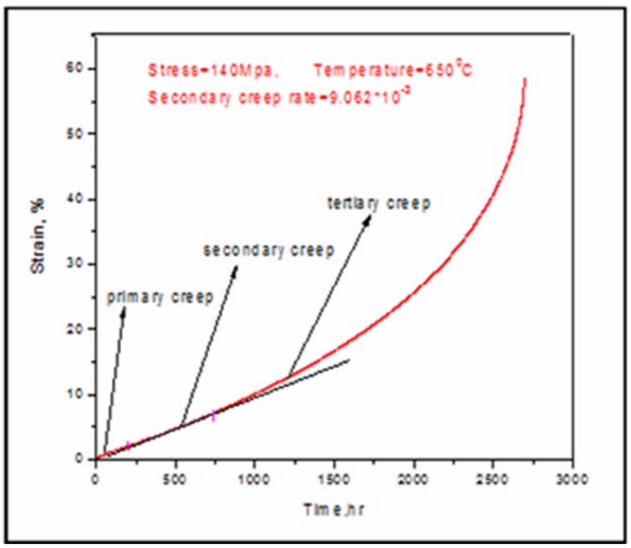

Figure 10. Creep behavior of SS 316 from literature indicates ~2% creep strain after 200 hours at 650C (1200F) at 140 MPa (20 ksi)[5].

Table 3. Creep test data obtained on the SS 316/316L extrusions

Test condition			Total creep Strain, %
Temp, °F	Stress, ksi	Time, hr	
800	13	100	No creep
	26	50	No creep
1000	12	100	No creep
	24	50	No creep
	48	140	0.44
1200	6.5	100	No creep
	13	50	No creep
	26	260	2.20

SUMMARY

- Extrusions can provide significant savings in terms of material and machining costs, since the final product is much nearer to the actual profile of the part compared to hot rolled or a forged bar/plate.
- Hot extruded 316/316L stainless steel parts can be made for applications such as power boilers, pressure vessels and nuclear components, satisfying the ASME requirements of minimum yield and tensile strength at ambient and elevated temperatures up to 1200°F to meet the maximum allowable stress criteria as prescribed in ASME BPVC II.D and ASME B31.1. This includes both time independent and time dependent regimes.
- Room temperature and elevated temperature mechanical properties of hot extruded products are very much comparable to the hot rolled and annealed 316/316L stainless steel, thus providing a significant confidence level for end users to utilize the extrusions in lieu of the conventional hot rolled/forged products, considering the savings offered by the extrusions.
- Data provided by the authors is particularly for 316/316L stainless steel, clearly citing the evidence that stainless steel extrusions comply and exceed the requirements for various industrial applications. The authors also believe that this comparison can be extended to other products extruded at PES using various other grades of stainless steel.

REFERENCES:

1) Online web search
2) 316/316L Bulletin, AK Steel
3) ASME BPVC II Materials Properties Part D. Customary-2017
4) ASME B31.1-2016- Power piping
5) V. Bindu Neeharika et al., "*Tensile and creep data of 316L (N) stainless steel analysis*", ARPN Journal of Engineering and Applied Sciences, Vol. 9, No. 5, May 2014.