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Process Parameters Affecting Inhomogeneity of Material Microstructure

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SSM perspective

Background

It is well known that the production methods used for manufacturing of austenitic stainless steel products affects the corrosion properties of the final material. In recent years it has also been revealed that modern manufacturing methods for austenitic stainless steel plates can result in unexpected microstructures of the produced material. The properties of the found microstructures are little known, just as how they occur and how common they are. Knowledge is today missing on how modern production methods and their process parameters affect the microstructure and the corrosion properties of austenitic stainless steels.

Objectives

The objectives of the project are to compile international (US) experiences in the field.

Results

There's been a tremendous change in the number, product types, locations, equipment, and manufacturing capabilities of stainless steel producers from the late 1960's to present. This reconfiguration of the global steel industry occurred between the early 1970's to the mid 1980's and continues today. These changes have produced a loss in manufacturing flexibility, due to the inherent constraints created by equipment and plant designs that were customized for making a few, high value-added products. A major change in the production processes for manufacturing of thick plate material are the use of continuous cast slabs instead of as previously cast ingots and accompanying changes of the forging and rolling processes. The changes in manufacturing technology as well as identified deficiencies in flexibility and knowledge at the today´s material suppliers and the resulting impact on the microstructure and the material properties of delivered products are discussed in detail in the report.

Modifications of the today's material specifications and an extended control and inspection of the manufacturing processes are necessary to avoid unwanted microstructures and unacceptable material properties. The author gives suggestions for more comprehensive material specifications and inspections.

Need for further research

Research is needed to investigate, catalog and document the microstructures of thick plate materials purchased with modified material specifications and extended process control. If the microstructures of the purchased material are found to deviate from earlier used material is further research needed in order to investigate the corrosion properties of the material. Of special interest in that case is to measure the crack growth rate (CGR) of intergranular stress corrosion cracks (IGSCC). The results should be compared to existing disposition curves.

Project information

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1. Introduction

Through short trips and phone calls, I was able to engage my contacts in the industry to host meetings with current and, most importantly, retired plant metallurgists and Nuclear QA personnel who were active in austenitic stainless steels in the 1960's to 1980's. Input from the retirees was critical since many of the stainless steel producers from the 1960's through 1980's no longer exist or were consolidated through purchases. Admittedly, it was very difficult to engage steel producers with whom I did not have a direct contact. Some major metal producers either would not engage in discussions or stated that they were no longer producing the heavier section product forms of austenitic stainless steels in their newer facilities, and that that work was being done in facilities outside their home countries. Most fruitful contacts were through prior forging metallurgy co-workers, plant contacts, and current business partners. Through GE-Hitachi Nuclear we were able to: catalogue current BWR plant components that are constructed of austenitic stainless steels; determine what product forms (forging, plate, etc.) are used to manufacture them; and review some internal specifications. With help from GE-Hitachi Nuclear we were able to compare austenitic stainless material certification paperwork from the 1960's through today.

In a short summary, it appears that manufacturers in the 1960's through early 1980's were strongly focused on melt practice to achieve good chemistry control, and that ingots typically started out as round or multi-sided in shape. Because of the starting shape, the material generally had to have more forging operations (generally including an upset) performed to get it into the final product form. Uniaxial forging was not the norm and would have been frowned upon by practicing forging metallurgist at the time.

It is clear that, although the specifications, ASME or ASTM, remain essentially unchanged or somewhat diminished through shedding prior requirements to supplementary statuses, the state of manufacturing stainless steel has changed dramatically. Some metal producers and Nuclear QA people felt that material specifications (customer specifications) and testing requirements were more stringent in the past and that current specifications and QA are more paperwork and chemistry checks. This was not generally true, but there were more customer written specifications during the plant build period that were consolidated, not eliminated, as the number of components being manufactured in volume decreased.

Interestingly, a variety of factors conspired to change the austenitic stainless landscape in the late 1980's: cost controls promoted the transition to slab or rectangular ingot casting (unidirectional work); the volume of material produced for nuclear applications decreased; metal producers with extensive experience in austenitic stainless steels closed or were acquired; the increased use of stainless steels for consumer products prompted many manufacturers to produce stainless steel strip product with little specification control except on chemistry and corrosion resistance; the change to strip product required little or different expertise from a forge metallurgist and so their experience levels diminished; many of the most advanced facilities were designed around either strip production or plate; and those plants are not designed to manufacture larger product forms. While tradition forge shops (custom forgers) still exist, the more numerous and newer facilities have lost manufacturing flexibility. This includes the ability to use multi-axial forging practice to achieve a more microstructurally and chemically homogeneous product. Along with this, slab and rectangular ingots have dendritic microstructures that require multi-axial forging to break up the dendrites, reduce segregation, and achieve full recrystallization. As designed, the dendritic orientations in continuously cast ingots are acceptable for thin strip and plate. Suppliers that produce thick plates generally only have the ability to uniaxially forge (draw) but not upset cast ingot. Up until the late 1980's, there were specialty forge shops, near the large metal producers, with large, open-die presses that could upset forge large ingots. These presses were used if the ingot size and dimensions exceeded the melter's capacity. Many, but not all, of those shops closed or changed ownership in the US. The capacity to upset forge large ingots remains, but is generally done on a toll basis by forge shops. It still remains a viable option if the stainless steel producer is willing to move their product outside of their plant for the initial processing.

During this entire time period, the one thing that improved significantly was the ability of metal producers to achieve excellent control over chemistry through more advanced melt practices. The industry appears to have focused very heavily on alloy chemistry control, as driven by regulators, but without the same emphasis, the forging or metal working aspects (more experience-based and less quantitative) were neglected. It was commented on by almost all people in the industry, that it is now easier to produce 316L chemistry than higher carbon 316 because of current melt practices. One stainless steel producer commented that it was easier to make (melt) stainless steel than carbon steel.

A specific example of what has become a common material quality issue is illustrated in Figure 1 by a 50.8 mm thick plate of nuclear grade 310S stainless steel plate that was purchased for testing. The macrostructure was examined and it was quite clear that the plate consisted of a mixed structure of unrecrystallized dendrites, from the ingot, and recrystallized grains. The plate was uniaxial rolled with a 4:1 reduction ratio. To illustrate how common these unrecrystallized macrostructures have become, a second 310S plate, also purchased for testing, is shown in Figure 2. The plate shown in Figure 2 was purchased from an entirely different manufacturer than that shown in Figure 1. We've recently purchased 309L and 316L in the same thickness ranges from other suppliers, and found very similar macrostructures. . Many more images of unacceptable thick plate macrostructures, could easily fill this report. An interesting and very telling explanation for the non-uniform macrostructures we received from one supplier was that 310S is typically used in corrosion applications, and in these cases, the presence of "abnormally large grains is not expected to be detrimental".

Figure 1
As-received condition 50.8 mm thick plate of ATI Allegheny Ludlum, heat 835342, piece 41044AA, lot 250651 310 stainless steel purchased to nuclear specifications.

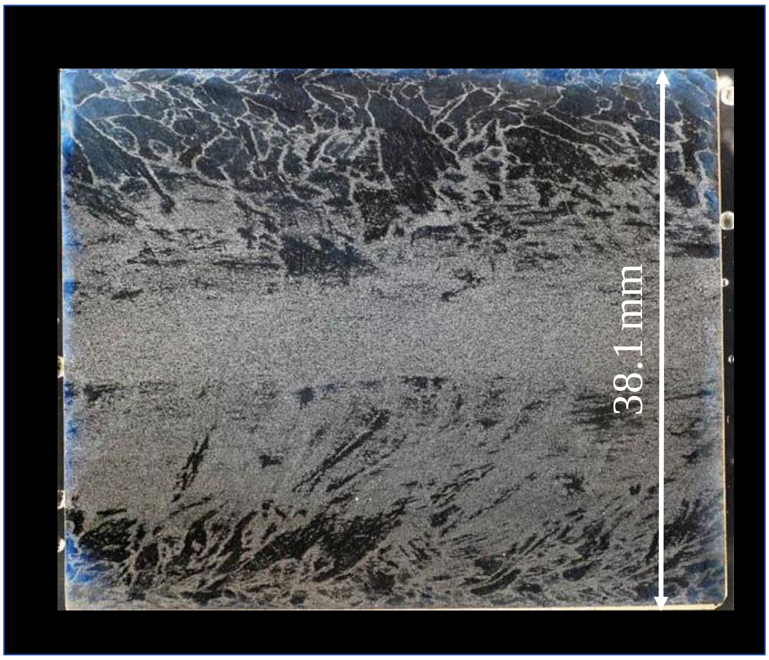

Figure 2
As-received condition of 38.1 mm thick plate of Outo Kumpu UNS S31000 certified 310 stainless steel.

In this report, forging will be defined as hot working of metal for the purposes of healing casting defects and achieving a uniformly recrystallized structure in the metal, consisting of equiaxed grains. When stainless steel is mentioned in this report, it should be assumed that the meaning is austenitic stainless steel.
The final product, whether it be an individual component that has been forged to dimensions that cover the sonic inspection shape, or a common product form (billet, bar, rod, plate, round corner square, square, etc.), should be free of ingot dendrites and casting porosity. Of course, as indicated above, the material requirements may be for chemical resistance only and the stainless steel may not need to meet requirements for mechanical properties or sonic inspection. In many cases it can be argued that having grossly non uniform microstructures in solid solution strengthened metals may not detrimentally impact their basic tensile properties, excluding directionality effects. The most common concern over grossly non uniform microstructures (grain size banding, retained ingot dendrites, planes or strings of inclusions, etc.) is whether these nonhomogeneities will mask more serious defects during sonic inspection. From forging experience and during discussions with retired forge masters, austenitic stainless steels are not particularly difficult to forge or achieve full recrystallization in, given their relatively low flow stresses which allow lower forge temperatures with large cross-sectional area forgings or lower tonnage equipment at higher forge temperatures. Indeed, during the forge process development stage for costly, large cross-sectional area closed die Ni-based superalloy forgings, it is common to do test runs of the process using austenitic stainless steels.
The key factors, however, are whether melting or forging plants have the equipment to fully refine an ingot's dendritic structures and whether they have the economic incentive to do so.

Analyses

The approach taken by this report will be to look at the dominant processes in practice today, with the assumption that the current pool of experienced production metallurgists is versed in those processes. These will be compared to past practices with help from retired metallurgists, some versed in stainless steel processing and others in the production of components for nuclear power plants.

2. Current Versus Historic Supplier Bases

Industry-wide changes

There's been a tremendous change in the number, product types, locations, equipment, and manufacturing capabilities of stainless steel producers from the late 1960's to present. This reconfiguration of the global steel industry occurred between the early 1970's to the mid 1980's and continues today. During this period the global stainless steel manufacturing base shifted both in geographic location and product focus. These changes have produced a loss in manufacturing flexibility, due to the inherent constraints created by equipment and plant designs that were customized for making a few, high value-added products. For austenitic stainless steels, the greatest loss has been the reduction in the number of options available to manufacturing low demand products, such as middle weight and heavy structural forgings. Along with the loss in manufacturing base came a loss in the experience needed to successfully design a custom forging process starting with now non-standard ingot types. In addition, when many of the traditional manufacturers moved to high value added Ni-based alloys and away from commodity stainless steels, it further contributed to the loss of product metallurgists that specialized in stainless steels. Further complicating matters has been the incredible number of mergers, acquisitions, and closing of steel producers that initiated in the 1970's and continues today. While a common practice, every one of these actions causes attrition of equipment, important technical contacts, skillsets, and memories of unique processing techniques. A snapshot that illustrates the merger and acquisition activities in the steel industry is shown in Figure 3. The result is a current high demand for experienced product metallurgists and an expertise base that is either retired or has moved on to other fields.

In many forge shops and mills there's a division in product metallurgists based on processes; melting, ingot conversion, forging, and rolling. Division may also be based on alloy system; steel, Ni-based, stainless steel, etc. This report will use a similar convention. Given the background outlined above, there were few currently-practicing stainless steel metallurgists available with knowledge extending back to the 1960's and 1970's. To counter this, a composite description of large section stainless steel processes then and now was developed from discussions with retired stainless steel production and melting metallurgists and current production metallurgists. Within the time frame and travel possible (US and European subjects interviewed), there were few current production metallurgists experienced in the melting and processing of large-section austenitic stainless steel forgings and plate. Most current production metallurgists were very familiar with melting procedures but were focused on very specific product types; thin strip, rod, wire, coil, and bars; using very specialize forging and rolling mills. Unlike the retiree group, current production metallurgists were less able to deal with process steps that were outside the dimensional or load limits of their specialized forge equipment, especially if the dimensions of the input stock or product did not match size requirements governed by the forge equipment. The overall result is a loss in flexibility to add forge processing steps needed to improve microstructure. It could be argued that this loss of flexibility results in better process control for standardized products and reduces scrap rates. Process standardization using standardized equipment and solid solution strengthened alloys, such as austenitic stainless steels, does to some extent promote a manufacturing (input to output) mentality that is different from a metallurgy centric one. So while it was easy to have in-depth discussions (on the metallurgical basis for why something was done) with the retirees, current production metallurgists dealt more with fixed parameters (temperature, feed rates, speeds, die temperatures, etc.) and were less likely to think in metallurgical terms. Basically, the current practice appears to be to make the alloy fit the process, as opposed to building a process that fits the alloy.

It will be seen from this composite description that, in the opinions of melting and production metallurgists, the greatest improvements in the quality of stainless steel product came through advances in melting technologies and melt furnace refractory materials. Most of these improvements were not initiated at large steel mills, but rather at big mini-mills and high speed mini-mills in the early 1980's.[1, 2]

1. Melting

In the 1960's to 1970's the primary melting of stainless steels occurred in Direct Arc Furnaces (DAF) with long heat times and fire clay used as a crucible liner material. Some melt shop metallurgists felt that the older refractories were self-correcting in terms of requiring fewer adjustments to the heat chemistry, but this could have a negative impact on cleanliness. In the 1960's top pouring of ingots was prevalent, whereas today bottom pouring is used to enhance cleanliness of the steel. All agreed that great improvements in stainless steel cleanliness were made by the introductions of melt process control systems, better slag practice, newer improved refractories with fewer slag/heat interactions, and in the 1980's, improved shrouding. The addition of Vacuum Oxygen Degassing (VOD) and Argon Oxygen Decarburization (AOD) gave stainless steel manufacturers much better control over carbon concentration. The effect of AOD processing was that manufacturers could economically reduce the carbon concentration in low carbon austenitic stainless steels without reducing the chromium levels. The process is so economical that almost all austenitic stainless steels start out as low carbon grades and the manufacturers must recarburize them to make higher carbon grades.[3]

One very important difference that has been noted in the steel making literature is the solidification structure found in continuously cast steel or stainless steel ingots versus the solidification structure in conventional ingots. The importance of this becomes significant when it is considered that continuously cast ingots constitute 98% of current steel production.[4]

Durand-Charre describes, with examples, the ingot solidification macrostructures which are formed in continuously cast stainless steels, or steel, versus conventional type ingots that would have been more common in the 1960's and early 1970's.[4] The distinction between the solidification macrostructures of the two general ingots types is not good versus bad, but what processing steps are needed to produce uniformly recrystallized microstructures in their final cast-wrought forms. For continuously cast stainless steel, the ingot has a central core of equiaxed grains or fine dendrites, surrounded by coarse, elongated dendrites oriented perpendicular to the surface, and with a fine dendritic surface skin produced in the rapid chill zone.[4] Hot working this structure will first refine the ingot's core, since this region will have a lower flow stress and more optimally oriented grains. The coarse, outer dendrites will have limited grains with optimal orientation for slip, the effect will be to cause strain build up at the dendrite boundaries, which produces a necklace structure around the dendrite grains. When the two structures are mixed it is very difficult to drive enough strain into the large dendrite remnants, since the lower flow stress material will be accommodating most of the strain. The 50.8 mm diameter compression test specimens shown in Figure 4 were taken from coarse, columnar dendritic regions of an ingot and fine dendritic material from the same ingot, and hot compressed under the same conditions to illustrate this effect. Additional compression test specimens taken from the same material but from a fine, equiaxed grain structure area, are shown for comparison. As seen in Figure 4, the specimens containing the coarse ingot dendrites show irregular flow, as the large dendrites flow past one another due to recrystallization at their boundaries. Flow in the finer dendrite sample is more uniform and closer to the uniform flow seen in fine grained material of the same alloy. An illustration of the inhomogeneity in total plastic strain is illustrated in the FEM plot of a 316L right circular cylinder shown in Figure 5. Looking at the plot in Figure 5 and the color coded scale for plastic strain, it is clear that many areas in the compressed cylinder are below the 0.7 plastic strain required for full recrystallization.

In practice, this effect can be seen in the plate cross-sections shown in Figures 1 and 2, where the center has fully recrystallized and the outer regions are partially recrystallized. Referring back to the macrostructure of a continuously cast plate or slab, it's clear that, without the introduction of sufficient plastic strain during hot working, some of the coarse dendrite grains below the surface may not fully recrystallize. As will be discussed later, these unrecrystallized regions also retain solidification segregation, which in austenitic stainless steels is associated with delta ferrite.

The previous discussion also includes conversion of ingots produced using premium melting processes such as ESR, VIM, or VAR, which have different and usually more refined macrostructures. The flow behaviors of ingot materials are often overlooked in many forge processes that do not require production of uniformly fine grained billet, but can be accommodated for austenitic stainless steel ingots if the correct forging processes are used.

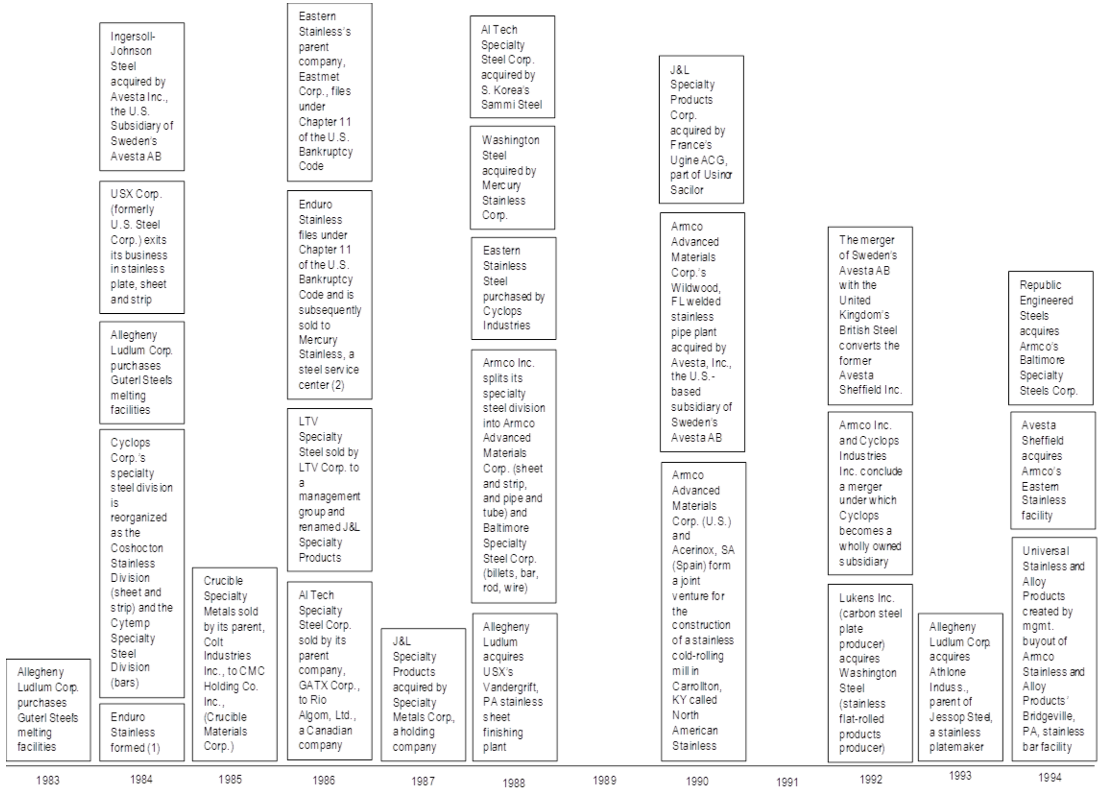

Figure 3
Timeline of major acquisitions, mergers, sales, and joint ventures affecting stainless steel mill products industries.[1]

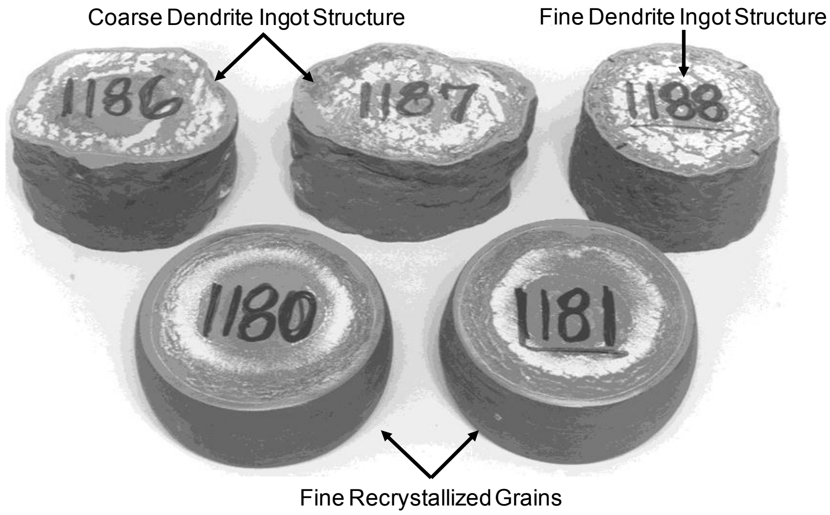

Figure 4
Effect of dendrite size on metal flow characteristics when compared to fine recrystallized grains in an austenitic alloy.[5]

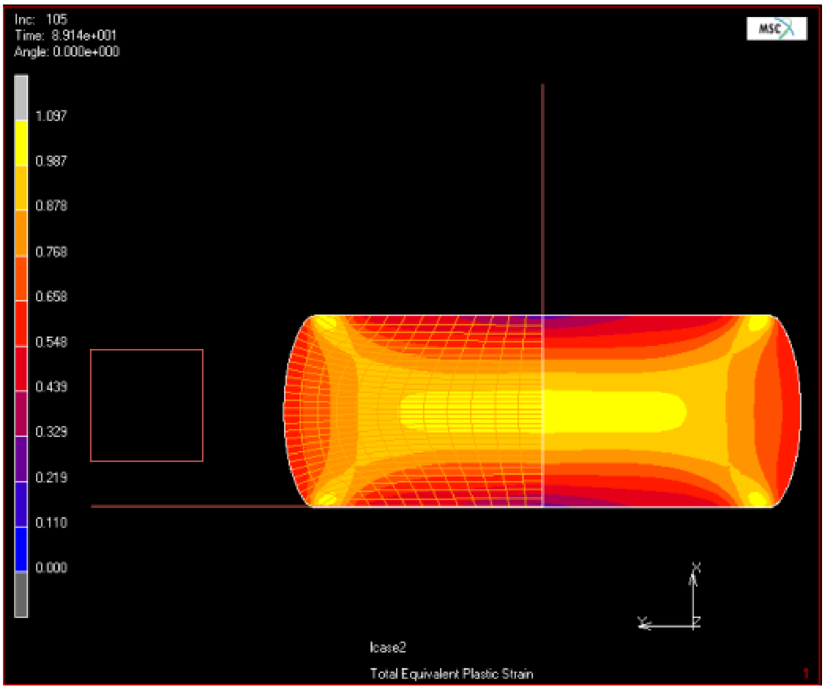

Figure 5
FEM plot of total plastic strain developed in a 316L right circular cylinder after compression at forge temperature. Bar scale on left indicates total amount of plastic strain.

2. Ingot Conversion and Dominant Product Forms

An important factor that is having an impact on the diversity of stainless steel production paths is how the pre-form, the shape that enters the mill or forge, is produced. As seen in Figure 6, there are two main processing paths, A and B, for producing castings, in ingot form (long polygonal or cylindrical shapes) or as rectangular slabs or continuously cast plate, respectively. As will be discussed, the transition to the more geometrically accommodating, economical, and uniform process of continuous casting to produce plate, sheet, and strip products occurred over the early 1970's to the mid 1980's during the global reconfiguration of the steel industry. By itself, the transition to continuous casting did not directly contribute to a decline in the quality of stainless steel structural forgings, unless components were machined from plate, but did change the metallurgical skill sets needed and reduced or eliminated the need for more traditional types of forging equipment.

Holden, et al [6] outlined many of the technical concerns over, what was in the late 1960's to early 1970's the newly introduced process of continuously casting steels, many of which are still relevant. One of the benefits of this process is that more of the steel can be used, since ingot top and bottom are no longer present, and so cropping is not necessary. Casting into ingot molds, however, allows inclusions to segregate to the top and bottom of the ingots, which are then cropped. If standard ingot cropping rules are followed, with 15% cut from the top and 10% from the bottom, then many of the inclusions will be removed before subsequent forge processing is done. More rapid production also reduces cooling times, which limits the ability of inclusions to move and coalesce, and so many fine inclusions tend to segregate to the center of the ingot. Another advantage that motivated the move to slab and continuous casting was the ability to get closer to the final dimensions and thereby eliminate the primary rolling steps. Primary rolling not only puts more work into the steel but it also breaks up and disperses inclusions. Holden, et al also referenced a comparison between working of conventional ingots that required a 20:1 reduction ratio to a 2:1 ratio for the same product made from continuously cast steel plates.[6] Aside from the mechanical mixing of the steel that occurs with high reduction ratios, there's a marked difference in inclusion morphology, from dispersed, high aspect ratio stringers in conventionally processed ingots, to thin plates in continuously cast plates.

Producing austenitic stainless steel plate in thicknesses greater than 130 mm typically requires a conventionally cast ingot, but even large steel producers appear to be limited in the amount of reduction they can achieve using their equipment. Many producers have sliding scales that correlate increasing plate thickness to decreasing reduction ratio. Large austenitic stainless steel producers appear to realize that decreasing reduction ratios results in poor refinement of microstructure. The inability to achieve ideal reduction ratios is recognized by many producers, but may not be stressed to customers whose own specifications have no reduction ratio requirements. Still, these same steel producers do not take their products outside of their own vertically integrated companies to facilities that have the required press tonnage and geometries. The transfer of product to achieve higher reduction ratios using 'toll shops' (companies willing to take on work that was outside of their normal product lines) was a consistent method of breaking down large ingots in the 1960's to 1970's. In the US, A. Finkl & Sons produces large forgings for closed forging dies and is an example of a company with the capability to reduce very large ingots to blooms and billets. The quality demands on the die steels they produce have allowed them to evolve into a company highly specialized in the conversion of ingots. For an excellent example of how the conversion of conventional ingots is performed, the reader is directed to the A. Finkl & Sons web site, www.finkl.com/Tour.aspx. There were several similar forge shops that converted large ingots of specialty and austenitic stainless steels ('toll shops'), but most of these facilities were phased out in the mergers and acquisitions that occurred in the steel industry. In many cases the 'toll work' served to maintain press work load and became unnecessary when plants were configured to produce less diverse and more specialized product lines.

An illustration showing the processing paths required to achieve improvements in both melt segregation and microstructure of forged material is presented in Figure 7. The ideal processing path would be to upset and draw the ingot, to achieve a fully recrystallized microstructure with no retained dendrites and a fairly uniform grain size through the billet cross-section (billetization). If done correctly the final forge operation will, at the least, not destroy the billet microstructure (coarsen the grain size) and, in the best case, refine it further. From descriptions of ingot conversion paths it's apparent that cast slabs and continuously cast ingots, by geometry and ingot dendrite structure, lend themselves to the forge processing path shown at the top, left to right steps, in Figure 7. If the ultimate product is plate, the drawing operation can be eliminated and the ingot sent directly to a rolling mill. For large forgings requiring high ingot input weights, thicknesses, and complex geometries, the middle, left to right steps in Figure 7, is the preferred path. Prior to the introduction of continuous casting, this processing path was used for converting traditional cylindrical and polygonal ingots to rectangular sections for rolling.

One step that is sometimes omitted, even in conventional ingot upset and draw operations, is to dimple the ends of the ingot during the upset to introduce more deformation into the regions under the dies and thereby refine the dendrite structure there. Using flat dies alone to perform an upset operation leaves deep regions of the ingot under the dies with little or no work, essentially dead zones for metal flow.[7] Although this effect was empirically recognized early in the forging industry, a surprising number of newer forge processes do not include this 'dimpling' operation, and in some cases rely on predetermined top and bottom crops to eliminate these dead zones along with segregation and defects from the original ingot's top and bottom ends.

The processing paths illustrated in Figure 6 attempt to show the production routes used to manufacture stainless steels in the mid 1990's. In actual fact, by the mid 1990's, approximately 75% of the stainless steel product was flat rolled product refined by Argon-Oxygen Decarburization (AOD) and then processed through path A in Figure 6. Of product processed through path B in Figure 6, approximately 14% went to bar or rod, 7% to semi-finished slabs, and the remainder to tube and pipe.[1] Of the 21%, most was processed through the lower, continuous casting, route shown in Figure 6. In the US, a very small percentage of the total volume of product was processed through the blooming to billet to structural shape path. If a similar analysis had been done in the 1960's and early 1970's, the picture would have been reversed, reflecting a very low volume of product that came through the continuously cast route, and AOD refining would have been less prevalent in the 1960's. A USITC report, compiled in 1979, reflects the changes that were occurring in the late seventies.[8] In 1979, for example, the capacity to melt stainless steel rose 7%, from 1978 to 1979, production of rolled stainless steel sheets and plates increased while the capacity to manufacture rod and bar through conventional processing decreased, and R&D investments rose to keep pace with the introduction of new processes.[8]

By 1991 the focus on specialization in plate and strip product had greatly reduced medium and heavy structural forgings from the US and Japan, while companies in the European Community (EC) and the UK retained some capacities in this area by maintaining broad product lines.[2] The current situation has further yielded the medium and heavy structural forgings from the EC and UK to third tier suppliers. Based on interviews with retired stainless steel product metallurgists and inference from literature sources, one result of this change in industry focus was a corresponding decrease in the number of people experienced in forging steps required for intensive ingot conversion processes. These were largely what could be described as custom forge processes developed within companies by metallurgists experienced in utilizing the forging tools their plants processed, and because the processes may have been plant equipment specific, the knowledge and experience was not readily transferable to other plants or to new facilities that focused on plate and strip production. Controlling these metallurgists were specifications written by other specialists or metallurgists who recognized the potential diversity that could exist in structural forgings produced using different processing paths. The specifications had to be expertly written to ensure that, whatever processing path a forger used, the end product would meet all property and microstructural requirements (sonic inspection requirements generally tie in with microstructure, including forging defects, voids, and inclusions).

Based on experience, the custom forging of heavy structural austenitic stainless steel and Ni-based components in the early 1990’s generally proceeded as follows: the steel metallurgist at the plant (experienced in manufacturing large structural components) would contact the metallurgist specializing in austenitic alloys (based on their stainless and Ni-based knowledge) to discuss a Request for Quotation (RFQ) submitted by a customer. They would review the specifications to determine what key properties and/or microstructure were needed, then perform a rough cost assessment; could we start with less expensive starting material, ingot versus billet, for example, and using the in-plant equipment, develop a forging process that would enable us to convert lower cost starting material to a forging that would meet the customer’s specifications? In the cost assessment, it was generally know what competitors’ capabilities were (based on plant equipment at their disposal or their ability to obtain lower cost starting materials through their own melting facilities), and in many cases it was decided that the capabilities of the in-plant equipment were such that a competitive forging process could not be designed and no bid was made on the RFQ. Other decisions points were based on how busy the plant was, availability of forging presses and furnaces, die and tooling requirements, and how flexible the shop schedule was to the introduction of a few components requiring customized forging operations. Basic factors also came into play; weight capacities of cranes, fork trucks, and forge manipulators, press opening dimensions and tonnages, or transfer times from forge furnace to the press, for example. This said, it was generally possible to make almost any large structural forging in austenitic stainless steel if the grain size and sonic requirements in the specification were left open to interpretation by the forger. So, into the equation, one could compensate for low press tonnage by increasing forge temperature and use less expensive starting material (non-homogenized ingot), if the specification did not have tight grain size requirements. Sonic inspections would generally catch gross microstructural inhomogeneities, but when tight schedule demands by the customer intervened, many sonic indications could be explained and the forging cleared through a supplier deviation request process.

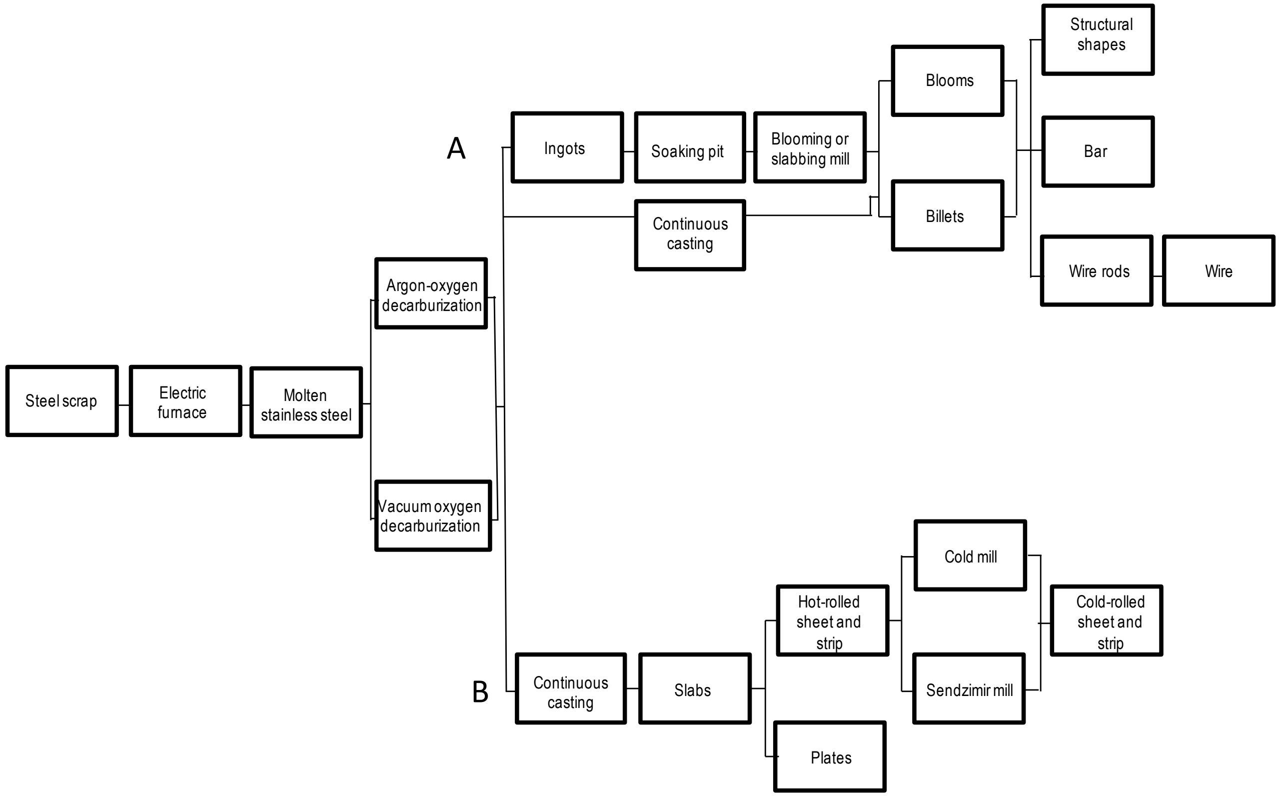

Figure 6
Stainless steel mill product production processing paths.[1]

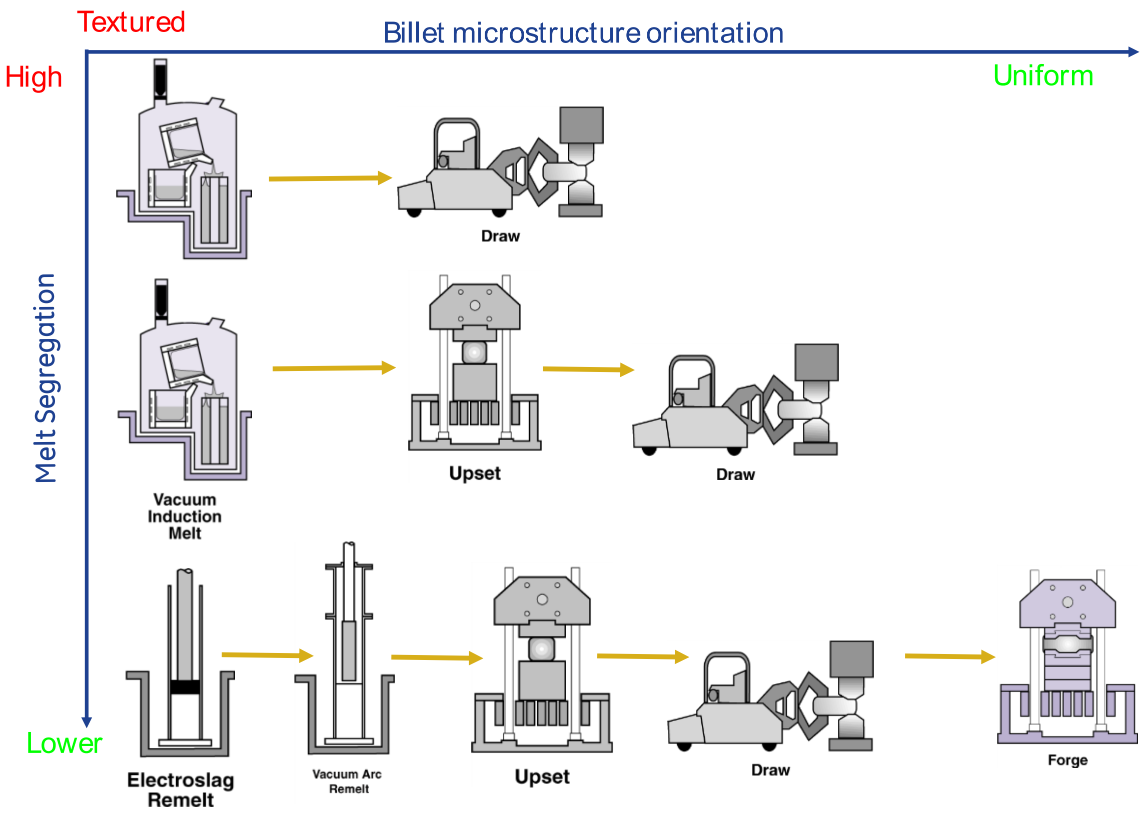

Figure 7
Processing steps relating improvements in final microstructure of a forged component as functions of melt practice and forge operations.

The literature indicates that there's some concern over the amount of reduction possible using continuously cast ingots, given their smaller starting size (thickness).[9] In theory, the finer dendrite size achieved in continuously cast ingots should compensate for the decrease in reduction ratio, but in reality there's less breakup of the dendrite structure. It should be mentioned that recrystallization practices developed for steel (where the focus of continuous casting development was centered), which undergoes an austenite to ferrite transformation, are not applicable to fully austenitic stainless steels that are very dependent on strain to achieve full recrystallization. A comment by Krauss, that relatively small reductions are required to achieve "wrought steel performance", is telling in that, so long as properties (performance) are met, focusing on control of microstructure, as was done in the past, may not have as great a weight today.[9] There is some evidence that these partially recrystallized structures in 310 stainless steel exhibit higher SCC growth rates than the same heat of material after it has been 'repair' forged and heat treated to produce a uniform, equiaxed grain structure.[10]

For austenitic stainless steels there's another important factor that is related to the amount of reduction the ingot receives before reaching its final product form, and that is delta ferrite content. As occurs in austenitic welds and cast stainless steels, delta ferrite forms during solidification as an interdendritic phase, and like any segregation-induced phase, if insufficient work is applied to the ingot, a larger percentage of delta ferrite remains in the finished product. As shown in the 316L plate in Figure 8, if the delta ferrite present in the ingot dendritic structure is not sufficiently broken up by hot working, then it can be drawn into stringers along the rolling direction. An Electron Backscatter Diffraction (EBSD) phase map in Figure 9 shows the delta ferrite in a 50.8 mm plate of 304L stainless steel. The larger volume fraction of delta ferrite seen in some austenitic stainless steels may be related to the amount of reduction being used in the conversion from ingot to equiaxed product. In his research, Krauss credits thinner section sizes as having less delta ferrite due to the amount of reduction they see, but in thicker plates and forgings delta ferrite can be more prevalent if insufficient hot work has been used to homogenize ingot segregation.[9]

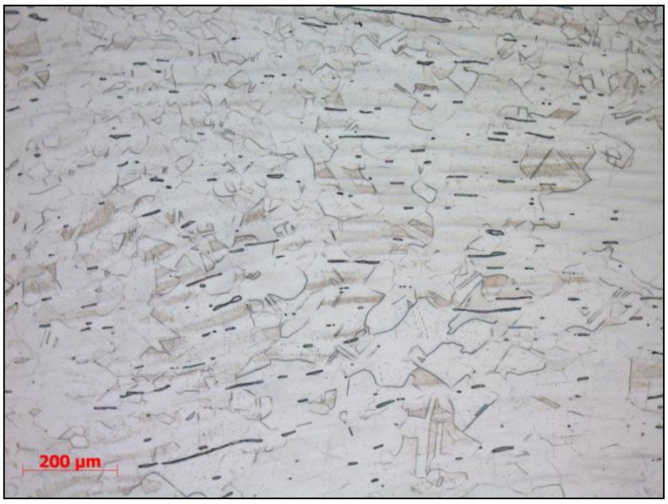

Figure 8
Retained interdendritic delta ferrite (dark phase) in 50.8 mm thick 316L plate. Electrolytic 10% oxalic acid etch.

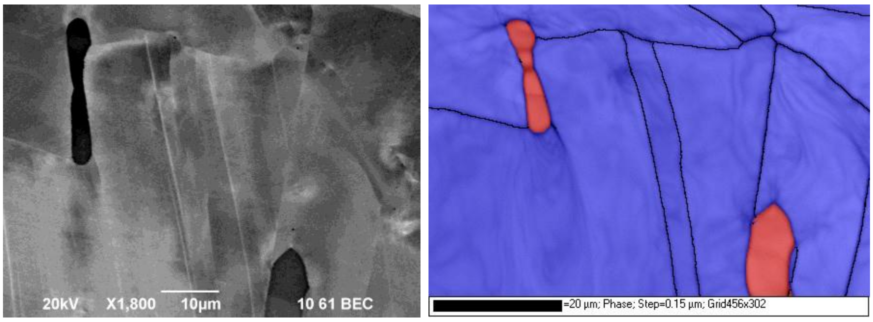

Figure 9
Delta ferrite stringers in 50.8 mm 304L stainless steel plate, left backscattered electron image and right EBSD phase map (blue austenite and red ferrite).

3. Use of Plate Versus Forgings

At first glance, the boundary between plate and forged products appears clear. Large and uniquely shaped or high weight components still require conventionally cast ingots to be processed into final shapes, but thick plate product can be machined into many components that were previously forged. Also, if the thick plate was open die forged, it may be classified as a forging. This becomes an issue if the plate was open die forged without using a forge process designed to induce sufficient plastic strain throughout the work piece. As seen in Table 1, there are many BWR primary system components that specify plate as the starting product form and other components in this listing that dimensionally could be produced from plate. Based on Table 1, and the ready availability of plate produced from continuously cast product in the current metals market, the starting ingot structures, processing routes, and potential microstructures in the finished plate appears to be another important factor that requires investigating. Also, in a limited nuclear plant building period, a manufacturer's sourcing department may find that plate is more readily available (based on market demand) and less expensive than locating forging stock and producing a unique forged component. It's also advisable to review if the material is a forging since, in some references, slabs or thick plates are considered open die forgings (in fact, due to thickness, may to be open die forged). A review of material certifications for 304L plate purchased in 2006 showed that the plates originated from electric arc melted and AOD refined slabs. Some of the exclusions in the specifications for forgings, one component per forging, for example, may not apply to a forged thick plate or slab where multiple components may be removed from it. Finally, the metallurgical experience in making hot rolled product can be very different from traditional open and closed die forging processes.

A look at Tables 2- 7 shows that the use of plate versus forging for different reactor components varies depending on the reactor design. Without knowing the specific process paths for each component there's always the possibility that forging refers to a uniaxial forge operation. If used, uniaxial forging can produce the same laminar alignment of inclusions or duplex grain structures as found in plate product. For many of the components listed in these Tables, flanges in particular, what is described as a forging may in fact be a uniaxial forged, rather than hot rolled, thick plate. Examples of structures found in uniaxial forged XM19 are shown in Figures 10 and 11. In Figure 10 the presence of large areas of abnormal grain growth (very coarse grains) due to insufficient strain introduced during the forging process are evident. As shown in Figure 11, stringers of MnS particles and NbC carbides in uniaxial forged are identical to the morphology produced during hot rolling of plate. These examples stress the need to clarify how some of the forgings listed Tables 1 through 7 are produced.

Table 1 Use of Stainless Steel Forgings and Plate in the BWR/2-6 Primary System, Including Repairs and Replacements, from XGEN.[11]

BWR Type	Component Group	Component	Material Type†	Product Form
All	RPV	Nozzle Safe Ends	F304	Forging
All	RPV	Replacement Nozzle Safe Ends	F316NG	Forging
BWR/3-6	RPV	Jet Pump Instrument Nozzle	F304/304	Forging or Plate
BWR/3-6	RPV	Replacement Jet Pump Instrument Nozzle	F316NG	Forging
All	RPV	Internals Support Brackets and Lugs	F304	Forging
All	RPV	Water Level Instrument Nozzle	304	Forged Bar
All	RPV	Core ΔP Nozzle and Tee	F304	Forging and Forged Fitting
All	RPV Appurtenance	CRD Housing Flange	F304	Forging
All	RPV Appurtenance	ICM Housing Flange	F304	Forging
BWR/2-4	Reactor Internals	Shroud	304	Plate
BWR/4*-6	Reactor Internals	Shroud	304L	Plate
BWR/2-6	Reactor Internals	Shroud Restraint Repair	F316L/316NG/ XM-19	Forging/Forged Bar
BWR/2-4	Reactor Internals	Core Plate	304	Plate
BWR/4*-6	Reactor Internals	Core Plate	304L	Plate
BWR/2-4	Reactor Internals	Top Guide	304	Plate
BWR/4*-6	Reactor Internals	Top Guide	304L	Plate
BWR/2-4	Reactor Internals	Shroud Head Rim and Dome	304	Plate
BWR/4*-6	Reactor Internals	Shroud Head Rim and Dome	304L	Plate
BWR/2-4	Reactor Internals	Shroud Head/Steam Separator Supports	304	Plate
BWR/4*-6	Reactor Internals	Shroud Head/Steam Separator Supports	304L	Plate
BWR/2-6	Reactor Internals	Steam Dryer	304**	Plate

*Material for major internals changed from 304 to 304L midway through BWR/4 series production.
**Four BWR/6 steam dryers were fabricated from 316L plate, but none were put in service because of project cancellation.
†Types 316L and 316NG have 0.02% carbon maximum.

Use of Stainless Steel Forgings and Plate in BWR/2-6 Primary System Including Repairs and Replacements, Including Repairs and Replacements, from XGEN.[11] Table 1 Continued

BWR Type	Component Group	Component	Material Type†	Product Form
BWR/3-4	Reactor Internals	Replacement Steam Dryer	316L/F316L and XM-19	Plate/Forging
All	Reactor Internals	Feedwater Sparger End Brackets	304/316L	Plate
All	Reactor Internals	CRD Guide Tube Body	304	Rolled and Welded Plate
All	Reactor Internals	CRD Guide Tube Flange and Base	304/F304	Plate or Forging
BWR/2-5	Reactor Internals	Core Plate Bolting	304	Forged Bar
BWR/6	Reactor Internals	Top Guide and Core Plate Bolting	304/XM-19	Forged Bar
All	Reactor Internals	Peripheral Fuel Supports	F304	Forging or Forged Bar
BWR/6	Reactor Internals	LPCI Flow Deflector	316L	Plate
BWR/6	Reactor Internals	LPCI Coupling	F304/304	Forging or Pipe
All	Reactor Internals	Feedwater Sparger Components	304 and F304	Plate (formed and welded) and/or Forging
All	Reactor Internals	Core Spray Piping	304	Plate (formed and welded)
All	Primary Piping	Recirculation System Pipe	304	Plate (rolled and welded)
All	Primary Piping	Replacement Recirculation System Pipe	316NG/F316 NG	Plate (rolled and welded) or Drawn Seamless
All	Primary Piping	Recirculation System Fittings	304/F304	Plate (formed and welded) or Forging
All	Primary Piping	Replacement Recirculation System Fittings	316NG/F316 NG	Plate (formed and welded) or Forging
All	Primary Piping	Isolation Valve Bodies and Bonnets	F304	Forging††
BWR/5	Primary Piping	Replacement Gate Valve	F316NG	Forging

†Types 316L and 316NG have 0.02% carbon maximum.

††Rarely used for large valves. Most valve bodies and bonnets in BWR/2-6 are cast stainless steel

Table 2 Use of Stainless Steel Forgings and Plate in the ABWR, from XGEN.[11]

Plant Type/Assembly	Component	Material Type*	Product Form
ABWR-RPV	RPV Drain Nozzle	F316L	Forging
ABWR-RPV	Water Level Instrument Nozzle	F316L	Forging
ABWR-RPV	In-core Housing	F316	Forging
ABWR-RPV	Core Plate ΔP Nozzle and Tee	F316	Forging
ABWR-RPV	Pump Deck ΔP Nozzle and Tee	F316	Forging
ABWR-RPV	CRD Housing	F316	Forging
ABWR-RPV	Internal Brackets and Supports	F316	Forging
ABWR-RPV	Thermal Sleeves	F316	Forging
ABWR-Reactor Internals	Core Shroud	316L	Plate
ABWR-Reactor Internals	Core Plate	316L	Plate
ABWR-Reactor Internals	Peripheral Fuel Supports	316L	Forged Bar
ABWR-Reactor Internals	Top Guide Grid	F316L	Forging
ABWR-Reactor Internals	Top Guide Flange and Skirt	316L	Plate
ABWR-Reactor Internals	CRD Guide Tube Body	304L or 316L	Plate
ABWR-Reactor Internals	Guide Tube Base	XM-19	Forged Bar
ABWR-Reactor Internals	Top Guide and Core Plate Fasteners	XM-19	Forged Bar
ABWR-Reactor Internals	Feedwater Sparger Components	F316L	Forging
ABWR-Reactor Internals	LP Core Flooder Sparger Components	F316L	Forging
ABWR-Reactor Internals	HP Core Flooder Couplings	F316L	Forging
ABWR-Reactor Internals	HP Core Flooder Brackets	316L	Plate
ABWR-Reactor Internals	HP Core Flooder Sparger Components	F316L	Forging
ABWR-Reactor Internals	In-core Guide Tube Stabilizers	316L	Plate
ABWR-Reactor Internals	Shroud Head	316L	Plate
ABWR-Reactor Internals	Steam Dryer Assembly Components	316L	Plate
ABWR-Reactor Internals	Steam Dryer Seismic Blocks	XM-19	Plate
ABWR-Reactor Internals	Reactor Internal Pump Guide Rails	316L	Plate

*All 300 series stainless steel is 0.02% maximum carbon

Use of Stainless Steel Forgings and Plate in the ABWR,from XGEN.[11] Table 2 continued.

ABWR-Reactor Internals	Surveillance Capsule Holder	316L	Plate
ABWR-Reactor Internals	Head Spray Nozzle	F316L	Forging

*All 300 series stainless steel is 0.02% maximum carbon

Table 3 Use of Stainless Steel Forgings and Plate in the ESBWR, from XGEN.[11]

Plant Type/Assembly	Component	Material Type*	Product Form
ESBWR-RPV	GDCS Nozzle Safe End	F304/F304L/F316/ F316L	Forging
ESBWR -RPV	GDCS Equalizing Line Nozzle Safe End	F304/F304L/F316/ F316L	Forging
ESBWR -RPV	Isolation Condenser Return Nozzle Safe End	F304/F304L/F316/ F316L	Forging
ESBWR -RPV	RWCU/Shutdown Cooling Nozzle Safe End	F304/F304L/F316/ F316L	Forging
ESBWR -RPV	Bottom Drain Nozzles (4)	F304/F304L/F316/ F316L	Forging
ESBWR -RPV	CRD Housing	F316	Forging
ESBWR -RPV	CRD Middle Flange	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	CRD Spool Piece	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	SLC Nozzle Safe End	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	In-core Instrumentation Housing	F316	Forging
ESBWR-RPV	Water Level Instrument Nozzles	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	Feedwater Sparger Support Bracket	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	Chimney Restraint Bracket	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	Surveillance Capsule Holder Bracket	F304/F304L/F316/ F316L	Forging
ESBWR-RPV	Guide Rod Support Brackets	F304/F304L/F316/ F316L	Forging
ESBWR-Reactor Internals	Shroud Support Ring	316L	Plate
ESBWR-Reactor Internals	Guide Tube Base	XM-19	Forged Bar
ESBWR-Reactor Internals	In-core Guide Tube Stabilizers	304/304L/316/316L	Plate
ESBWR-Reactor Internals	Core Plate	F304/F304L/F316/ F316L	Forging
ESBWR-Reactor Internals	Peripheral Fuel Supports	F304/F304L/F316/ F316L	Forging
ESBWR-Reactor Internals	Core Shroud Assembly	316L	Plate
ESBWR-Reactor Internals	Top Guide	F304/F304L/F316/ F316L	Forging
ESBWR-Reactor Internals	Core Support Bolting	FXM-19/XM-19	Forging (or forged bar)

*All 300 series stainless steel is 0.02% maximum carbon

**Isolation Condenser return line

†Pipe may also be 304/304L/316/316L extruded or drawn

Use of Stainless Steel Forgings and Plate in the ESBWR, from XGEN.[11]
Table 3 Continued

Plant Type/Assembly	Component	Material Type*	Product Form
ESBWR-Reactor Internals	Chimney Structure	304/304L/316 /316L	Plate
ESBWR-Reactor Internals	Chimney Head Rim and Cover	304/304L/316/316L	Plate
ESBWR-Reactor Internals	Chimney Head Bolt Support Structure	304/304L/316/316L	Plate
ESBWR-Reactor Internals	Steam Dryer Assembly	304/304L/316/316L	Plate
ESBWR-Reactor Internals	Feedwater Thermal Sleeves	F304/F304L/F316/ F316L	Forging
ESBWR-Piping Systems	Condensate** Lines, Fittings, and Valve Bodies	F304/F304L/F316/ F316L	Forging†
ESBWR-Piping Systems	GDCS Lines, Fittings, and Valve Bodies	F304/F304L/F316/ F316L	Forging†
ESBWR-Piping Systems	RWCU Lines, Fittings, and Valve Bodies	F304/F304L/F316/ F316L	Forging†

*All 300 series stainless steel is 0.02% maximum carbon
**Isolation Condenser return line
†Pipe may also be 304/304L/316/316L extruded or drawn

Table 4 Use of Stainless Steel Forgings and Plate in the AP1000, from XGEN.[11]

Plant Type/Assembly	Component	Material Type	Product Form
AP1000-RPV	Primary Inlet/Outlet Safe Ends	F316L/F316LN	Forging
AP1000-RPV	Direct Injection Nozzle Safe Ends	F316L/F316LN	Forging
AP1000-RPV Closure Head	CRDM Latch & Rod Travel Housings	F304LN	Forging
AP1000-RPV Closure Head	CRDM Adapter	F304LN	Forging
AP1000-RPV Closure Head	CRDM Guide Funnel and Extension	F304LN	Forging
AP1000-RPV Closure Head	Instrument Penetration Adapter and Housings	F304L/F304LN/F316L/F316LN	Forging
AP1000-Reactor Internals	Upper Support Welded Assembly	304/304L/304LN/304H	Plate
AP1000-Reactor Internals	Upper Guide Tube Flanges	304/304L/304LN/304H	Plate
AP1000-Reactor Internals	Upper Core Plate	304	Plate
AP1000-Reactor Internals	Core Shroud	304	Plate
AP1000-Reactor Internals	Upper Core Barrel	304	Plate
AP1000-Reactor Internals	Core Barrel Flange and Nozzles	F304	Forging
AP1000-Reactor Internals	Lower Core Barrel and Reinforcement Plate	304	Plate
AP1000-Reactor Internals	DVI Deflector	F304/304L	Forging
AP1000-Reactor Internals	Lower Core Support Plate	F304H	Forging
AP1000-Reactor Internals	Radial Supports	304	Plate
AP1000-Reactor Internals	Secondary Core Support Assembly	304	Plate
AP1000-Reactor Internals	Neutron Shield Panels and Spacer Blocks	304	Plate
AP1000-Reactor Internals	Vortex Suppression Plate	304	Plate
AP1000-Reactor Internals	Core Shroud	304	Plate

*Mostly forged pipe and fittings, but may also include some extruded pipe

**NPS 6 inch (150 mm) nominal and greater

Use of Stainless Steel Forgings and Plate in the AP1000, from XGEN.[11]
Table 4 Continued

Plant Type/Assembly	Component	Material Type	Product Form
AP1000-Reactor Internals	Core Shroud	304	Plate
AP1000-Reactor Internals	Upper Core Barrel	304	Plate
AP1000-Reactor Internals	Core Barrel Flange and Nozzles	F304	Forging
AP1000-Reactor Internals	Lower Core Barrel and Reinforcement Plate	304	Plate
AP1000-Reactor Internals	DVI Deflector	F304/304L	Forging
AP1000-Reactor Internals	Lower Core Support Plate	F304H	Forging
AP1000-Reactor Internals	Radial Supports	304	Plate
AP1000-Reactor Internals	Secondary Core Support Assembly	304	Plate
AP1000-Reactor Internals	Neutron Shield Panels and Spacer Blocks	304	Plate
AP1000-Reactor Internals	Vortex Suppression Plate	304	Plate
AP1000-Primary Piping**	Hot Leg and Cold Leg Piping and Branches	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	Surge Line Piping	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	ADS Squib Valves and Piping Components	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	Passive Core Cooling Heat Exchanger Outlet Piping	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	RHR Suction and Return Piping Components	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	Core Makeup Tank Outlet Header	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	DVI Header and Piping	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	Accumulator Injection Header and Piping	F304/304L/304LN / 316/316L/316LN	Forging*

*Mostly forged pipe and fittings, but may also include some extruded pipe
**NPS 6 inch (150 mm) nominal and greater

Use of Stainless Steel Forgings and Plate in the AP1000, from XGEN.[11]
Table 4 Continued

Plant Type/Assembly	Component	Material Type	Product Form
AP1000-Primary Piping**	IRWST Header Piping Components	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	ADS Header, Valves, and Piping	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	Safety Relief Valves and Piping	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000-Primary Piping**	Passive Core Cooling Return Header	F304/304L/304LN / 316/316L/316LN	Forging*
AP1000- Pressur-izer	Surge Nozzle Safe End	F316LN	Forging
AP1000- Pressur-izer	Safe Ends-Safety and ADS Valve Nozzles	F316LN	Forging
AP1000- Pressur-izer	Heater Support Plates	304L	Plate
AP1000-SG Channel Head	Primary Inlet and Outlet Safe Ends	F316LN	Forging
AP1000-SG Channel Head	PXS PRHR Heat Ex-changer Return Nozzle	F316LN	Forging
AP1000-SG Channel Head	CVS Return Nozzle Safe End	F316LN	Forging
AP1000-Core Makup Tank	Inlet and Outlet Nozzle Safe Ends	F316	Forging
AP1000-Passive RHR Heat Ex-changer	Tube Supports, Mounting Frame, etc.	304	Plate
AP1000-Passive RHR Heat Ex-changer	Extended Flanges	F304	Forging
AP1000-Passive RHR Heat Ex-changer	Inlet and Outlet Nozzle Safe Ends	F316LN	Forging

*****Mostly forged pipe and fittings, but may also include some extruded pipe
**NPS 6 inch (150 mm) nominal and greater

Table 5 Use of Stainless Steel Forgings and Plate in the U.S. EPR, from XGEN.[11]

Plant Type/Assembly	Component	Material Type	Product Form
EPR-RPV	Primary Inlet and Outlet Safe Ends	F316*	Forging
EPR-Closure Head	CRDM Adapter Flanges	F304*	Forging
EPR-Closure Head	Instrument Adapter Con-nector	F304*	Forging
EPR-Reactor Internals	Upper Support Assembly	304*	Plate
EPR-Reactor Internals	Upper Core Plate	F304*	Forging
EPR-Reactor Internals	CRGA Columns	F304/304*	Forging/Plate
EPR-Reactor Internals	Level Monitoring Probe Columns	F304/304*	Forging/Plate
EPR-Reactor Internals	Normal Column Flanges and Brackets	304*	Plate
EPR-Reactor Internals	Guide Tube Support Plates	304*	Plate
EPR-Reactor Internals	Instrument Guide Brackets	304*	Plate
EPR-Reactor Internals	Heavy Reflector Slabs	F304*	Forging
EPR-Reactor Internals	Vertical Keys	304*	Plate
EPR-Reactor Internals	Core Barrel Assembly (flange, shells, outlet noz-zles)	F304*	Forging
EPR-Reactor Internals	Lower Support Plate	F304*	Forging
EPR-Reactor Internals	Heavy Reflector Positioning Keys and Inserts	304*	Plate
EPR-Reactor Internals	Access Plugs	F304*	Forging
EPR-Reactor Internals	Flow Distribution Support Columns	F304*	Forging
EPR-Reactor Internals	Flow Distribution Plate	F304*	Forging
EPR-Primary Piping	Hot Leg and Integral Branch Connections	F304*	Forging
EPR-Primary Piping	Crossover Leg and Branch Connections	F304*	Forging
EPR-Primary Piping	Cold Leg and Integral Branch Connections	F304*	Forging
EPR-Primary Piping	Surge Line Pipe and Fittings	F304*	Forging
EPR-Primary Piping	Piping other than Main Loop and Surge Line	304L/316LN	Pipe
EPR-Primary Piping	Pipe Fittings other than Main Loop and Surge Line	F304L/F316LN or WP304L/WP316 LN	Forging or Fitting
EPR-RCPB Valves	Bodies and Bonnets	F304*/F304L/F3 04LN/F316*/F31 6L/F316LN	Forging
EPR-Primary Coolant Pump	Thermal Barrier Flange	F304*	Forging
EPR-Pressurizer	Nozzle Safe Ends	F316*	Forging
EPR-Pressurizer	Heater Support Plate	316L	Plate

*0.03% maximum carbon

Use of Stainless Steel Forgings and Plate in the U.S. EPR, from XGEN.[11]
Table 5 Continued

Plant Type/Assembly	Component	Material Type	Product Form
EPR-Pressurizer	Spray Heads and Sleeves	F316L or 316L	Forging or Plate
EPR-Pressurizer	Heater Support Hardware and Brackets	F316L or 316L	Forging or Plate
EPR-Pressurizer	Surge Nozzle Debris Screen	F316L or 316L	Forging or Plate
EPR-Steam Generator Channel Head	Primary Inlet and Outlet Nozzle Safe Ends	F316*	Forging
EPR-Steam Generator	Upper Tube Bundle Wrap-per and Roof	304L	Plate
EPR-Steam Generator	Feedwater Pipe, Fittings, Deflector Plate, Supports	316L/F316L	Pipe/Plate/Forging

*0.03% maximum carbon

Table 6 Use of Stainless Steel Forgings and Plate in the APR1400, from XGEN.[11]

Plant Type/Assembly	Component	Material Type	Product Form
APR1400-RPV	DVI Nozzle Safe End	F316LN	Forging
APR1400-Closure Head	CEDM Motor Housing Fittings	F347	Forging
APR1400-Closure Head	CEDM Guide Cone	F304LN	Forging
APR1400-Reactor Internals	Upper Guide Structure Support Barrel Assembly	304	Plate
APR1400-Reactor Internals	Upper Fuel Alignment Plate	304	Plate
APR1400-Reactor Internals	Lift Rig Guide and Guide Lugs	304	Plate
APR1400-Reactor Internals	Inner Barrel Assembly	304/F304	Plate/Forging
APR1400-Reactor Internals	Control Element Assembly Guide Tubes/Webs	304	Plate
APR1400-Reactor Internals	Upper Core Barrel (flange, shell, nozzles)	304/F304	Plate/Forging
APR1400-Reactor Internals	Lower Core Barrel and Flange	304/F304	Plate/Forging
APR1400-Reactor Internals	Snubber Lugs	304 or F304	Plate or Forging
APR1400-Reactor Internals	Core Shroud Top Plate	304	Plate
APR1400-Reactor Internals	Core Shroud Panels, Ribs, Ring, Braces	304	Plate
APR1400-Reactor Internals	Core Shroud Bottom Plate	F304	Forging
APR1400-Reactor Internals	Lower Support Structure Beams and Plates	304	Plate
APR1400-Reactor Internals	Instrument Nozzle Support Plate	304	Plate
APR1400-Primary Piping	Surge Line Pipe and Fittings	347/F347/WP347	Pipe/Forging*/ Fittings
APR1400-Primary Piping	Shutdown Cooling Pipe and Fittings	316/F316/WP316	Pipe/Forging*/ Fittings
APR1400-Primary Piping	Direct Vessel Injection Line	304 or 316 and WP304 or WP316	Pipe/Fittings
APR1400-Primary Piping	Safety Relief Valve Body	F316LN	Forging
APR1400-Pressurizer	Surge Nozzle Safe End	F347	Forging
APR1400-Pressurizer	Spray Nozzle Safe End	F316 or F347	Forging
APR1400-Pressurizer	SRV Nozzle Flanges	F316 or F347	Forging
APR1400-SG Channel Head	Divider Plate	410S	Plate

*Branch connection safe end

Use of Stainless Steel Forgings and Plate in the APR1400, from XGEN.[11]
Table 6 Continued.

Plant Type/Assembly	Component	Material Type	Product Form
APR1400-Steam Generator Internals	Tube Supports (Egg crates and Bars)	409	Plate
APR1400-Steam Generator Internals	Feedwater Flow Distribution Plate	405	Plate
APR1400-Primary Pump	Seal Housing and Cover	Type 630 (17-4PH)	Forging

*Branch connection safe end

Table 7 Use of Stainless Steel Forgings and Plate in the APWR, from XGEN.[11]

Plant Type/Assembly	Component	Material Type	Product Form
APWR-RPV	Primary Inlet and Outlet Safe Ends	F316* or F316LN	Forging
APWR-RPV	DVI Nozzle Safe End	F316* or F316LN	Forging
APWR- Closure Head	CRDM Housings	F316* or F316LN	Forging
APWR- Closure Head	In-Core Instrument Nozzle Adapter Flange	F316*	Forging
APWR- Closure Head	In-Core Instrument Housings	F316*	Forging
APWR-Internals	Upper Support Assembly	304/F304	Plate/Forging
APWR-Internals	Top Slotted Column Flanges	304	Plate
APWR-Internals	Upper Core Plate	304 or F304	Plate or Forging
APWR-Internals	Control Rod Guide Plates	304	Plate
APWR-Internals	Instrumentation Support Flanges and Brackets	304	Plate
APWR-Internals	Mixing Devices	304	Plate
APWR-Internals	CRDM Thermal Sleeve Guide Funnels	F304	Forging
APWR-Internals	Neutron Reflector Ring Blocks	F304	Forging
APWR-Internals	Upper Core Barrel (flange, shell, nozzles)	304/F304	Plate/Forging
APWR-Internals	Lower Core Barrel Shell	304	Plate
APWR-Internals	Head and Vessel Align-ment Pins	F304	Forging
APWR-Internals	Lower Core Support Plate	F304	Forging
APWR-Internals	Radial Support Keys	F304	Forging
APWR-Internals	Secondary Core Support Columns	F304	Forging
APWR-Internals	Diffuser Plate Support Columns	F304	Forging
APWR-Internals	Upper and Lower Diffus-er Plates	304	Plate
APWR-Internals	Base Plate	304	Plate
APWR-Primary Piping	Main Loop Pipe and Fittings	F316* or F316LN	Forging
APWR-Primary Piping	Surge Line	316*/316L	Pipe and Forged Fittings
APWR-Primary Piping	RHR Suction Line	316*/316L	Pipe and Forged Fittings
APWR-Primary Piping	Safety Injection Line	316*/316L	Pipe and Forged Fittings

*Carbon limited to 0.05% maximum

Use of Stainless Steel Forgings and Plate in the APWR, from XGEN.[11] Table 7 Continued.

Plant Type/Assembly	Component	Material Type	Product Form
APWR-Primary Piping	Pressurizer Spray Line	316*/316L	Pipe and Forged Fittings
APWR-Primary Piping	Safety Depressurization Piping Components	316*/316L	Pipe and Forged Fittings
APWR-Primary Piping	Depressurization and Safety Valves	F304*/F304L/ F304LN/ F316*/F316L/ F316LN	Forging
APWR-Primary Piping	Isolation Valves	F304*/F304L/ F304LN/ F316*/F316L/ F316LN	Forging
APWR-Primary Pumps	Thermal Barrier/Diffuser Flanges	F304*/F304LN /F31*/ F316LN	Forging
APWR-Primary Pumps	Main Flange	F304*/F304LN /F316*/ F316LN	Forging
APWR-Primary Pumps	Seal Housing	F304*/F304LN /F316*/ F316LN	Forging
APWR-Pressurizer	Surge Nozzle Safe End	F316* or F316LN	Forging
APWR-Pressurizer	Safe Ends-Safety and Depressurization Valve Nozzles	F316* or F316LN	Forging
APWR-Pressurizer	Spray Nozzle Safe End	F316* or F316LN	Forging
APWR-Pressurizer	Spray Head	F316* or F316LN	Forging
APWR-Pressurizer	Internal Spray Piping	F316* or F316L	Forging
APWR-SG Channel Head	Primary Inlet and Outlet Safe Ends	F316* or F316LN	Forging
APWR-Steam Generator	Tube Support Plates	405	Plate

*Carbon limited to 0.05% maximum

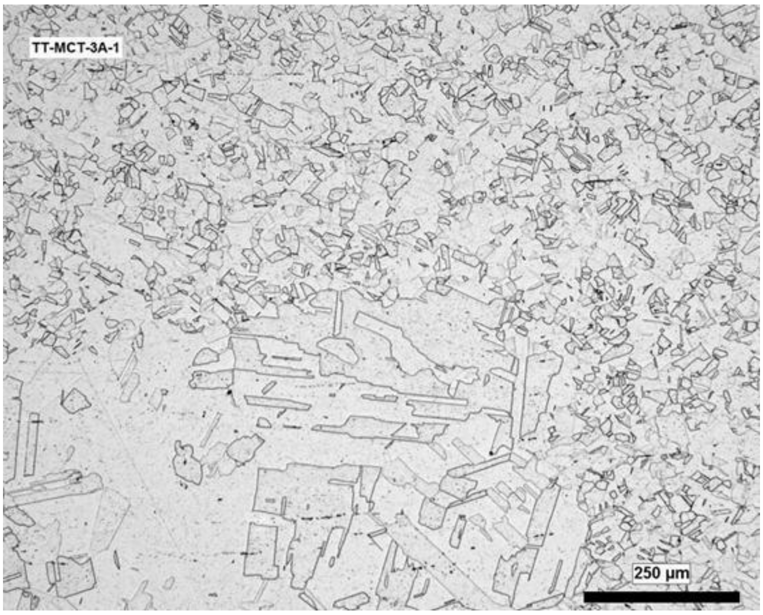

Figure 10
Region of abnormal grain growth (lower left) in uniaxial forged XM19.

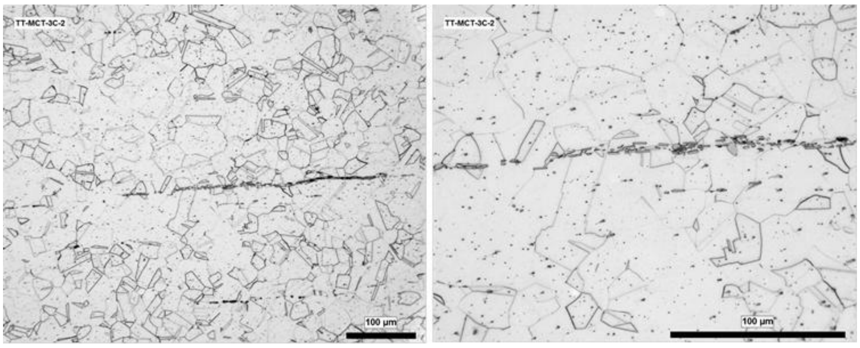

Figure 11
Stringer of MnS plus NbC carbides in uniaxial forged XM19.

Technologically, the best case condition is achieved and expected of Ni-based and Fe-Ni based superalloys used in critical engineering applications. In many cases, Finite Element Modeling (FEM) is used to predict strains produced by each forging step and grain size refinement resulting from recrystallization. The FEM work itself is supported by data on; flow stresses of the metals being forged, temperature and strain to recrystallization; and forge strain rate effects. Similar technology could be applied to much simpler metals such as stainless steels to produce consistent bulk forgings, but the cost impact would be significant and if the specification environment does not require microstructural uniformity, then there's no motivation for vendors to adopt these methods. A critical factor in achieving uniform microstructures is, in many cases, the ability to forge at lower temperatures. Forging at lower temperatures does require higher press tonnages and hence returns to the original issue of vendor capability.

A good, practical example is the 310s stainless steel plate that was received in the partially recrystallized condition shown in Figure 1. The material clearly never received sufficient strain during hot working to recrystallize the dendrite grains and the resulting microstructure consists of fine, nucleated-then-recrystallized, equiaxed grains surrounding the dendrite boundaries. The introduction of greater than 70% strain during hot working is typically required for full recrystallization of ingot structures. Since the objective of procuring this material was for testing, this microstructure was unacceptable. Poor as-received microstructures are a common occurrence in plate materials, and so a repair forging and heat treatment was needed to make the material usable. The starting microstructure is compared to the repaired microstructure, as seen in Figure 12. In this example, the fix required a cold working step to force deformation into the dendrite grain cores. Forging at high, "recommended" temperatures would have concentrated plastic strain in the fine grained necklace structure, drive further recrystallization there, and left intact dendrite cores. The 1054°C forge step was low enough to ensure uniform dynamic recrystallization during forging.

So when we ask what factors could have influenced the quality of austenitic stainless steels used to construct nuclear power plants from the plant build period of 1960's to 1970's to present, the overwhelming factor was the upheaval in the global steel industry that occurred between 1974 and 1986.[2]

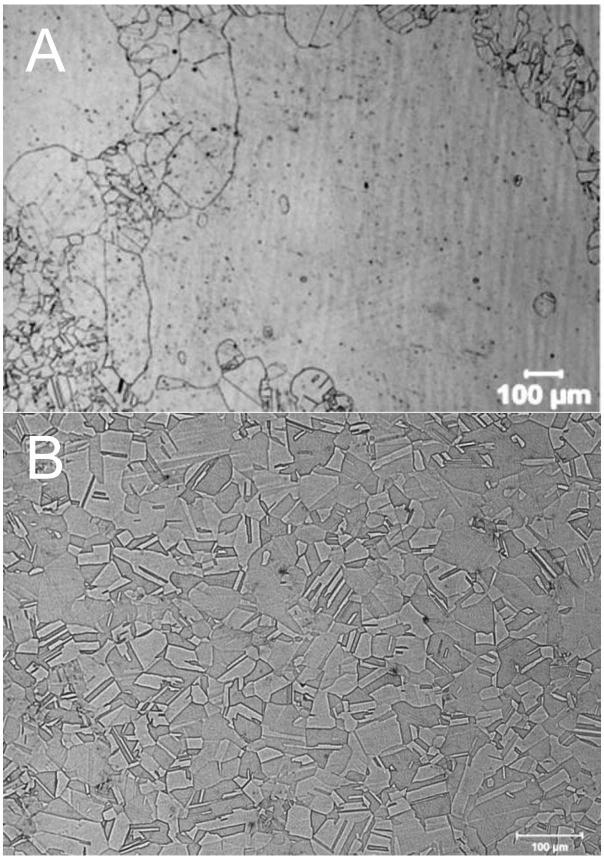

Figure 12
A) As-received microstructure of ATI Allegheny Ludlum 310 stainless steel, heat 835342, piece 41044AA, lot 250651. B) Material re-processed using a 20% cold reduction by forging in thickness direction, followed by a 1054°C for 30 minute heat treatment then hot forged at 1054°C with isothermal dies at 1054°C to a 50% reduction followed by a 1065°C for 1 hour recrystallization anneal then water quenched.

4. Evolution to the Current State of Materials

Specifications and Process Controls Then and Now

It is interesting that, given the broad changes in the metals industry that have occurred from the 1960's to present, the commonly referenced standards have remained fairly static in scope. They represent one of two approaches to specification writing that have much different aims. One approach is the internal plant manufacturer's specification that is written to ensure that all concerns are addressed and that the metal supplier cannot take short cuts in processing, either because they will reduce the supplier's cost or because they do not have the equipment to do the job properly. The others are the generic ASME, ASTM, Military, SAE, etc. specifications that ensure consistency of metal chemistry and of the most basic of properties. These specifications ensure that 316L is chemically 316L and that it will be processed to behave like 316L in terms of strength and corrosion. Unlike a plant manufacturer's specifications, the basic 'alloy check' specifications do not generally instruct metals suppliers on the processing details, with the exception of heat treatment guidelines. The best manufacturer specifications, tight controls, will generally require metal suppliers to have internal specifications and manufacturing process controls that exceed customer specifications, with the goal of reducing scrap rates. As the number of new plants under construction diminished and then stopped, large volume metal orders were supplemented by low volumes to be used for repairs and upgrades. Without a large volume of metal orders, there was less incentive to write or utilize detailed specifications. The trend was to utilize broader specifications that opened the pool of potential metal suppliers (which also diminished over that period).

It was found from reviews of plant material specifications from the 1960's that there was a similar reliance on ASME and equivalent ASTM specifications to ensure that the stainless steels used met the base material chemistry requirements. There was no underlying change in this reliance over the intervening years. Many specification and testing controls were in place to ensure that austenitic stainless steels met corrosion requirements, but there was little, if any, specification control over as-processed microstructures unless they pertained to their corrosion response (intergranular $Cr_{23}C_6$, delta phase, and the transformation of delta ferrite to sigma phase), welding or inclusions (effect on corrosion). In summaries of stainless steels used in the construction of the Savannah River plant, much of the emphasis was on test guidelines, heat treatments, and specifications to prevent corrosion related failures.[12] Interestingly, in the foreword to Volume I, "Stainless Steel Information Manual for the Savannah River Plant", the author describes the intent of "preserving previously developed 'know how'".[12] Over the 1960 to 1964 period in which these reports were assembled, know how was transferred in the areas of metal joining (welding in particular), inspection (UT in particular), and manufacturing of tubing.[13] Austenitic stainless steel plate (over 254 mm in width and over 4.76 mm in thickness), sheet (610 mm and over in width and under 4.76 mm in thickness) and strip (under 610 mm in width and under 4.76 mm in thickness) used in the manufacture of the plant were all briefly described with quality centered on base requirements in ASTM specifications. A great deal of effort was expended in describing the additional costs associated with “testing extras” for plates that were beyond material supplied to ASTM specifications; elevated temperature tensile tests, Charpy tests, chemical analysis check of major elements, surface penetrant testing, and ultrasonic testing of material rejected in the first tests and requiring repeat testing. An interesting note in the material testing section is that, requiring more rigorous ultrasonic acceptance standards was “subject to negotiation”, perhaps implying a best effort approach at supplying austenitic plate material was used, since even plates rejected by ultrasonic testing could be reclassified based on defect location.[13] Reviewing the ultrasonic testing guidelines from the same document, it is clearly stated that testing is limited by “large grain size, porosity, high inclusion content, dispersed precipitates, etc.”

The evolution of commonly referenced standards from ASME or ASTM (International Committee A01 (Steel, Stainless Steel, and Related Alloys, and General Requirements Specifications for Forgings) can be incredibly convoluted. As indicated on title page of most ASME specifications, with some exceptions, they are identical to ASTM specifications. So, for example, ASME SA-965/SA-965M is identical to ASTM specification A 965/A 965M-06a. It is suggested that the reader review Nesbitt’s explanation and history of how these standards evolved over time to encompass definitions of products and processes, input materials, new fabrication methods, and significant input from steel manufacturers.[14,15] Interestingly, many of the more rigorous requirements introduced in the first versions of the specifications were, in many cases, relegated to supplementary requirements, specifically those in ASME SA-788.[16] The supplementary requirements were intended to add additional requirements to the product specifications, not detract from them, and must be included in the purchase order.[14] The supplementary specifications were not invoked at the start of the BWR build period in the early 1960’s, and in the late 1970’s they were written into manufacturers’ specifications, independent of ASME, for specific components.[17] From the viewpoint of an experienced forging professional, none of the commonly referenced ASME specifications are sufficient to guide an inexperienced manufacturer in designing a sound forging process for austenitic stainless steels, as this was not their intended purpose. Some of the supplementary requirements did include more details, but many of these were developed in the 1950’s and 1960’s to cover specific manufacturing processes, melting, for example. It is believed that part of the reason why forge process steps are not described in detail, beyond reduction ratio, is that there are many processing paths possible dependent on starting ingot dimensions and equipment availability. Melting, by contrast, is more constrained by furnace design and melting parameters, with heat analyses being fairly definite quality checks. Comparing the historic evolution of the specifications for forged products, the one item that has been deleted for all but the most critical applications (rotating disks and shafts) is ingot upsetting.[14] Part of this omission is that based solely on reduction requirements, suppliers could achieve the necessary reduction ratios during other processing steps. Ingot upsetting, forging parallel to an ingot’s long axis, plays a greater role in breaking up dendritic structure in ingots, especially if additional work is to be unidirectional. Because the dendrite breakup or homogenization effect produced by upsetting (especially if incorporated with a high temperature/long time ingot homogenization heat treatment and end dimpling) is often overlooked in current practice, there appear to be more ingot segregation structures retained in austenitic alloys.

Another rather unusual feature of the specifications for austenitic stainless steels, or austenitic grades in general, is the lack of a largest allowable grain size. In general, specifications SA-965 (section 9.1), SA-479 (section 7), and SA-182 (section 9) specify an ASTM grain size of 6 or 7 or coarser.[18,19,20] The exceptions are for specific grades where the specification restricts grain sizes to ASTM 3 or finer. It could be interpreted to mean that as-cast or dendrite grains of any area fraction are acceptable, as were the plates illustrated in the Introduction to this report. This means that the primary means of ascertaining forging quality (percent recrystallization) is not a key criterion available to customers unless their internal specifications require better microstructure control.

A review of BWR material certification reports from the early 1970's to present for 304L plate showed no real differences in the way properties were reported out, in the amount of testing performed, or in referenced specifications. All referenced both standard specifications and internal specifications required by the plant's manufacturer. Newer material certifications even appear to have more details on how the metal was melted (very seldom, if ever, are the processing steps from ingot to plate mentioned, then or now). One big difference is the chain of material transfer. In the material certifications from the early 1970's, one metal supplier was listed as melting and rolling the plates. Only in the case of tube pipe was an additional metal supplier (tube and pipe forming) referenced. More current material certification reports can encompass multiple metal processors, cast slabs supplied by a large stainless steel company that were melted at a sub-tier supplier, and then hot rolled at a different metal supplier. Experience has taught that best practice, for metals companies supplying critical products, is vertical integration. In an example of this, a metal supplier will optimize their melting processes to produce ingots with structures and geometries adaptable to their processing capabilities, or billets with microstructures optimized for their forging processes. The customer in turn will have a single contact to work with to obtain their desired microstructure and properties. Within the retired metallurgist community, it was often mentioned that suppliers who could melt, then process to final product, had the option of throwing badly processed material back in the pot for melting without losing the cost of the material.

With orders for large quantities of stainless and other steels during the plant build period, reactor manufacturers could reinforce the more basic ASME specifications with their own, more detailed specifications. Such documentation, however, required both cooperative vendors and technically knowledgeable or experienced people to write the specifications. Further, the vendors were motivated by the potential for large orders of stainless steel. Those countries in limited reactor build or repair and upgrade environments and with cost restrictions will find their options limited to procuring metals made using existing processes and basic specifications. Of course, custom heats can be melted and forged to more demanding specifications, but the number of metal producers willing to bid and commit to producing a small lot of material may be very small.

1. Vendor Capability

It is clear that, even as early as 1964, much of the fine tuning of process controls that would ensure good material was left to the plant's manufacturer, in cooperation with material vendors. From discussions with retired colleagues from the melting and forging industries, these direct interactions were fairly common with numerous, experienced industry metallurgists to call on. In the current supplier/sourcing/fabrication mix, many material suppliers utilize sub-tier suppliers to provide all or parts of their metal processing. For example, the OutoKumpu 310L stainless steel shown in Figure 2 was supplied to Rolled Alloys, who supplied it to Arcadia Manufacturing, from whom it was purchased. In recent years, material certifications cover multiple suppliers and sometimes trace back so many layers that some detective work is required to determine how the stainless steel was melted and forged. Similarly, the ATI Allegheny Ludlum 310L stainless steel plate discussed in the introduction was supplied by Rolled Alloys, and permission to discuss the microstructure with the manufacturer had to be granted by Rolled Alloys.

Vendors and their capabilities have evolved as the more experienced, and what can be termed higher quality, vendors have moved into value added metal markets (Ni-based alloys) and away from commodity metals. Austenitic stainless steels appear to have reached commodity status in the late 1970’s to early 1980’s as production equipment and techniques to produce low carbon grades became widely available. This shift from traditional suppliers to new ones created the first break in the chain of forging and metallurgical experience in producing austenitic stainless steels. A contributing factor was the consolidation of traditional stainless steel manufacturers through mergers and acquisitions. The mergers and acquisitions that occurred from 1983 to 1994 were shown in Figure 3, and with these changes came the loss in more flexible, though not profitable, facilities and equipment. This was clear in almost all my interviews with retired stainless steel metallurgists where they would describe a stainless steel ingot conversion process they had used that, in many cases, required shipping the ingot to an outside forging company to perform upset operations on their large opening and high tonnage open die press. On further discussion with the retired metallurgist, it became apparent that many of those facilities no longer exist due to plant closings that resulted from mergers or acquisitions. The benefit of these upset forge steps performed on the ingot was not always on recrystallization, but could also improve chemical homogeneity if the upset followed a high temperature ingot homogenization heat treatment.
Meanwhile, the demand for stainless steel strip and plate product for consumer and industrial markets increased the specialization of forge, rolling, and melting equipment to meet market demands. Combined with this new product focus was the removal of commodity materials or product forms from experienced forge-masters (at updated manufacturing sites) to older and/or lower technology plants or sub-tier suppliers.

On a bright note, access to high tonnage conversion presses and associated facilities has become more available as the metals market responds to overcapacity that developed after the metal price bubble of the early 2000’s. Special Metals, for example, is advertising its experience and its stable of large, open die presses for toll ingot conversion services, www.specialmetals.com/conversion.php. Lehigh Heavy Forge Corporation is also offering toll services for custom open die forgings but their experience may not be related to ingot conversion without a supplied conversion process, www.lhforge.com/CustomOpenDieForgings.htm.

2. Stainless Steel Forging and Plate Suppliers[17]

The following list includes material suppliers for stainless steel plate and forgings that have in the past supplied materials for nuclear plant applications or are currently available to supply such materials. In some cases, suppliers that were at one time ASME certified have dropped their material manufacturer certification. In other cases, suppliers, such as some forge shops, never had ASME certification, but worked under the certificate of a material supplier. At this time, there are a number of materials supply houses in the U.S. that routinely extend their ASME certification to cover sub-tier material manufacturers. Some suppliers outside the U.S. currently have ASME certificates, particularly the Japanese companies, but others supply material for nuclear plants under other regulations and standards (e.g. KTA Merkblatt). This listing is not intended to be comprehensive, but to give sampling of potential suppliers of stainless forgings and plate for nuclear applications.

1. ATI Allegheny Ludlum - Plate.
2. G.O. Carlson/Electralloy – Plate from Carlson, Ingot and billet from Electralloy. Electralloy has demonstrated good chemistry control in consistently producing low cobalt 316L (0.01-0.02% Co) when specified.
3. Wyman-Gordon – Closed die forgings and seamless pipe.
4. Scott Forge – Forgings. Produced CRD and ICM housing forgings for ABWR.
5. Sandmeyer Steel – Plate. Has an ASME Section III certificate.
6. Japan Steel Works – Large forgings and plate. Produced the large top guide forgings for ABWR and large hollow cylinders for replacement shrouds. Maintains ASME certifications.
7. Forge Masters (UK) – Capable of large stainless steel forgings, but has issues with achieving low carbon (< 0.03%). Approved to NCA-3800.
8. Thyssenkrupp – Thyssen merged with Krupp a number of years ago to form a large material manufacturing business based in Germany, but with operations worldwide, including the U.S. They mainly supply plate, but can melt stainless steel in large capacity so theoretically can supply ingot or billet to other material processors. They have a relatively new stainless plate facility in Alabama.
9. Böhler-Uddeholm – Wholly owned by Voestalpine. An Austrian specialty steel maker with capability to produce high quality material in relatively small lots in VAR and ESR furnaces at their Edelstahl facility in Kapfenburg, Austria. There is an associated plate mill about 10 km away from the melting and forging facilities.
10. JFE Steel (merger of Kawasaki and NKK) – Supplier of stainless steel plate, but supply for nuclear applications is uncertain. In the past Kawasaki supplied large, low alloy steel forgings and plate for Japanese nuclear plants including the Kashiwazaki 6/7 ABWRs.
11. Sumitomo Metals (Sumikin) – Currently in the process of merging with Nippon Steel. Sumikin has supplied seamless pipe and fittings for recirculation system replacement in U.S. BWRs from their mill at Amagasaki.

Heavy wall stainless pipe is produced by upsetting and piercing the ingot followed by multiple diameter and wall thickness reductions on a horizontal draw bench. Sumitomo Amagasaki works has ASME certification and was inspected by the USNRC two years ago.

12. Mannesmann (now Salzgitter Mannesmann) – Stainless pipe and tube production.
13. Creusot Forge (subsidiary of AREVA) – Large forge shop primarily dedicated to production of material for nuclear plants. Has produced large stainless forgings for replacement reactor internal components in Sweden (e.g. BWR top guide forgings subsequently machined to final dimensions by Skoda).
14. AK Steel (Armco) – Stainless plate, sheet, and slab production. AK Steel is a holding company that is primarily Armco, but with some interest held by Kawasaki Steel (presumably now JFE Steel).
15. Taylor Forge – Forged shapes and fittings. Taylor currently has NA, NS, and NPT certificates. Produced special pipe fittings for BWR replacement recirculation systems that involved extruded outlets and integral reducers. Taylor does not melt their own stock, but relies on raw forms produced by others.
16. Coulter Forge – Small forge shop that produced many safe end forgings for BWRs. Open die forging and Wagner ring rollers using raw stock produced by others.
17. Anderson Shumaker – Primarily an open die forge shop producing custom forgings in various stainless steels. Raw stock is produced by others.
18. Dubose National Energy Services – This organization is listed as an example of a common practice in the U.S. over the last ten to fifteen years. Dubose produces no material in-house, but will supply material with full ASME Code certification. When material is ordered requiring certification, Dubose will subcontract the material production to various shops (melting, forging, plate rolling, etc.) and extend a Code "umbrella" over these shops by active oversight of material production by their quality assurance staff. The material is then brought in-house at the Dubose facility for ASME specified NDE and any necessary quality checking which may include over checks of chemistry and mechanical properties. Dubose is allowed to certify material this way under the specific terms of their ASME certificate.

The 'middle man' approach described in item 18 above does have the big disadvantage of further removing the plant manufacturer from the technical details of the metals processing paths used and places a big reliance on generic specifications that do not contain many controls on metals processing. From experience with arrangement, as a customer, it is very difficult to obtain details of the all the processing steps used to produce the material, with sub-tier suppliers holding the process details as proprietary. Similar situations develop as the customer becomes more distant from the manufacturer who actually produces the metal. This is very different from the earlier practice of factory floor participation by customers with metals processing experience that sometimes witnessed or audited processing steps. Such participation is still common for some large safety critical components in the Energy and Aviation industries. From experience in both those industries, it's apparent that, the greater technical participation a customer has, the more likely it will be that the metal suppliers will develop their own tighter internal specifications to guarantee they meet customer requirements.

3. Changing Role of Sourcing

Ties between sourcing departments with engineering through technical qualification of processes and audits of equipment and documentation are less rigorous now than they were even in the recent past, the 1990s. It would have been typical for nuclear plant manufacturers to conduct quality audits using highly experienced employees with years of metals processing and manufacturing experience. In many cases, these same people oversaw the manufacturing process and could stop processes that were not capable of meeting quality requirements. Best practice for highly critical components would be for sourcing personnel to have engineering staff accompany them to supplier sites and perform a technical evaluation and risk analysis of the manufacturing process. With contraction of the industry, retirement or loss of experienced employees made these practices impractical. Audits are still conducted, but at lower frequencies and with more attention to paperwork requirements than actual metals processing steps. Sourcing, faced with a shrinking supplier base, smaller orders, and less technical oversight, is fairly constrained to locating material and then negotiating price. In this situation, plant manufacturers' specifications that cover key metal processing steps become more critical, since those details are not covered in the generic specifications.

Discussions with the nuclear quality assurance (QA) departments (sometimes one person) at a few metal producers revealed that many of them thought that the specification environment had become less rigorous over time, and all were very fluent in the generic ASME, ASTM, etc. specifications, sometimes to impressive detail. One complaint the more senior members of QA departments voiced was that, while they had contact with customer sourcing departments, there was less guidance from customers' technical departments. For example, a metals producer may be faced with an irrelevant specification requirement that hinders them from making changes to their processes to improve metal quality. Some very good sourcing departments can address cases such as these, but they tend to be staffed with former metallurgists with metals processing experience, General Electric Energy is one such example. This in-depth experience gives plant manufacturers the ability to locate those metal suppliers with proven capabilities and equipment. An important benefit of this arrangement is the rapport that develops between customer and supplier.

5. Adaptation of Material Controls to the Current State of the Industry

Recommended Changes in Material Specifications

Only well written and process specific controls incorporated into specifications can produce high quality products. A diverse supplier base and weak processing specification, with a focus on alloy chemistry controls and not final microstructures, leave wide allowances on interpreting the processing path needed to forge an austenitic stainless steel component. The changes in specifications need to be written and controlled by the final customer. Use of specification committees with metal industry representation will impair the ability to put in place meaningful changes, especially if the changes restrict the number of manufacturers.

The following recommended specification controls are divided between microstructural and processing. The specifics paths through which these specification controls can be developed and then enforced will be discussed in the next section.

Microstructure controls:

1. Inclusion content rating required.
2. Grain size, carbide, MnS, and delta ferrite banding.
3. Delta ferrite and sigma phase.
4. Incorporate lower grain size limits with accommodation for isolated grains As-Large-As (ALA), unrecrystallized dendrite grains not permitted.
5. Controls on grain size banding.
6. Require macro etching of bloom (or billet) top and bottom crops as checks on unrecrystallized dendrite grains.
7. Incorporate larger diameter gages on tensile test bars (12.7 mm) for better sampling of microstructure.
8. Perform tensile testing in multiple orientations dependent on product form and orientation of component that will be machined from that product form.

Process controls:

1. A manufacturing process plan should be submitted by each supplier, approved by the purchaser, and any deviations from that manufacturing process plan should be reported and approved by the purchaser.
2. Ingots should receive a long time (minimum 24 hours) high temperature homogenization heat treatment.
3. An ingot upset forging operation should be incorporated, the use of dimpled end dies is recommended.
4. Recrystallization anneal heat treatment should be used during processing to aid recrystallization of regions that may have cooled during forging or rolling operations.

5. Each region from the original ingot should receive sufficient strain (reduction) to assist with recrystallization at the forging or rolling temperature.
6. The objective of all hot working steps should be to achieve a uniform equiaxed grain size.

Recommended Material Processing Controls

In theory, very well defined microstructural controls are an excellent way to control quality but there's a serious monetary investment requirement to develop and then fix a metal's manufacturing process using microstructure. Since spot checks of microstructure are inadequate for large forgings, the customer will have to commit to a manufacturing process qualification that will require cut up and testing of the first forging produced. The cut up forging will be examined for compliance to microstructure, ultrasonic, chemistry, and mechanical properties in multiple locations deemed critical to the life of the component. A forge cover allowance will be needed to ensure that any surface related defects be removed. If the first piece passes the qualification procedure, then the process is fixed. Once defined, the decision to change a fixed manufacturing process can only be made by technically qualified members of the customer's organization. Fixing a manufacturing process encompasses everything from melt practice (furnaces used), ingot conversion (if used), heat treatment, and to final machining. Developing a fixed process can be simplified by performing forging experiments (compression testing) to determine the recrystallization behavior of ingot dendrites and equiaxed grains of the austenitic stainless steel as functions of temperature, strain, and strain rate. There are laboratories that specialize in this testing.[23] Data from these experiments can then be run in FEM simulations of the forging operations to ascertain whether the FEM predicts acceptable microstructures throughout the forging. This approach, if well executed with good data, ensures that the first forging will be pass qualification tests. Although seldom done for stainless steels, the melting process can also be modeled to minimize chemical segregation and determine dendrite orientation.

The alternate approach is to specify processing steps, assuming the customer has the ability to do this, or fund the data collection and modeling capabilities required to design a process. Developing a metals processing path requires that the customer have an in-depth knowledge of melting, melt furnaces, forging or metal deformation, forge press, manipulator or crane capacities, heat treatment furnaces, etc. Generally, the metal supplier who is engaged to follow an externally developed process will do so only on a best effort basis. Following this path can either develop good technical collaboration or a highly charged stalemate. An intermediate path, whereby the metal producer develops a process following the recommendations cited above then collaborates with a technically capable customer to review the manufacturing process, identify risks, and run qualification tests of the process, is sometimes the best approach.

Although the exact paths described above may not have been followed during the 1960's to 1970's plant build period, there's sufficient anecdotal evidence from metallurgists active during that period that greater technical interaction and process controls were in place. It's not clear whether, with more rigorous controls in place, the existing stainless steel manufacturers have sufficient market share in products for nuclear power plants to be motivated to accommodate significant changes. There are precedents for this, an example being the production of high cleanliness grades of austenitic stainless steels using VIM/VAR melting technology for markets that require high cleanliness or property requirements.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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