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Metallurgical Aspects Influencing the Potential for Hydrogen Flaking in Forgings for Reactor Pressure Vessels

1. Background/Purpose

Ultrasonic testing (UT) was performed on the reactor vessel shell of Doel 3, a Belgian pressurized water reactor, during June-July 2012. (b)(4)

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The purposes of this document are:

1. To summarize the NRC staff's state of knowledge regarding hydrogen flaking of steel forgings;
2. Provide background for NRC staff participation in the metallurgical/root cause working group;
3. Assess the potential of forgings in U.S. plants reactor pressure vessels to have (b)(4)
4. Indentify indicators that U.S. plants could use to screen for susceptibility to flaking.

2. What is hydrogen flaking?

Hydrogen flakes (Figure 1) are short, discontinuous internal fissures caused by stresses produced by localized transformation and decreased solubility of hydrogen during cooling (Ref. 1). Hydrogen flaking is also referred to as internal hairline cracking, snow flakes, and shatter cracking.

The primary source of hydrogen is water vapor which in the atmosphere, furnace charge materials, slag ingredients and alloy additions, refractory linings, and ingot molds. The water vapor reacts with the liquid metal at high temperatures to form hydrogen. Hydrogen solubility is much higher in molten steel (5-12 ppm) than in solid steel at room temperature (0.1 ppm). Therefore, as the steel cools the hydrogen precipitates in molecular form at imperfections such as inclusions, grain boundaries, or microvoids. The high pressures of this gaseous hydrogen causes localized cracking. Formation of flakes generally occurs at temperatures below 390°F (Ref. 2). Flakes appear as small shiny spots on a fracture surface (hence the name "snow flakes

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or flakes"). Flakes tend to be located in bands in the midline of the forging, up to 1/3 of the radius from the surface.

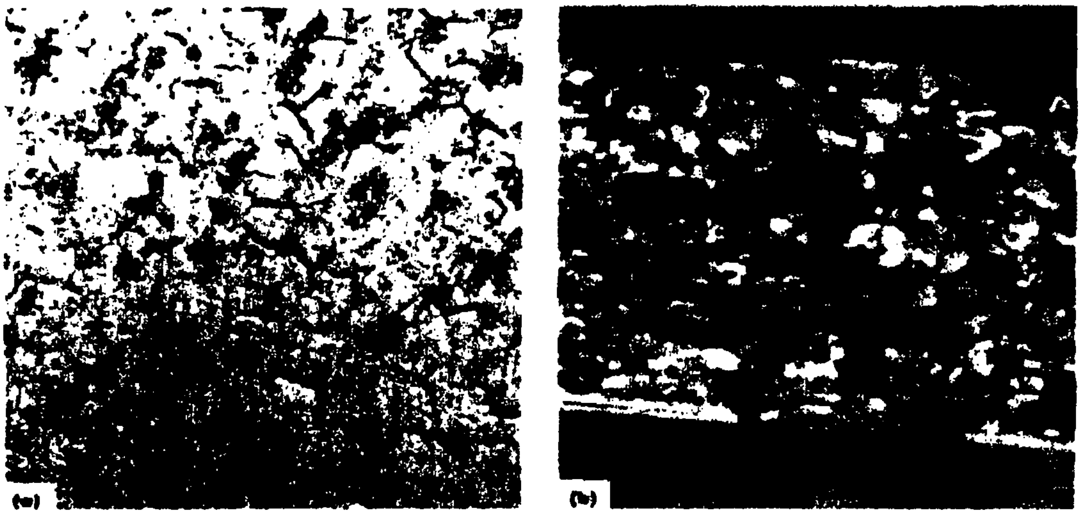

Figure 1 – Hydrogen Flaking. Left – Flakes on polished cross section of an alloy steel bar. Right – Fracture surface containing flakes

Other types of forging discontinuities include laps and seams, which are surface defects, bursts, pipe, and porosity. Of these, only bursts are subsurface defects that are cracklike. Bursts are caused by a forging temperature that is too low, or a forging process that is inadequate to work the metal through its entire cross section, or internal weakness due to pipe, porosity, segregation or inclusions. Bursts would typically be larger and less numerous than flakes, and are often located near the center of the forging if related to the forging process. Therefore, it is unlikely bursts would be mistaken for flaking.

3. History of Hydrogen Flaking

Producers of forgings have long known of the potential for hydrogen flaking. It was recognized as early as the 1920's that flaking was related to hydrogen (Ref. 3). During the 1950's, with the use of forged turbine rotors in steam power plants at higher temperatures and pressures, flaking became more of a problem and several costly failures occurred. Additionally, ultrasonic examination technology was also introduced during this time period, which allowed deep seated defects to be more readily detected. These problems with flaking led to the development of more efficient degassing processes to be applied during steelmaking to reduce the hydrogen levels in the ingot. These degassing procedures, mainly the vacuum stream and vacuum lift procedures, were well established the time period (late 1960's) when forgings for first-generation commercial nuclear power plants were being manufactured.

4. Forgings for Nuclear Reactor Pressure Vessels

Forging for reactor pressure vessels (RPVs) were procured to specification ASTM A 508, "Standard Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels (Ref. 4)". This specification was initially published in 1964. Earlier forgings were mainly ASTM A 508, Grade 2. Due to problems with underclad cracking, A 508 Grade 3 was developed. Both are low-alloy steels containing manganese, nickel, and molybdenum, but Grade 2 also contains some chromium. The major modifications to Grade 3 are elimination of chromium, a lower maximum carbon, higher manganese, lower nickel, and lower molybdenum.

Underclad Cracking

Underclad cracking was first identified in 1970 at a European RPV fabricator (Ref. 5). Underclad cracks occur immediately beneath the cladding as a result of the cladding process. Cladding is a thin layer of austenitic stainless steel applied to the inner surfaces of the RPV via a weld process. Two types of underclad cracking have been identified, reheat cracking and cold cracking. Reheat cracking occurred during post weld heat treatment of single-layer austenitic stainless steel cladding applied using a high heat input welding process to ASTM A 508, Class 2 forgings. Cold cracking occurred in multi-layer clad ASTM A 508, Class 3 forgings after deposition of the 2nd and 3rd layer of cladding, when no preheat or postweld heat treatment was applied. The cracking is caused by high residual stresses in the heat affected zone of the cladding combined with high levels of diffusible hydrogen originating from the austenitic or stainless steel weld metal. Both types of underclad cracks originate at the clad/base metal interface and penetrate into the base metal, and are shallow, with reheat cracks typically confined to 0.125 inches in depth and cold cracks typically less than 0.160 inches, although the largest measured was 0.295 inches. Length could be up to 2 inches for cold cracks but more typically are less than 0.6 inches.

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Nuclear Industry Experience with Hydrogen Flakes

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5. Production Sequence for RPV Forgings

Production of large steel forgings for pressure vessels involves many steps as detailed below. For an RV shell forging, these steps include, as a minimum, melting, pouring, forging, machining, and NDE. Optional steps may include refining of the molten heat of steel in a ladle refining furnace (LRF) prior to pouring the ingot, and remelting of the ingot.

Melting

Heats of steel to be poured into ingots or blooms for later forging have historically been produced by a number of different steelmaking processes. Steelmaking processes evolved during the last century to allow production of steel with fewer impurities, resulting in fewer inclusions in the steel.

- Acid or basic air-blown furnace, open hearth furnace, basic oxygen (oldest process)
- Acid open hearth – relief from hydrogen problems at expense of cleanliness
- Basic open hearth – cleaner steel but more hydrogen
- Basic electric furnace – cleanest steel but most hydrogen. This is the most modern process. The furnace is charged with scrap or pig iron. This is the process specified by ASTM/SA-508. Japan Steel Works (JSW) uses this process.

Vacuum Degassing

Vacuum degassing processes refer to the exposure of molten steel to a low-pressure environment to remove gasses (chiefly hydrogen and oxygen) from the steel (Ref. 7, 8) Problems with turbine rotor hydrogen flaking in late 1950's prompted installation of vacuum degassing equipment. Vacuum degassing processes can be broadly divided into stream processes and recirculation processes. Stream processes include ladle-to-ladle degassing and ladle-to-mold degassing and involve degassing the whole heat continuously, while recirculation processes, draw a portion of the molten heat into a smaller vacuum chamber in which the degassing takes place. In ladle-to-mold degassing, shown in Figure 2, the molten steel is poured from a ladle into the ingot mold which is inside a vacuum tank. As the molten steel exits the "pony ladle," it forms a stream of droplets in the vacuum tank, exposing a large surface area of the molten steel thus allowing efficient degassing of the heat. Figure 3 shows a schematic of the Ruhrstahl-Heraeus (R-H) recirculation degassing process. In the R-H process, a vacuum vessel with two legs or "snorkel tubes" is lowered such that the snorkel tubes are immersed in the molten steel. An inert gas is introduced into one of the legs and the lower density of the gas steel mixture cause the steel to flow up that leg into the vacuum chamber where it is degassed and flows back down the other leg via gravity.

The D-H process is another common recirculation degassing process in which the vacuum vessel is lowered so that the molten steel in the ladle is forced up into the vessel through a single snorkel tube on the bottom of the vessel, by atmospheric pressure. The vessel is then raised allowing the steel to flow back into the ladle. The cycle is repeated 40 to 50 times. In both the R-H and D-H processes, alloying additions can also be made through the hopper while degassing.

ASTM A508 requires that "the steel shall be vacuum treated prior to or during the pouring of the ingot, in order to remove objectionable gasses, particularly hydrogen." A508 does not restrict the degassing to certain processes, but does place specific requirements on particular processes if they are used. Notably, the blank-off pressure (final pressure) required for both vacuum stream and vacuum lift processes is the same, 1000 µm (1 Torr). (vacuum lift is synonymous with recirculation degassing). Reference 3 indicates that vacuum stream degassing is the preferred process for making large forging ingots using multiple heats.

A secondary benefit of vacuum stream degassing is that carbon in the molten steel reacts with oxygen to produce carbon monoxide, which is removed by the degassing process, thus deoxidizing the steel without requiring the addition of aluminum or silicon (which leaves behind aluminum or silicon oxide inclusions). Silicon must be limited to 0.10% for this process to be effective. Recirculation degassing processes perform this vacuum carbon deoxidization process less efficiently.

Reference 3 notes that reducing hydrogen content below 1.5 ppm in the ingot is very difficult, because the practical limit for degassing of the molten steel is 1 ppm, and some hydrogen pickup during casting (0.2 to 0.8 ppm) is inevitable.

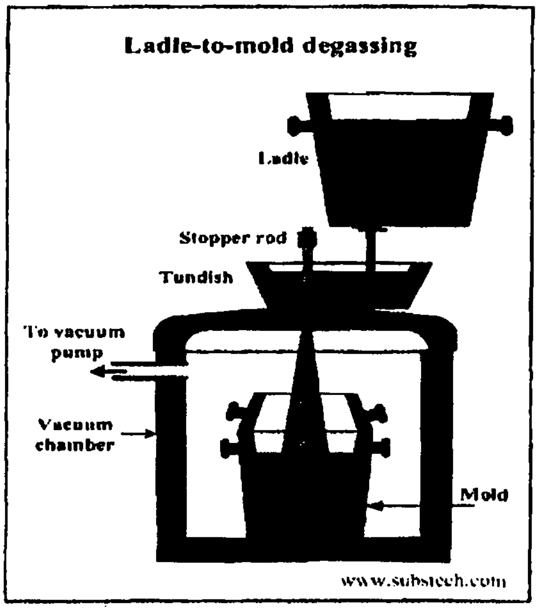

Figure 2 – Schematic Arrangement of Ladle-to-Mold Degassing Process

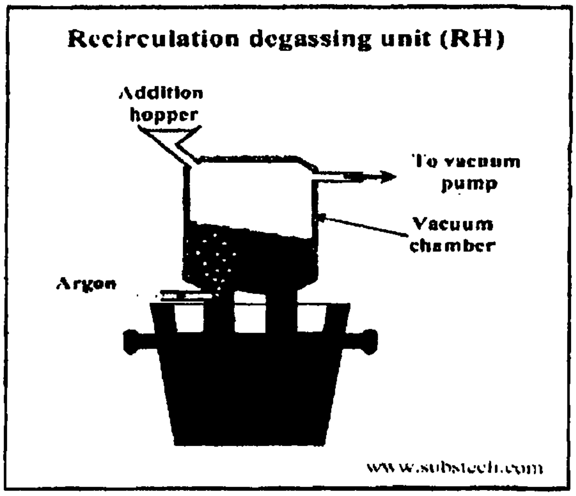

Figure 3 – Schematic of the Ruhrstahl-Heraeus (R-H) Process for Vacuum Degassing, a Recirculation Degassing Process

Refining

While still in the molten state, the steel can be refined to remove impurities such as sulfur and to make alloying additions. This is typically done in a ladle refining furnace (LRF) which is a separate vessel to which the heat of molten steel is transferred prior to pouring. The various types of LRF have the capability to stir and reheat the molten steel. Some LRF processes can also degass.

Argon Oxygen Decarburization (AOD) is a process typically used for stainless steel production to economically decarburize the steel via controlled blowing of argon and oxygen. Carbon dioxide and monoxide formed by reaction with the oxygen are swept away by the argon before equilibrium is established. AOD can also effectively reduce the sulfur in low-alloy steels. AOD can also reduce hydrogen, but not lower than 2 ppm, therefore this process does not replace vacuum degassing.

Pouring/Casting

Ingots for large forgings such as RPV shell forgings are some of the largest forging ingots (Figure 4). These ingots may require multiple heats of steel, thus may have more variability in chemical composition then smaller ingots. Due to the longer times required for solidification, large ingots also tend to have a larger degree of segregation than smaller ingots. Segregation is caused by the rejection of the solutes from a solidified alloy into the liquid phase. This rejection is a result of different solubility of impurities in liquid and solid phases at the equilibrium temperature. Macrosegregation refers to differences in the chemical composition over a large scale. Positive segregation refers to enrichment in alloying elements and impurities (solutes) while negative enrichment refers to relative depletion of alloying elements and impurities (solutes). Figure 5 is a diagram of macrosegregation in a large steel ingot. There are differences not only in chemical composition but grain structure, distribution of inclusions, and other defects such as porosity and shrinkage cavities.

Since segregation is most prevalent in the last material to solidify, these large ingots are often cast with a "hot top," or "sinkhead" which is a portion of the ingot at the top of the mold which is cut off before forging. Trepanning to remove material from the core of the ingot also eliminates one of the most segregated regions. Nonmetallic inclusions tend also to segregate during ingot solidification, especially towards the top and bottom, giving rise to the so-called inverted "V" or "A" and "V" segregates, respectively (Ref. 7). The hot work imparted by the forging process reduces the effects of segregation by breaking up and redistributing the segregated regions, and grain refinement through recrystallization.

Ingots may be top or bottom poured, denoting whether the molten steel enters the mold from the top or the bottom. Bottom-poured ingots are less likely to experience reoxidation during pouring and have smoother surfaces; however, if vacuum stream degassing is used, ingots must be top-poured.

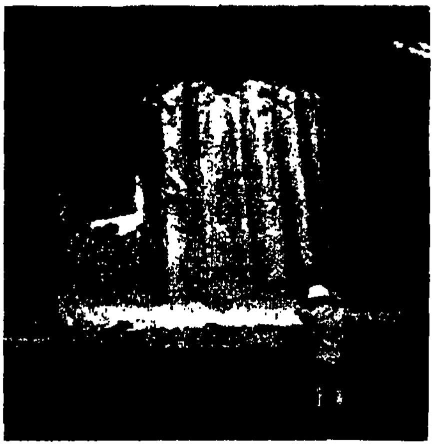

Figure 4 – A 600-ton Low-Alloy Steel Forging Ingot at Japan Steel Works

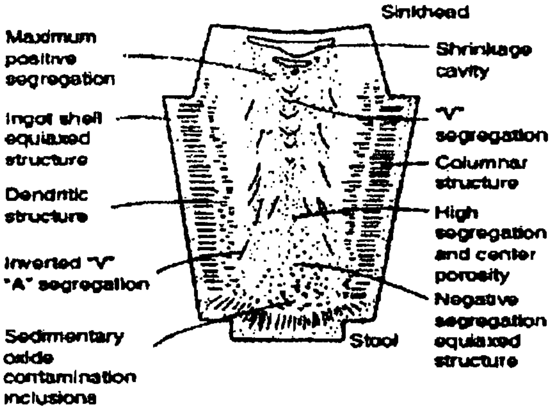

Figure 5 – Macrosegregation in a Large Steel Ingot (Ref. 13)

Remelting

Several refining processes are available that involve remelting the ingot. Vacuum arc remelting (VAR) refines the grain structure and reduces segregation in the ingot, as well as degassing. Electroslag remelting (ESR) has similar benefits to VAR, but does not degass. Due to the high cost, both these processes are usually used only for specialty steels, thus would probably not be used for large low-alloy steel pressure vessel forging ingots.

Forging

The actual forging process for a large, cylindrical ring forging for a pressure vessel involves multiple steps. The operations involved will differ depending on the manufacturer. The sequence provided below is partially based on information from the Doel 3 root cause investigation in Reference 9, depicted in Figure 6, as modified by information from References 7 and 8. These processes are mainly open die forging processes using hydraulic presses.

1. Cogging – A process to smooth the surfaces of the ingot, which is typically fluted to prevent cracking of the ingot during solidification or cooling
2. Blooming – Metal removal to smooth out ingot? (Doel Presentation)
3. Upsetting – An open die forging process that compresses the ingot axially to increase the diameter of the forging
4. Piercing or punching – Makes a hole in the center of the ingot by displacing material. No material is removed.
5. Hot trepanning or trephining – Makes a hole by means of a hollow punch that removes some of the central material of the ingot
6. Mandrel drawing – Reduces the wall thickness and extends the length of the cylinder
7. Ring rolling – Rotary forging of a hollow cylindrical forging to increase its diameter while maintaining the axial length (Figure 7).

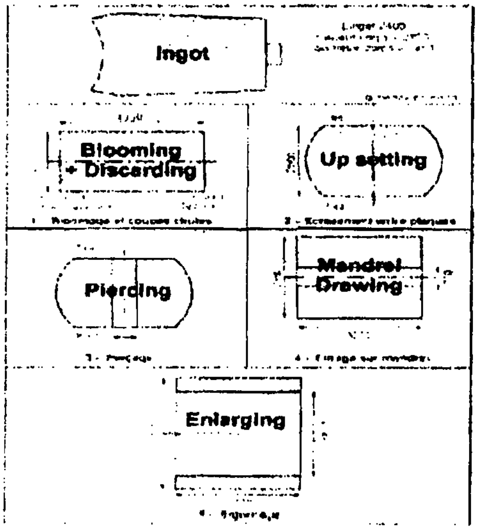

Figure 6 – Reconstituted Forging Sequence for Doel 3 RV Shells (Ref. 9)

Whether punching or hot trepanning is used is important in that punched (pierced) ingots will have a larger degree of macrosegregation since the most highly segregated portion of the ingot is not removed as it is in trepanning.

Prior to forging, the ingot must be heated to the forging temperature. Heating for large ingots would typically be done in a gas-fired car-bottom furnace. Forging temperature must be carefully chosen to optimize the properties of the finished forging but is always above the recrystallization temperature of the steel. Excessive forging temperatures can result in "burning" of the steel, in which low-melting constituents of the steel melt, while temperatures which are too low can cause forging bursts. Finishing the forging at a lower temperature results in a finer grain size. Sometimes reheating between the various forging operations is necessary.

Figure 7 – Ring Rolling Forging Operation for Nuclear Pressure Vessel (Doosan Heavy Industries)

Post-Forging Practices

Prior to vacuum degassing, forgings were often cooled in the furnace, under an insulated hood or in a refractory insulating medium to prevent flake formation. This slow cooling was then followed by an extended subcritical heat treatment (sometimes after reaustenitizing to refine the grain structure). For higher-hardenability alloy steels, these practices are still used to prevent flaking. Controlled cooling also reduces hardness and internal stresses (which also contribute to flaking). Since flaking is a delayed process, occurring 2 to 20 days after hot working (Ref. 3), it is desirable to perform special heat treatments to prevent flaking promptly after hot working, sometimes without allowing cooling to room temperature. With modern temperature control, some steels, depending on the transformation characteristics, can be quenched to a certain temperature, allowed to transform, and then cooled to room temperature, while other steels need to be heated up from the transformation temperature to a higher temperature, and then held for a certain time, for flake prevention (Ref. 8). To reduce the possibility of flaking, Reference 3 recommends cooling to a temperature above 390 °F (200 °C), but below the temperature for complete transformation to bainite, holding to ensure complete transformation, then reheating to a temperature around 1112 °F (600 °C) to temper the bainite (Figure 8).

Whether or not the special heat treatment for flaking is performed, forgings are then heat treated to achieve the desired mechanical properties, typically by quenching and tempering.

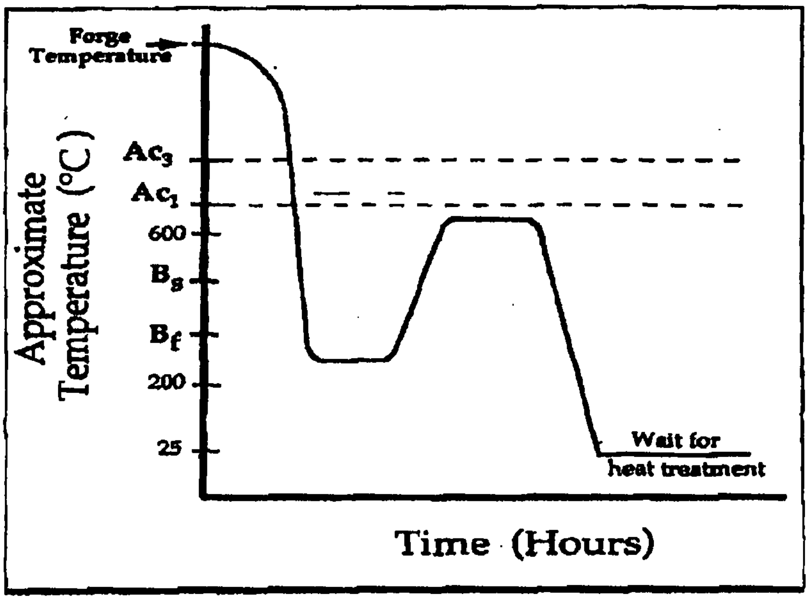

Figure 8 – Schematic Diagram of a Hydrogen Flaking Prevention Heat Treatment (from Reference 7)

Machining

Machining is typically performed after forging and heat treatment to the extent necessary to perform UT, with final machining performed after the UT examination. Per ASTM A388, "Standard Practice for Ultrasonic Examination of Heavy Steel Forgings (Ref. 10)," round forgings shall be machined to provide cylindrical surfaces for examination and the end of the forging shall be machined perpendicular to the axis of the forging for the axial examination .UT of the forging volume must performed prior to the machining of any openings such as holes, cutting keyways, tapers, grooves.

Non-Destructive Examination

Ultrasonic examinations are required by both the ASTM material specification (A 508) and ASME Code, Section III. A 508 requires longitudinal wave and angle beam tests. Complete loss of back reflection or and indication equal in amplitude to that of the back reflection in a defect –free portion of the forging, would be cause for rejection. For the angle beam, calibration is accomplished using notches of 3% of the nominal section thickness. ASTM A388 is referenced.

ASME Code, Section III UT acceptance criteria for vessel shell forgings (NB-2540) essentially would cause forgings to be rejected for reflectors in the same plan within a certain radius.

Surface examination via magnetic particle testing (MT) is required by A508 after final machining. For forgings with extensive machining, such as nozzle forgings, if hydrogen flaking were present in the forging, machining would probably expose the flaking to the surface such that it would be detected by the MT.

Welding

RV shell forgings are joined via circumferential full-penetration welds to form larger subassemblies which are finally assembled into a complete RV. After each weld, the subassemblies are subject to post-weld heat treatment. The stainless steel cladding is typically applied to the shells before the shells are joined into subassemblies, with the cladding then completed in the weld area once the segments are joined.

6. Factors Influencing Hydrogen Flaking

Metallurgical Factors

Any factor that lowers the toughness of the material matrix will lower the resistance to cracking due to hydrogen. These factors include larger grain size, and lower toughness microstructures, such as martensitic or bainitic microstructures. Hydrogen is also known to be trapped by grain boundaries, therefore, steel with larger grains has less grain boundary area, thus the concentration of hydrogen at the grain boundaries is greater. Tramp elements such as phosphorus, tin, arsenic and antimony are known to segregate to grain boundaries along with manganese and silicon, which reduces grain boundary cohesive strength, making the steel more prone to hydrogen embrittlement (Ref. 3).

Nonmetallic inclusions and segregation are metallurgical factors that contribute to flaking. Manganese Sulfide (MnS) inclusions are weak hydrogen traps in that they trap hydrogen below 300 °C (Ref. 3). However, if the number of MnS inclusions is reduced, more hydrogen will accumulate at each inclusion (Ref. 3). Therefore, in low sulfur steels, flaking can occur at a lower hydrogen concentration (Ref. 3). Freuhan (Ref. 3) defines a low sulfur steel as having a sulfur content < 0.02 weight %. Modern steelmaking practices can reduce sulfur as low as 0.005 weight %. Oxides can also trap hydrogen. Therefore, very clean steels, which are low in oxygen and sulfur, mainly produced since the 1980's, may have an order of magnitude lower density of inclusions. Therefore, the ultraclean steels can have an increased susceptibility to flaking at lower hydrogen concentrations because the hydrogen concentration at each inclusion will be greater (Ref. 3).

Inclusion shape can also influence flaking, because long narrow inclusions have greater potential to create a stress concentration. Reference 3 indicates that in general, larger, more elongated inclusions are more prone to flake problems. The tip of an inclusion often acts as a stress riser.

Segregation refers to local differences in chemical composition within the steel. The later the material solidifies during the solidification of the ingot, the more enriched in solute it becomes (a solute would typically be an alloying element, for example chromium or nickel), due to the greater solubility of such elements in the liquid versus the solid. Segregation affects flaking in two ways. Areas of positive segregation (i.e. higher in alloying element content) will transform at a lower temperature, therefore are more likely to transform to low-toughness phases such as martensite. Second, areas of positive segregation will contain more elements that create hydrogen traps. It should be noted that all large ingots will contain significant areas of segregation.

Hydrogen Content

Various thresholds have been defined with regard to the maximum hydrogen concentration in the forging to prevent hydrogen flaking. For hydrogen-insensitive steels, which generally means lower-hardenability steels, a threshold hydrogen content of 5 ppm has been proposed (Ref. 2). However, for more hydrogen-sensitive steels, a maximum of 1.5 ppm to 2 ppm is generally recognized (Ref. 3, 7). (b)(5)
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Hydrogen is controlled by degassing as discussed in Section 4, but ladle additions after degassing can be a potential source of increased hydrogen and the molten steel can pick up hydrogen from atmospheric moisture during teeming (transfer of molten steel to the ingot mold).

Section Thickness

As section thickness increases, reduction of hydrogen by thermal treatment becomes impractical due to the long times required. For example, Reference 3 presents data showing the almost 300 hours would be required to reduce hydrogen at the center of a 36 inch (90 cm) radius forging from 4 ppm to 2 ppm if held at 1260 °F (700 °C).

Steel Hardenability

Higher hardenability steels are more likely to have lower fracture toughness and a more susceptible to hydrogen embrittlement. Therefore, a lower hydrogen concentration will be required to cause flaking. Examples of high hardenability steels include medium carbon steels, nickel-chromium-molybdenum alloy steels (e.g. Type 4340), and age-hardenable copper-nickel-chromium-molybdenum low alloy steels (ASTM A859) (Ref. 7).

Post-Forging Handling

As discussed in Section 4, improper cooling practices, such as excessively rapid cooling, or transforming at a temperature below 390 °F, or lack of a dehydrogenation heat treatment, could increase the flaking susceptibility.

Summary – Factors Increasing Flaking Susceptibility

- Metallurgical factors
  - Steel cleanliness –impurities create lots of inclusions which are collection sites for hydrogen
  - Ultra-clean steels
  - Segregation
- Hydrogen content in forging > 5 ppm, >1.5 ppm for sensitive steels
- Poor or no hydrogen control
  - No vacuum degassing
  - Moisture-bearing ladle additions after degassing
  - Teeming under humid conditions if degassed
  - Melting under high-humidity conditions
- Heavy sections
- High hardenability steels
  - Medium to high carbon steels
  - Nickel-chromium-molybdenum alloy steels (very susceptible)
  - Age-hardenable copper-nickel-chromium-molybdenum low alloy steels (ASTM A859) – not used in RPV
- Post-forge practices
  - Rapid cooling after hot working (forging)
  - Allowing to transform below 390 °F.
  - Lack of a de-hydrogenation thermal treatment, particularly if not vacuum degassed

Summary - Factors Mitigating Hydrogen Flaking

- Effective Vacuum Degassing, hydrogen < 1.5 ppm in melt or ingot
- Proper treatment after hot working
  - Controlled cooling after hot working
  - Prevention of transformation at temperatures below 390 °F
  - Separate de-hydrogenation thermal treatment, if needed for the grade of steel and considering whether degassing is performed
- Lower hardenability steels
- Thinner sections

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State of Knowledge Regarding Susceptibility of Forgings in US Plants

Based on the Reactor Vessel Integrity Database (RVID) the staff determined there are 31 US plants that have large cylindrical forgings that make up major parts of the RV shell in the beltline region. However, most if not all RV's use forgings for major nozzles such as PWR reactor coolant hot and cold leg (inlet and outlet nozzles), and BWR reactor recirculation inlet and outlet nozzles. Many RVs also have forgings for the nozzle shells, even if the core region shells are made from welded plate. These nozzle shell forgings and nozzle forgings were not considered to be in the beltline so are not generally in RVID. However, some nozzles and nozzle belt forgings have been included as extended beltline materials in license renewal application. Also, many RV closure heads are forgings and many bottom heads are also forgings. Since these are non-beltline materials they are not tracked in RVID. → publicly available

The forgings in US RVs are all A508 Class 2 or A508 Class 3. Several different manufacturers used forgings for the major shell segments including Rotterdam Dockyard, Babcock & Wilcox, Chicago Bridge & Iron, Combustion Engineering, Societe Creusot, and Hitachi. All these large forgings were supplied by one of five manufacturers: Bethlehem Steel, Creusot-Loire, Japan Steel Works, Ladish, or RDM. Attachment 1 provides additional detail and tabulation of the data on forgings from RVID.

publicly available

Eight U.S. reactors have forgings partially or completely fabricated by RDM, which forged the Doel 3 core shells and also the Tihange 2 core shells under the same contract. Three reactors had some fabrication performed by RDM, but it is unclear whether these plants have any forgings made by RDM. The NRC staff has not learned of any factors unique to the forging practices of RDM, or the practices used by Krupp in making the ingots, which would be unique or would increase the susceptibility to hydrogen flaking. The staff needs to obtain information on the production of forgings by the all the manufacturers in order to make meaningful comparisons to the Krupp and RDM practices.

The only manufacturers of large forgings for nuclear pressure vessels known to be currently active by the NRC staff are Japan Steel Works, and Doosan Heavy Industries (Korea).

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Appendix 1 - U.S. Plants with Forgings

Revision 2 of the Reactor Vessel Integrity Database (RVID) lists 72 forgings in 33 US plants. RVID only contains those materials that are in the RV beltline. Of these, 64 are shell forgings, or large cylindrical forgings forming major segments of the RV, while 8 are nozzle forgings. Two of the 33 plants have only nozzle forgings listed. Therefore, there are 31 plants that have large cylindrical forgings that make up major parts of the RV shell. However, most if not all RV's use forgings for major nozzles such as PWR reactor coolant hot and cold leg (inlet and outlet nozzles), and BWR reactor recirculation inlet and outlet nozzles. Most of these nozzles are not in RVID since they were not considered beltline materials for the initial 40 years of operation.

The forgings in US RVs are all A508 Class 2 or A508 Class 3. Several different manufacturers used forgings for the major shell segments including Rotterdam Dockyard, Babcock & Wilcox, Chicago Bridge & Iron, Combustion Engineering, Societe Creusot, and Hitachi. All these large forgings were supplied by one of five manufacturers: Bethlehem Steel, Creusot-Loire, Japan Steel Works, Ladish, or RDM.

In addition, it was desirable to know for which RVs the forging was actually performed by Rotterdam Dockyard (RDM). The staff determined that eight reactors had forgings partially or completely fabricated by RDM. Three reactors had some fabrication performed by RDM, but it is unclear whether these plants have any forgings made by RDM.

Table A-1 lists all the RV forgings from RVID.

Forging Manufacturers for New Plants

Manufacturers that are currently making nuclear pressure vessel forgings include JSW (Japan), and Doosan Heavy Industries (Korea).

Table A-1 – Plants With Forgings Fabricated by RDM

Plant Name	Comment
Catawba 1	
McGuire 2	
North Anna 1	
North Anna 2	
Sequoyah 1	
Sequoyah 2	
Watts Bar 1	
Watts Bar 2	Operating license application review in progress.

Table A-2 – Plants with Some Fabrication by RDM

Plant Name	Comment
Quad Cities 2	Bottom head assembly and lower shell course were seam-welded together by RDM and returned to the United States as a fully completed subassembly including control rod drive (CRD) stub tubes, shroud support skirt, and vessel support skirt.
Surry 1	RV fabricated primarily from plate, nozzle belt is a forging. Circumferential welds were made by RDM. It is not known whether the nozzle belt forging was forged by RDM.
Surry 2	RV fabricated primarily from plate, nozzle belt is a forging. Circumferential welds were made by RDM. It is not known whether the nozzle belt forging was forged by RDM.

Table A-3 – All Forgings from RVID

Plant	Designer	Reactor	Heat ID	Beltline	Material Spec.	Forging Supplier
Arkansas Nuclear 1	B&W	PWR	528360(AYN 131)	Lower Nozzle Belt Forging	A 508-2	
Braidwood 1	Westinghouse	PWR	5P-7016	Lower Nozzle Belt Forging	A 508-2	
Braidwood 1	Westinghouse	PWR	49D867-1-1/49C813-1-1	Lower Shell Forging	A 508-3	JSW
Braidwood 1	Westinghouse	PWR	49C344-1-1/49D383-1-1	Upper Shell Forging	A 508-3	JSW
Braidwood 2	Westinghouse	PWR	49D963-1-1/49C904-1-1	Upper Shell Forging	A 508-3	JSW
Braidwood 2	Westinghouse	PWR	5P-7056	Lower Nozzle Belt Forging	A 508-3	JSW
Braidwood 2	Westinghouse	PWR	50D102-1-1/50C97-1-1	Lower Shell Forging	A 508-3	JSW
Brunswick 1	GE	BWR	Q2Q1VW	Nozzle Forging N16a	A 508-2	
Brunswick 1	GE	BWR	Q2Q1VW	Nozzle Forging N16b	A 508-2	
Brunswick 2	GE	BWR	Q2Q1VW	Nozzle Forging N16b	A 508-2	
Brunswick 2	GE	BWR	Q2Q1VW	Nozzle Forging N16a	A 508-2	
Byron 1	Westinghouse	PWR	5P-5951	Lower Shell Forging	A 508-2	Ladish
Byron 1	Westinghouse	PWR	5P-5933	Int. Shell Forging	A 508-2	Ladish
Byron 1	Westinghouse	PWR	123J218	Lower Nozzle Belt Forging	A 508-2	Ladish
Byron 2	Westinghouse	PWR	49D329-1-1/49C297-1-1	Intermediate Shell Forging	A 508-2	JSW
Byron 2	Westinghouse	PWR	4P-6107	Lower Nozzle	A 508-2	JSW

Plant	Designer	Reactor	Heat ID	Beltline	Material Spec.	Forging Supplier
				Belt Forging		
Byron 2	Westinghouse	PWR	49D330-1-1/49C298-1-1	Lower Shell Forging	A 508-2	JSW
Catawba 1	Westinghouse	PWR	527708	Lower Shell 04 Forging	A 508-2	RDM
Catawba 1	Westinghouse	PWR	411343	Intermediate Shell 05 Forging	A 508-2	RDM
Crystal River 3	B&W	PWR	AZJ94	Nozzle Belt Forging	A 508-2	
Davis-Besse	B&W	PWR	5P4086 (BCC241)	Lower Shell Forging	A 508-2	
Davis-Besse	B&W	PWR	123Y317 (ADB 203)	Nozzle Belt Forging	A 508-2	
Davis-Besse	B&W	PWR	123X244 (AKJ233)	Upper Shell Forging	A 508-2	
Ginna	Westinghouse	PWR	125P666VA1	Lower Shell	A 508-2	
Ginna	Westinghouse	PWR	125S255VA1	Intermediate Shell	A 508-2	Beth Steel
Ginna	Westinghouse	PWR	123P118VA1	Nozzle Forging	A 508-2	
Hope Creek	GE	BWR	19468-1	Low Pressure Coolant Injection Nozzle Forging	A-508	
Hope Creek	GE	BWR	10024-1	Low Pressure Coolant Injection Nozzle Forging	A-508	
Kewaunee	Westinghouse	PWR	122K208VA1	Intermediate Shell B-6306	A 508-2	Beth Steel
Kewaunee	Westinghouse	PWR	123K167VA1	Lower Shell B-6307	A 508-2	Beth Steel
Mcguire 2	Westinghouse	PWR	411337-11	Lower Shell 04	A 508-2	RDM
Mcguire 2	Westinghouse	PWR	526840	Intermediate Shell 05	A 508-2	RDM
North Anna 1	Westinghouse	PWR	990311/298244	Intermediate	A 508-2	RDM

Plant	Designer	Reactor	Heat ID	Beltline	Material Spec.	Forging Supplier
				Shell Forging 04		
North Anna 1	Westinghouse	PWR	990286/295213	Nozzle Shell Forging 05	A 508-2	RDM
North Anna 1	Westinghouse	PWR	990400/292332	Lower Shell Forging 03	A 508-2	RDM
North Anna 2	Westinghouse	PWR	990598/291396	Nozzle Shell Forging 05	A 508-2	RDM
North Anna 2	Westinghouse	PWR	990496/292424	Intermediate Shell Forging 04	A 508-2	RDM
North Anna 2	Westinghouse	PWR	990533/297355	Lower Shell Forging 03	A 508-2	RDM
Oconee 1	B&W	PWR	AHR54 (ZV2861)	Lower Nozzle Belt	A 508-2	Ladish
Oconee 2	B&W	PWR	AWG-164 (4P1885)	Lower Shell Forging	A 508-2	Ladish
Oconee 2	B&W	PWR	AAW-163 (3P2359)	Upper Shell Forging	A 508-2	Ladish
Oconee 2	B&W	PWR	AMX-77 (123T382)	Lower Nozzle Belt Forging	A 508-2	Ladish
Oconee 3	B&W	PWR	AWS-192/522314	Upper Shell	A 508-2	Ladish
Oconee 3	B&W	PWR	ANK-191/522194	Lower Shell	A 508-2	Ladish
Oconee 3	B&W	PWR	4680	Lower Nozzle Belt Shell Forging	A 508-2	Ladish
Point Beach 1	Westinghouse	PWR	122P237	Nozzle Belt Forging	A 508-2	
Point Beach 2	Westinghouse	PWR	122W195	Lower Shell Forging	A 508-2	Beth Steel
Point Beach 2	Westinghouse	PWR	123V500	Intermediate Shell Forging	A 508-2	Beth Steel
Point Beach 2	Westinghouse	PWR	123V352	Nozzle Beltline Forging	A 508-2	Beth Steel
Prairie Island 1	Westinghouse	PWR	21887/38530	Lower Shell Forging D	A 508-3	Creusot-Loire
Prairie Island 1	Westinghouse	PWR	21918/38566	Int. Shell Forging	A 508-3	Creusot-

Plant	Designer	Reactor	Heat ID	Beltline	Material Spec.	Forging Supplier
				C		Loire
Prairie Island 1	Westinghouse	PWR	21744/38384	Nozzle Shell Forging B	A 508-3	Creusot-Loire
Prairie Island 2	Westinghouse	PWR	22231/39088	Nozzle Shell Forging B	A 508-3	Creusot-Loire
Prairie Island 2	Westinghouse	PWR	22829	Intermediate Shell Forging C	A 508-3	Creusot-Loire
Prairie Island 2	Westinghouse	PWR	22642	Lower Shell Forging D	A 508-3	Creusot-Loire
Sequoyah 1	Westinghouse	PWR	980919/281587	Lower Shell Forging 04	A 508-2	RDM
Sequoyah 1	Westinghouse	PWR	980807/281489	Intermediate Shell 05 Forging	A 508-2	RDM
Sequoyah 2	Westinghouse	PWR	288757/981057	Intermediate Shell Forging 05	A 508-2	RDM
Sequoyah 2	Westinghouse	PWR	990469/293323	Lower Shell Forging 04	A 508-2	RDM
Surry 1	Westinghouse	PWR	122V109VA1	Nozzle Shell Forging	A 508-2	
Surry 2	Westinghouse	PWR	123V303VA1	Nozzle Shell Forging	A 508-2	
Tmi-1	B&W	PWR	ARY 059	Lower Nozzle	A 508-2	
Turkey Point 3	Westinghouse	PWR	123P461VA1	Intermediate Shell Forging	A 508-2	Beth Steel
Turkey Point 3	Westinghouse	PWR	123S266VA1	Lower Shell Forging	A 508-2	Beth Steel
Turkey Point 3	Westinghouse	PWR	122S146VA1	Upper Shell Forging	A 508-2	Beth Steel
Turkey Point 4	Westinghouse	PWR	123P481VA1	Intermediate Shell Forging	A 508-2	Beth Steel
Turkey Point 4	Westinghouse	PWR	122S180VA1	Lower Shell Forging	A 508-2	Beth Steel
Turkey Point 4	Westinghouse	PWR	124S309VA1	Nozzle Belt Forging	A 508-2	

Plant	Designer	Reactor	Heat ID	Beltline	Material Spec.	Forging Supplier
Watts Bar 1	Westinghouse	PWR	528522	Lower Shell 04	A 508-2	RDM
Watts Bar 1	Westinghouse	PWR	527536	Intermediate Shell 05	A 508-2	RDM
Zion 1	Westinghouse	PWR	ANA 102	Upper Shell Forging	A 508-2	
Zion 2	Westinghouse	PWR	ZV 3855	Lower Nozzle Belt Forging	A 508-2	

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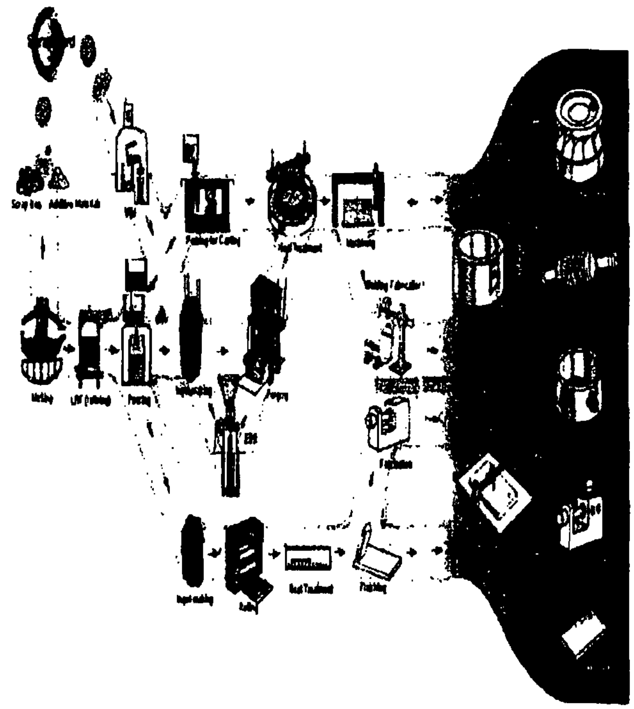

Main Facilities


120-ton Electric Arc Furnace


100-ton Electro Slag Remelting


14,000-ton Water Hydraulic Forging Press


3,000-ton High-speed Hydraulic Forging Press


Heat Treatment Furnace


4-high Plate Mill


12,000-ton Pipe Forming Press


NC Lathe

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