Feasibility study for Ultrasonic Examination of High thickness Austenitic Stainless Steel Forgings

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Abstract

The Ultrasonic Examination of Austenitic Stainless Steel (ASS) Forgings block for critical shielding block was a challenge, due to high thickness, isolated coarse grain structure and its complex configurations as specified in the specification.

To detect and characterize defects in these ASS forgings, we at L&T Special Steels and Heavy Forgings have done feasibility study for ultrasonic examination technique based on stringent acceptance and reporting criteria by conventional manual scanning for thickness ranging from 350mm to 900mm.

This paper will give details of Demonstration UT Blocks, Equipment, Search Unit, Couplant and Extent of Examination done with respect to complex configuration of the forgings.

Key words – Austenitic Stainless Steel, coarse grain structure, Demonstration UT blocks, Equipments, Extent of Examination

1. Introduction & background

Heavy Austenitic Stainless Steels (ASS) forgings are widely used for various main components. Ultrasonic examination of these heavy Austenitic Stainless Steel forgings are very difficult due to ultrasonic scattering and attenuation from the coarse grain structure. When ultrasonic energy passes through the material, grain structure scattering results in noise echoes which often interferes with the indication signal. In ASS material grain refinement can’t be achieved through heat treatment as in the case of carbon steel and it has to be done during open die forging process only (i.e., in minimum number of reheating cycle forging shall be done). Usually there are limits on controlling the grain size by temperature and strain...
in respect to productivity and quality. In particular, controlling the grain size is more difficult on thick forgings because forging effect hardly gets to the center during process and the cooling rate is slower at the center during heat treatment. The feasibility study was conducted for defect detection to obtain a better signal-to-noise (S/N) ratio by selecting appropriate search unit, electronically controlling the ultrasonic waves passing through forgings having thickness ranging from 350mm to 900mm by conventional ultrasonic test.

2. **Constraints in Ultrasonic Examination of ASS Forgings**

In order to carry out conventional ultrasonic test to cover 100% volume of the forgings, following constraints were encountered before the execution of the project.

1. High attenuation in higher thickness to be examined.
2. Complex geometry of the forgings to be examined. (See fig. 1 below)
3. To obtain the scanning sensitivity i.e., 6mm FBH for all thicknesses.
4. Which search unit and flaw detector to be used for such high thickness forgings

![Complex shaped Forgings](image)

Fig. 1 – Complex shaped Forgings

Among the restraints mentioned above, (a) and (b) can’t be eliminated as it is material property. The remaining two were established to obtain desired results.
The ultrasonic examination of polycrystalline material like ASS metal produces low signal amplitude and high noise levels when compared to the examination of fine grained ferritic steel. If a closer comparison is made between the ultrasonic examination of ferritic and austenitic material it is apparent austenitic stainless steel -

- A higher and variable level of attenuation occurs due to the focusing/defocusing effects.
- A much higher level of scattering from grain boundaries occurs.

Apparent attenuation due to focusing/defocusing depends on the wave mode, the shape of the beam and beam to grain angle. It is not however frequency dependent. It is very difficult to separate the above effects practically and measure the attenuation of ASS material. Grain boundary scattering arises because neighboring grains will in general have different crystallographic orientations as shown in fig. 2 and sound beam crossing the boundary between grains will undergo a change in phase velocity. This change in velocity will result in a change in acoustic impedance between the grains, producing a partial reflection at the boundary. In the frequency range between 2 and 4 MHz the attenuation due to scattering ranges between 0.2 and 1.0 dB/mm for all three wave modes, however this does not include other factors such as beam divergence for example. For compression waves attenuation is relatively high for the direction along the columnar grains or across the grains. It is relatively low at $45^0 – 50^0$ to the grains.

![Fig. 2](image)

Elastic anisotropy and the impedance mismatch at grain boundaries influence wave propagation and scattering. Elastic anisotropy $K$ for cubic crystallites is given by –

$$K = \left[ \frac{c_{11} - \langle c_{11} \rangle}{\langle c_{11} \rangle} \right]^2$$

Where $c$ is the elastic tensor coefficient (compression modulus); and $\langle c \rangle$ is its average value.

For cubic crystallites, the elastic anisotropy may also be expressed in terms of acoustic impedance-

$$K = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

Where the acoustic impedances $Z = \rho v$ are based on principle longitudinal velocity.
The above equation is exactly the same for the reflection coefficient $R$ at the boundary between two materials.

In any material attenuation from scattering and other mechanism is measured by an attenuation coefficient $\alpha$ usually expressed in terms of the intensity $I$ of sound after traversing a distance $X$ through a material –

$$I = I_0 \exp(-\alpha X)$$

Where $I_0$ is the initial intensity and $I_0 - I$ is the loss in intensity over distance $X$.

Single-frequency, continuous wave ultrasound is used in those cases where unique relations exist at a specific frequency but speed and attenuation are both functions of frequency. With transducers that emit broad band pulsed ultrasound, signals have a wide frequency spectrum. Generally, each spectral component is affected differently as the ultrasound propagates in a material. In polycrystalline solids, each frequency component and wavelength is affected differently according to grain size, elastic anisotropy. Frequency dependence of speed and attenuation are very important in the ultrasonic characterization of material microstructures, porosity and diffuse discontinuities.

Scattering and absorption are the energy loss mechanism that govern ultrasonic attenuation in the frequency ranges of interest for characterizing most engineering solids. Diffusion, Rayleigh and stochastic (phase) scattering losses are extrinsic whereas absorption losses from dislocation damping, anelastic hysteresis, relaxation and thermoelastic effects are intrinsic to individual grains such as crystallites. Scattering usually accounts for the greatest portion of losses in engineering solids. The scatter attenuation coefficient $\alpha$ is a function of frequency $f$. In polycrystalline metals, there are three scatter attenuation processes defined by the ratio of mean grain size $D$ to the dominant wavelength $\lambda$.

For the Rayleigh scattering process where $\lambda \gg \pi D$

$$\alpha_r = C_r D^3 f^4$$

Where $C_r$ the constants contain geometric factors, longitudinal and transverse speeds, density and elastic anisotropy factors.

For the stochastic (phase) scattering process where $\lambda \cong \pi D$

$$\alpha_p = C_p D f^2$$

Where $C_p$ the constants contain geometric factors, longitudinal and transverse speeds, density and elastic anisotropy factors.
For the Rayleigh scattering process where $\lambda \ll \pi D$

$$\alpha_d = C_d D^{-1}$$  

Where $C_d$ the constants contain geometric factors, longitudinal and transverse speeds, density and elastic anisotropy factors.

### Table - 1

<table>
<thead>
<tr>
<th>Wavelength Relation</th>
<th>Attenuation Mechanism</th>
<th>Attenuation Coefficient (Np.m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>True absorption</td>
<td>$\alpha_a = C_a f$</td>
</tr>
<tr>
<td>$\lambda \gg \pi D$</td>
<td>Rayleigh scatter</td>
<td>$\alpha_r = C_r D^3 f^4$</td>
</tr>
<tr>
<td>$\lambda \approx \pi D$</td>
<td>Phase scatter</td>
<td>$\alpha_p = C_p D^2 f^2$</td>
</tr>
<tr>
<td>$\lambda \ll \pi D$</td>
<td>Diffusion scatter</td>
<td>$\alpha_d = C_d D^{-1}$</td>
</tr>
</tbody>
</table>

$D$ = Nominal or mean grain size ($\mu$m)

$\lambda$ = wavelength (m)

$f$ = frequency (Hz)

$\alpha$ = attenuation coefficient (Np.m$^{-1}$)

$C$ = experimental constants

3. **Acceptance norms comparison from ASME Code & Customer**

### Table - 2

<table>
<thead>
<tr>
<th>ASME Standard</th>
<th>Customer Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examination Thickness</td>
<td>Reporting / Recordable norms</td>
</tr>
<tr>
<td>Upto 75mm</td>
<td>3mm FBH</td>
</tr>
<tr>
<td>Upto 200mm</td>
<td>6mm FBH</td>
</tr>
<tr>
<td>Upto 300mm</td>
<td>10mm FBH</td>
</tr>
<tr>
<td>Upto 600mm</td>
<td>13mm FBH</td>
</tr>
<tr>
<td>Over 600mm</td>
<td>Indications equal to or exceeding 50% of the applicable reference acceptance curve</td>
</tr>
<tr>
<td>For all thicknesses (350mm to 1750mm)</td>
<td>Complete loss of back reflection accompanied by an indication</td>
</tr>
<tr>
<td>All the indication shall be reported in terms of Supplementary requirement S1 (thickness over 150mm, 6mm FBH) of SA 388</td>
<td>Complete loss of back reflection accompanied by an indication</td>
</tr>
</tbody>
</table>

Seeing the mismatch in ASME standard and Customer specification, we have done some feasibility study for conforming that whether we can detect 6mm FBH from thickness above 600mm to 1000mm. For this LTSSHF has forged a trial forging (material grade – SA965 Gr. 304L) with Length 2650mm, width 2330 and thickness 970mm. Fig. 3 (a) and (b) shows the trail forging...
and microstructure of the same forging at 100X magnification, which was found to be greater than ASTM 2 as per ASTM E-112.

![Trial Forgings with microstructure.](image)

**Fig. 3 – Trial Forgings with microstructure.**

(a)(b)

**4. Practical Demonstration**

As we know that for carry out ultrasonic examination, procedure need to be prepared and approved by customer. But before preparing the procedure, we need to know whether 6mm FBH is feasible to detect up to 930mm thickness or not. For this we have prepared five demo blocks from the trial forging with thickness 400mm, 675mm, 745mm, 895mm and 931mm were made which contain Flat Bottomed Hole (FBH) of 6mm dia. and 13mm dia. 25mm deep. With metal path of 375mm, 650mm, 720mm, 870mm and 906mm respectively. Refer below photos (fig. 4) showing the blocks and FBH replica for conforming the flatness of the FBH.

![Demo Blocks](image)

(a) ![Demo Blocks](image)

(b) ![Demo Blocks](image)

(c) ![Demo Blocks](image)

(d) ![Demo Blocks](image)

(e) ![Demo Blocks](image)

**Fig. 4 – Demo Blocks**
This practical demonstration was done using two ultrasonic flaw detectors (UFD) with same set of search unit.

**Table - 3**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Model</th>
<th>Make</th>
<th>Pulsar type</th>
<th>Digital filters</th>
<th>PRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>UFD-01</td>
<td>Epoch 1000</td>
<td>Olympus</td>
<td>Square wave</td>
<td>30 filter</td>
<td>5 to 6000 Hz</td>
</tr>
<tr>
<td>UFD-02</td>
<td>USM 35XS</td>
<td>GE</td>
<td>Peak</td>
<td>4 filters</td>
<td>4 to 1000 Hz</td>
</tr>
</tbody>
</table>

Three search unit where used along with UFDs mentioned above.

**Table - 4**

<table>
<thead>
<tr>
<th>Model</th>
<th>Make</th>
<th>Relative band width (%)</th>
<th>Central frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2S</td>
<td>GE</td>
<td>52.5</td>
<td>2</td>
</tr>
<tr>
<td>K2G</td>
<td>GE</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td>PF1R</td>
<td>Olympus NDT</td>
<td>50.4</td>
<td>1</td>
</tr>
</tbody>
</table>

Since ultrasonic examination is being done on ASS material, there are restriction on using regular couplant. A special couplant(Model - EchoMix powder couplant, make Echo Ultrasonics) which has less than 25ppm of sulfur and halides was tested and approved for the examination.

Below table shows the results of demonstration using two UFD and three search unit combinations

**Table - 5**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Thickness of the block</th>
<th>UFD-01 (Model – Epoch 1000, Make – Olympus)</th>
<th>UFD-02 (Model – USM 35XS, Make – GE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6mm FBH</td>
<td>12mm FBH</td>
</tr>
<tr>
<td>1</td>
<td>400</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>2</td>
<td>675</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>3</td>
<td>745</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>4</td>
<td>895</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>931</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- √  required FBH detected
- √  required FBH not detected.
- √  required FBH detected but signal-to-noise ratio was less than 3:1

The above feasibility demonstration was conducted and approved by customer, to implement the same setup during execution of the project.
4. Complex geometry of the forgings

Geometry of any forgings play an important role in extent examination. We have prepared the scan plan to cover 100% volume of the forgings meeting the code requirements i.e., “scan all sections of forgings in two perpendicular directions”. Due to complex geometry some portions of the forgings, ultrasonic examination is possible but application of acceptance criteria is not possible. Below are the scan plan (fig. 5) showing different position of search units on different shape of the forgings. As per standard Ultrasonic examination shall be performed after heat treatment for mechanical properties but prior to drilling holes, cutting keyways, tapers, grooves, or machining sections to contour. But as per the requirement heat treatment properties to be certified near the profile. Hence for our internal control, all the forging were examined before heat treatment in rectangular shape for compliance and after heat treatment examination done in profile shape.
For region where indication evaluation by back-reflection method is not possible due absence of back reflection. So for evaluation of indications in those areas, back reflection shall be taken from approximately same thickness and same material condition. At that reference setting, if indication equals to or exceeds 80% full screen height (FSH) the indication is unacceptable e.g., in any of the forging shape mentioned above blue region is approx. 600mm, so take the back reflection from 600mm thickness block. This new acceptance norms was also reviewed and accepted by customer.

5. Conclusion –

5.1 The difficulties for carry out ultrasonic examination of ASS material, can be overcome by selecting appropriate Ultrasonic Flaw Detector and search unit.

5.2 Up to 900mm thickness of ASS forgings, 6mm FBH can be detected by search unit with 1MHz frequency and approx. 50% bandwidth; UFD with tunable square wave pulsar.

5.3 The region where no back reflection is observed and acceptance norms is based on total loss of back reflection, then the reference back reflection shall obtained from other thickness block with same thickness and material condition. At that reference setting, if indication equals to or exceeds 80% full screen height (FSH) the indication is unacceptable.

5.4 Considering all the above points, procedure was prepared and approved by customer for execution of the project.