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RESEARCH ARTICLE

Assessment on mechanical working of a rolled ring using ultrasonic techniques

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Abstract

The variations in the achieved level of mechanical working across the thickness of a mechanically worked product causes variations in the strains induced in the cross section. Though the subsequent thermal treatments are aimed to have uniformity across the cross section, in some cases it is observed that it is not happening. As these imperfections do not show greater abnormality in its mechanical properties, the standard qualification procedures for evaluating such mechanically worked products is not that much sensitive to indicate such imperfections. However, in subsequent downstream processes like welding and x-ray radiography of the weld joint of such products, say a rolled ring welded with sheets/plates and subsequent x-ray, shows these imperfections and attracts special metallographic test procedure for deciding its acceptance. This paper explains a non-destructive test procedure that can reveal such imperfections. The procedure was applied on a rolled ring and the observations and an inference of the non-destructive test procedure was verified by doing standard metallography investigations.

Keywords

Mechanical working

Strain

Attenuation

Velocity

Grain size

Aspect ratio

Introduction

Sound energy transmission through materials happens by the movement of particles that are vibrating from their mean position of rest. Considerable amount of sound energy is lost during transmission. A portion of the energy loss gets utilized for over coming the internal friction and the rest of the sound energy gets scattered by the microscopic interfaces in every direction [1,2]. The combined effect of these two energy loses are known as ultrasonic attenuation. Due to variations in internal friction and internal scattering, the sound attenuations from point to point in a material can vary [3]. The attenuation variations thus happening can appropriately be interpreted for detecting the variations in strain hardening of mechanically worked products across its cross section. The worked products include rolled rings, forged blanks etc. As the ultrasonic pulses pass through the cross sectional thickness of the

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product it will be difficult to locate precisely the localized strained region, especially in depth direction, by ultrasonic methods alone. However by measuring attenuation in different directions and also by using the micro density variations data of X-ray film of these cross sections, the location of high strain area can be identified. In this paper, an ultrasonic method adopted for analyzing an unusual observation of a weld radiograph (weld joint between ring and sheet) wherein x-ray film showed a mosaic like appearance due to film density variations on ring image is explained. This analysis yields a method that can be adopted for assessing the uniformity of mechanical working across the cross section of forged or rolled products

Theory

According to Hall-Petch equation [4]

$$\sigma_0 = \sigma_1 + k' D^{-\frac{1}{2}} \quad \ldots (1)$$

where σ_0 is the yield stress, σ_1 is the frictional stress opposing motion of dislocation, k' is unpinning constant measuring the extend to which dislocations are piled up at barriers and D the grain diameter. As the rings are annealed after mechanical working the piling up of dislocations are unlikely. Hence modified model of Hall Petch equation [4,5] is considered here. Accordingly the equation will be as follows

$$\sigma_0 = \sigma_1 + \alpha G b \rho^{\frac{1}{2}} \quad \ldots (2)$$

Where α is a numerical constant (generally between 0.3 to 0.6), G the shear modulus, b the breadth or width over which shear modulus acts and ρ the dislocation density. In this equation the magnitude of the term Gb depends upon the aspect ratio of the grains and the term ρ is an inverse function of the grain size.

Ultrasonic waves are propagated through materials by the movement of particles of the medium. As sound energy passes through the material, attenuation losses are happening throughout its travel path. But energy can neither be created nor destroyed. Hence the energy loss thus happening during transmission gets utilized to come over the internal friction. The factors that accounts for internal frictions are σ_1, G, b and p_x. In case of an annealed part σ_1 is insignificant. Hence the main factors that can affect particle movement are G, b and ρ [6]. In addition to this, the sound energy gets scattered by the microscopic interfaces in every direction. Microscopic interface scattering will be more if the interfaces, namely grain size and its aspect ratio, are large. Suppose p_x is the sound pressure at a distance x and p_0 is that at the probe exit point then

$$\frac{p_x}{p_0} = e^{-2\alpha x} \quad \ldots (3)$$

where α is the attenuation coefficient. In dB methods this can be represented as

$$20\log\left(\frac{p_x}{p_0}\right) = -(20\log\alpha\log e)2x = -2\beta x. \quad \ldots (4)$$

Here β is the attenuation coefficient in dB/meter. This equation on substitution yields

$$\left(\frac{p_x}{p_0}\right) = 10^{-2\beta x/20}. \quad \ldots (5)$$

Due to the divergence of sound energy while traveling along the material a small amount of energy is lost and that is denoted as v_D. The divergence loss and attenuation loss depend upon the distance. In general the distance law is given by

$$\frac{p_x}{p_0} = D(x) \bullet s(x). \quad \ldots (6)$$

As the measurements taken in this experiment are in far field, divergence effect is not considered [2,7]. Hence the equation can be written as

$$\left(\frac{p_x}{p_0}\right) = const \quad (x) \bullet 10^{-2\beta x/20}. \quad \ldots (7)$$

On simplification the equation becomes

$$20\log\left(p_{(x)}/p_{(0)}\right) = const - 20\log x - 2\beta x \quad \ldots (8)$$

As the losses due to divergence are in logarithmic scale and also the location of the attenuator is at constant distance, it is assumed that the measured attenuations are the attenuation that is caused by the material alone. From this it can be inferred that the attenuation loss is directly proportional to the distance. As the attenuation loss due to the distance is negligibly small, a graph representing the attenuation measured along the cross section with respect to distance in logarithmic scale is expected to be linear. Deviation from this linear relationship indicates abnormality in attenuation that is caused because of changes in ρ and p_x (G) is a constant being the characteristic property of the material as explained above. As ρ being a factor related to the length to width ratio (l/d ratio) and p_x is an inverse function of the grain size, the variation in attenuation indicates the variation in grain size and l/d ratio.

Like wise the velocity with which ultrasonic waves travel in a material depends mainly on its elastic properties especially the Poisson's ratio and Lami's constant μ and λ. As the attenuation varies across the cross section due to the above explained variations, the velocity of the particle movement responsible for sound energy transmission also gets varied and there by causing small variations in sound velocity. If we consider the Navier's wave equation for an isotropic elastic medium, its dilatation and rotational components need to be modified to accommodate this variation that causes attenuation variations [8,9]. Hence λ and μ will become respectively as

$$\lambda + \frac{\lambda'}{\varpi}\frac{\partial}{\partial t} \quad \text{... (9)}$$

$$\mu + \frac{\mu'}{\varpi}\frac{\partial}{\partial t} \quad \text{... (10)}$$

where $\lambda' and\, \mu'$ are the viscoelastic constants, ω is the angular frequency and $\frac{\partial}{\partial t}$ is the time derivative of particle displacement. Hence the longitudinal velocity equation reduced from the Navier's wave equation will be

$$(c_L)^2 = \left(\frac{\lambda + 2\mu - i(\lambda' + 2\mu')}{\rho}\right) \quad \text{... (11)}$$

$$(c_L)^2 = \frac{(\lambda + 2\mu)}{\rho} - \frac{i(\lambda' + 2\mu')}{\rho} \quad \text{... (12)}$$

This equation indicates that the velocity depends on μ and λ. The variations in mean velocity are due to $\lambda' and\, \mu'$ that are depending again on the grain size and its l/d ratio. In x-ray radiography technique, the defect images are formed due to differential absorption of electro magnetic radiation energy while it travels along the material path. This can be represented by an equation. where μ is the linear absorption coefficient

$$I = I_0 e^{-\mu x} \quad \text{... (13)}$$

and x is the thickness. On simplifying the above equation we get

$$\log\left(I / I_0 \right) = -\mu x \quad \text{... (14)}$$

Hence from basic principles of film density (D) it can be derived that

$$D \propto 1/(-\mu x) \quad \text{... (15)}$$

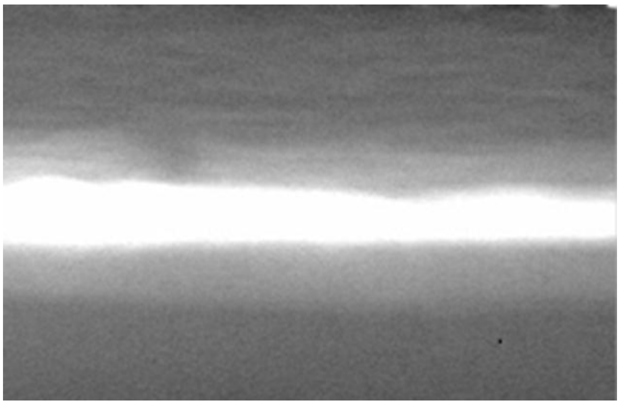

Fig 1 Radiograph showing.

For a constant thickness component the film density varies with variation in absorption coefficient within the component. The absorption of radiation includes the scattering of radiation and absorption of radiation happening within the medium. Higher the size of the scatterer when compared to the wavelength, greater will be the scattering. Hence the radiation absorption depends upon the density/compactness of the matrix and size of scatterer. In case of metallic components the density will remain same and hence the absorption variations happens because of the compactness of the scatterer and its size.

Experimental

The validation of above mathematical arguments can be inferred in one of the observations wherein a weld radiograph showed a mosaic like appearance (**Fig 1**). This is a weld joint between rolled ring (diameter 800 mm and 41.36 to 41.46 mm height) of aluminum – copper alloy and a same alloy sheet. The welding process adopted was Tungsten Inert gas welding process. The weld joint was x-ray radiographed for weld quality evaluation. On those radiographs, localized white patches like (mosaic like)

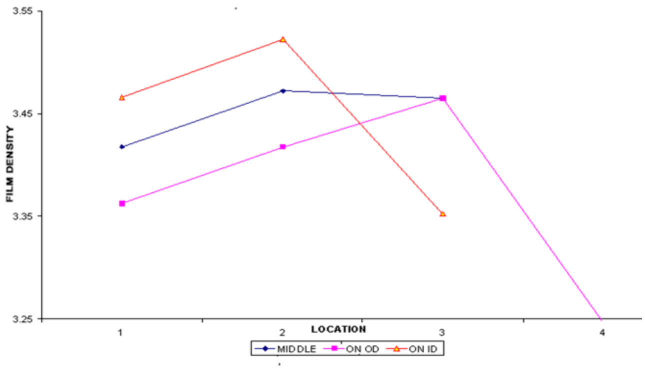

Fig 2 Film density variation.

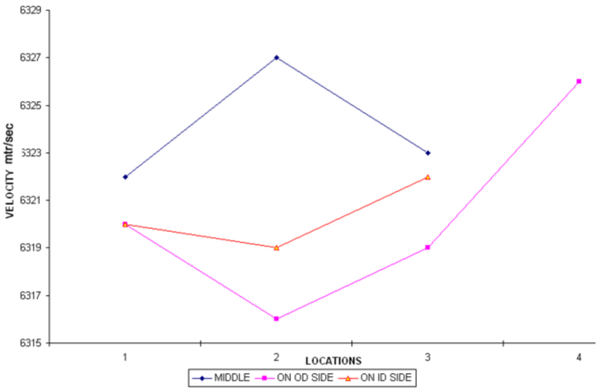

Fig 3 Velocity variations.

appearance on ring image were noticed.

This is a typical and unusual appearance (**Fig 1**) and hence attracted attention. This ring met all the mechanical property and metallurgical test requirements. In order to evaluate the mosaic like appearance the above mathematical arguments were tried on this. The film density was measured on different locations. On representing the film density at locations across the cross section it is expected to have a straight line as the ring is not expected to have any heterogeneity. Deviations from this linear relationship indicate the abrupt changes in energy absorption. Like ultrasonic, here also the absorption coefficient will vary with the variations in the characteristics of the material path through which x-rays travel. Such abrupt changes can be caused by either inclusions both gas and metallic inclusions or tight compactness and size of scatterer if any.In cases of gas and metallic inclusions the differential absorption will be so High as to form a well-defined image on radiographs. On the other hand variations in lattice compactness and scatterer size can cause only a diffused image of light density.

To under stand the reason for this appearance and to evolve appropriate modifications in the process so as to eliminate this type of imperfections in future, a series of non-destructive testing were carried out based on the theoretical explanations as detailed above. A small portion of the ring (of arc length 300 mm) was cut and

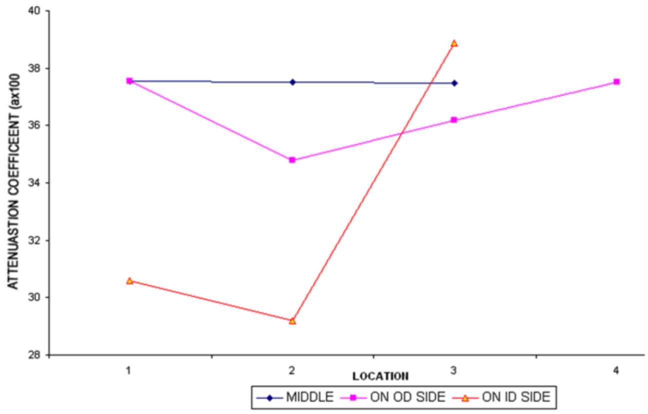

Fig 4 Attenuation variations.

the cross-section (radial direction) was subjected to x-ray radiography. Same white patch like appearance were seen on its cross section. It is observed that these patches are seen on the top and bottom sides of the ring *(i.e.* on OD and ID of the ring) when it is viewed in radial direction. The center portion of the cross section is uniform in radiographic (density) appearance. The distinct density (film density) different areas are marked and the film densities on these locations are measured using a calibrated film densitometer. The accuracy of the densitometer is 0.02 densities. The readings are presented in **Fig 2**. Ultrasonic velocity (longitudinal wave velocity) at these points was measured using a calibrated thickness/velocity gauge (krautkramer make CL304). As the accuracy of the thickness gauge is one micron, the random error in velocity will be less than 1mtr/sec. The ultrasonic attenuation measurements on these points were made in dB scales using an ultrasonic flaw detector (USD 15) and attenuation coefficients were derived using first principles. The velocity and attenuation values against their locations are presented in **Figs 3, 4**. As the accuracy in attenuation Measurement is 0.5 dB the random error in attenuation coefficient caused due to measurement could be less than 1.39×10^{-3}.

Results and discussion

From **Fig 4** it can be seen that the velocity that is expected to be same at Top, Middle and Bottom are not the same. Also there are variations even at points on the same portion. The variations noticed are well above the possible random errors. This indicates that, as explained earlier, the values of viscoelastic constants are different at top, middle and bottom. These constants will vary if there is a damping for propagation of sound energy. The presences of damping elements at these locations are due to the different straining undergone by these locations.

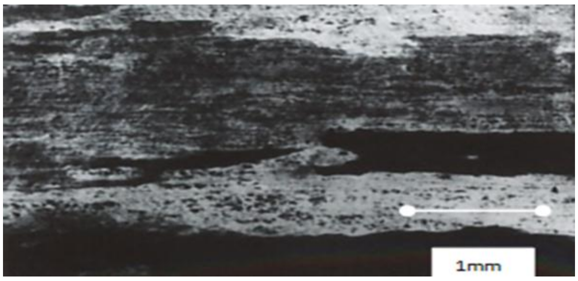

Fig 5 Specimen cut from ID side of the ring showing elongated grains.

Likewise the **Fig 5** also shows variations in attenuation coefficients at different locations. Since the total cross section thickness is 41.36 to 41.46 mm the attenuation loss due to the distance is negligibly small and hence the graph representing the attenuation measured along cross section with respect to distance in logarithmic scale is expected to be linear. But it is not so. Also the variations noticed are well above the random variations and are occurring on the same locations in velocity and film density measurements. Hence it is a causative variation [10]. The attenuation is deviated from linear relationship (as explained earlier) indicating the presence of damping elements at these locations.

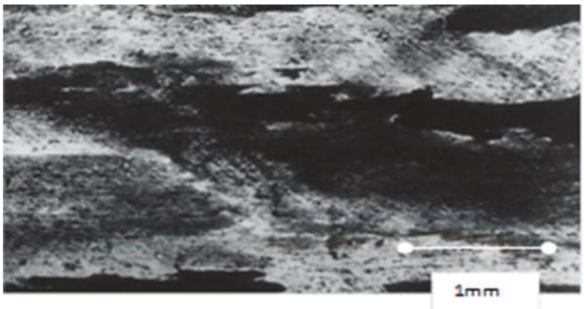

Fig 6 Specimen cut from the OD side showing elongated grains.

As x-ray radiography of these locations are not showing any inclusion type defects, the grains are attributing the abnormality in attenuation.

Since there are no objectionable deviations in mechanical strength of the ring, the possible reasons for the grains to exhibit such a behavior are its l/d ratio and anisotropy that might have been resulted due to localized straining/working. In order to cross verify the evaluations derived from non-destructive testing, small cut pieces one from each OD, Top and Middle portion of the ring were taken and subjected to metallurgical analysis. The micrographs of the grains on different locations are shown in **Figs 5-7**. The metallographic examination revealed the presence of elongated grains with very high length to width ratio and also the presence of a large number of undissolved precipitates.

The observation of large l/d ratios could be attributed to the non-homogenous working carried out on the material during ring rolling. Regions close to the internal and outer diameter have been deformed heavily, while the core has experienced lesser deformation; upon subsequent heat treatment, the heavily deformed regions, which have lower recrystillasation temperature have undergone recrystillasation and subsequent exposure at the elevated temperature has resulted in grain coarsening. This non-uniformity in the grain structure resulted in matt like appearance seen while doing metallographic investigation. The grain size and its l/d ratio at top and bottom locations are shown in **Table 1**.

Table 1

Location	Grain size in μm	Length to width ratio (l/d ratio)
OD side	320	6-18
ID side	200-400	6-18

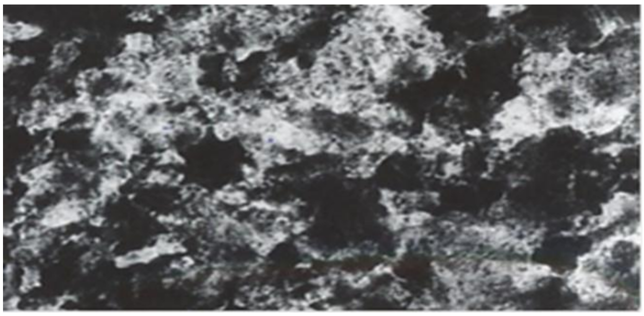

Fig 7 Specimen cut from middle portion showing normal I/d ratio grains.

The film density values as shown in **Fig 3** does not indicate a linear relationship as predicted based on theory explained earlier. The deviated locations are found to be on the outer and inner skin of the ring piece. The corresponding image appearances on these locations are not well defined and are diffused images. By heuristics these images cannot be co related to any probable rolled product defects like high-density metal inclusion *etc*. As the input billet for this ring was thoroughly checked for metallurgical uniformity and absence of inclusions by standard metallography test procedures the unusual white patch like appearance likely to have happened only during ring rolling. As such ring rolling process cannot introduce any internal inclusions. Hence the reason for the observed appearance could be a process-induced defect such as elongated grains, lattice compactness *etc*.

The ultrasonic velocity and attenuation values presented in **Figs 3, 4** were not in agreement with the theoretical predictions as explained earlier. The attenuation values show abrupt changes at locations on top and bottom of the ring (in radial direction). As there is no defect (like segregations and inclusions) observed in radiographs of these locations the cause for attenuation could be metallurgical damping alone. The ring being a mechanically worked product, there cannot be any grain size variations and so the damping must be because of localized heavily worked regions. The micrographs of these locations (**Figs 5-7**) show elongated grains of l/d ratio of 18 on top and bottom of the ring. The micrographs of the specimen cut from the middle portion is in contrast to the above-mentioned two micrographs.This indicates that the working at OD and ID are severe when compared to the center. But in normal ring rolling process this is unlikely because the rolling pressure applied on axial and radial directions are expected to cause uniform strain along the cross section of the ring. However the most probable possibility could be, during rolling, if the temperature of the ring is not maintained then the cross section of the ring might have under gone different level of mechanical working. Due to these variations in mechanical working, the cross section of the ring will have localized strained region resulting in elongated grains on high strained regions.

Conclusions

This experiment provided a method for assessing non-destructively the level of mechanical working and subsequent strain of different regions of rolled rings.The method is validated by cross verification using metallography test procedures. This method, though not be practicable as a routine test, can be adopted for optimizing the parameters for mechanical working. However a controlled experimentation to quantify the mechanical working is envisaged so as to make this test procedure as routine test.

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