Ultrasonic Inspection Of Cylindrical Centrally Bored Forged Steel Product, A Basic Guide For Detecting Longitudinal Cracks On The Inside Diameter.

Information for technicians, designers, suppliers, manufacturers and end users.

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1. Introduction

This guide is for anyone involved in the testing, manufacture or use of cylindrical forged steel products that have been centrally bored. Specifically we are interested in detecting longitudinal cracks which may have been formed on the inside diameter (ID) of the bar during the heat treatment process (quench cracks) although the same methods could be used to detect the remnants of axial defects that were introduced during the forging process, i.e. axial bursts and cracks, that were not full removed during the boring process.

2. Ultrasound

Ultrasound is any sound wave whose frequency is above the ability of humans to hear (around 20 KHz), for industrial ultrasonic inspection we are working in the MHz range, typically 1-5 MHz for the manual inspection of heavy forgings.

Above 100 KHz ultrasonic waves follow the laws of optics, so therefore the familiar concepts of reflection, refraction and diffraction apply when using high frequency sound waves.

In gases such as air only compression (longitudinal vibration) type sound waves may propagate, however in solid materials such as steel a number of other propagation modes can occur. Compression and shearwave (transverse vibration) modes are commonly used in the ultrasonic inspection of forged steel, although other modes are sometimes used in special applications.

In the ultrasonic inspection of steel, compression waves are typically described as being at 0^0, that is they propagate perpendicular to the face inspected and are at 0^0 from the normal. Shearwaves are created by refraction and typically propagate at an angle which is given as the number of degrees from the normal. Commercially available probes have a range of angles from 38^0 to 70^0, although angles slightly lower and higher than this can be made for special applications, *the range of angles available for shearwave probes is limited by the law of refraction*.

As compression wave probes are at 0^0 they are unidirectional, however as shearwave probes emit sound at an angle they are directional, with the sound propagating in the direction the probe is facing. This is why it is often necessary to repeat a shearwave scan in multiple directions but the compression wave scan needs only to be done once.

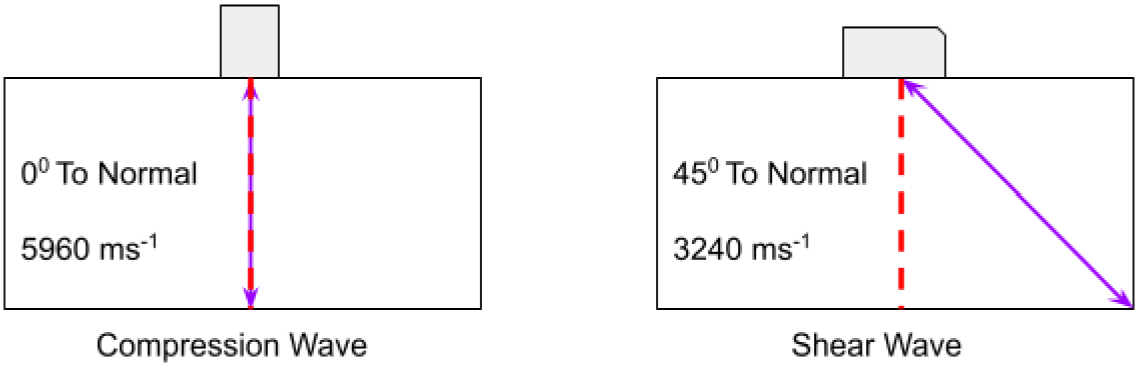

Figure 1

In air sound waves travel at 330 ms^{-1}. The speed of sound in steel is much higher, with compression waves travelling at 5960 ms^{-1} and shearwaves travelling at 3240 ms^{-1}.

3. Ultrasonic Testing Of Bores Using Shearwaves In The Circumferential Direction

The maximum angle that can be used so that the beam makes contact with the ID on a circumferential scan of a bore is given by the following formula:

$$\theta_{max} = \sin^{-1} (ID/OD)$$

ID = Inside diameter, OD = Outside diameter
θ_{max} = The maximum angle of probe that can be used.

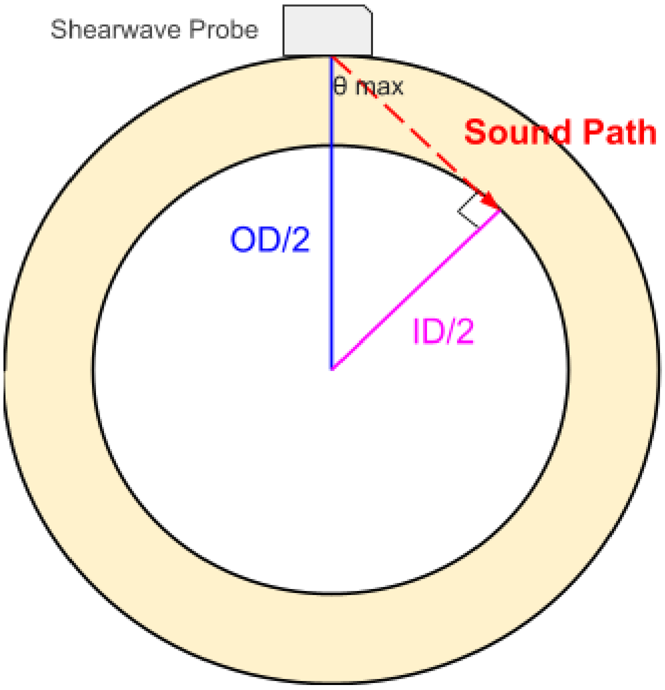

Figure 2

From Figure 2 it can be seen that if the angle θ_{max} was calculated and a probe of this exact angle was available the sound beam would hit the apex of the curve created by the inside diameter as shown above. If a probe was chosen whose angle was less than θ_{max} the sound beam would still make contact with the ID but the sound path to the ID face would be shorter. If a probe was chosen whose angle was greater than θ_{max} then the sound path would miss scanning the ID face and continue onwards through the material until it made contact with the OD. *In this scenario there is a high possibility that longitudinal defects propagating from the ID face will not be detected.*

The critical value that determines whether the ID can be satisfactorily tested and what angle probe is to be used is the ratio between the ID and the OD. The actual physical size of the bore alone does not determine the suitability for testing.

Some notable ratios are given in the table below.

ID/OD (Used in formula above)	**OD to ID Ratio** (Often given in specs)	θ_{max}	**Notes**
<= 0.5	>= 2:1	-	Angle beam inspection (shear wave) not required (ASTM A-388)
>0.5	<2:1	30^0	Less than 2:1. Ratio specified in ASTM A-388 in which angle beam inspection is to be used.
0.616	1.624:1	38^0	Steepest commercial available shearwave probe.
0.707	1.414:1	45^0	Recommended angle to use in ASTM A-388
0.866	1.155:1	60^0	
0.940	1.064:1	70^0	Shallowest commercially available shearwave probe.

Table 1

So from the table above it can be seen that any part with an OD to ID ratio of 2:1 or greater is not required to be tested with a shearwave probe (ASTM A-388 Section 9.3.1). ASTM A-388 stipulates the use of a shearwave probe for any ratio less than 2:1, although commercially available probes are only suitable for ratios or 1.624:1 or less. So there is a grey area between 30 and 38 degrees where an angle scan is specified but suitable probes are not readily available!

Although Snell's Law shows that a minimum shearwave probe angle of 34^0 is theoretically possible, they are generally not commercially available, most likely due to performance issues with the operation of the probes at angles close to the 1st critical angle.

Technically it is possible to produce a probe with an angle of less than 34 degrees, but because this would result in a refracted sound wave less than the 1st critical angle both a compression wave and a shearwave would simultaneously be introduced in the item under test, with both refracted at different angles and with both travelling at different speeds. Due to it being not possible to differentiate between the signals returned by the two different waves on the screen of the UT flaw detector interpretation of the resulting combined data is difficult and for this reason they are seldom used.

4. Conclusion

In conclusion, although the sherwave circumferential test is excellent in many cases for finding longitudinal cracks on the inside diameter of bored bars and pieces, the ratio between the OD and ID is critical, not only to determine if the test is suitable but also to determine the correct angle probe that should be used.

It is my opinion that where the OD:ID ratio is greater than 1.624:1 (θ_{max} is less than 38^0) then it should be regarded that shearwave testing cannot be guaranteed to provide a comprehensive test to find longitudinal defects on the ID. This would contradict ASTM A-388 which states that angle testing is mandatory for all ratios less than 2:1 and thus implies that angle beam examination be adequate in finding longitudinal defects on the ID.

Where the OD:ID ratio is greater than 1.624:1 then one of the following options could be used in lieu of or supplementary to the shearwave ultrasonic test.

1) Perform the heat treatment operations in the solid state and bore out after the heat treatment and ultrasonic testing stages.

2) Perform surface NDT on the bore of the part. Magnetic particle inspection or dye penetrant inspection are quick and reliable methods for finding surface breaking defects and would be suitable for finding longitudinal linear (crack like) defects on the ID of bored items. It should be noted that in order to perform a satisfactory test post heat treatment the surface of the items would need to be in a dressed / proof machined condition. Another constraint would be the difficulty in inspecting long parts particularly with small diameter bores where access for inspection could be difficult.