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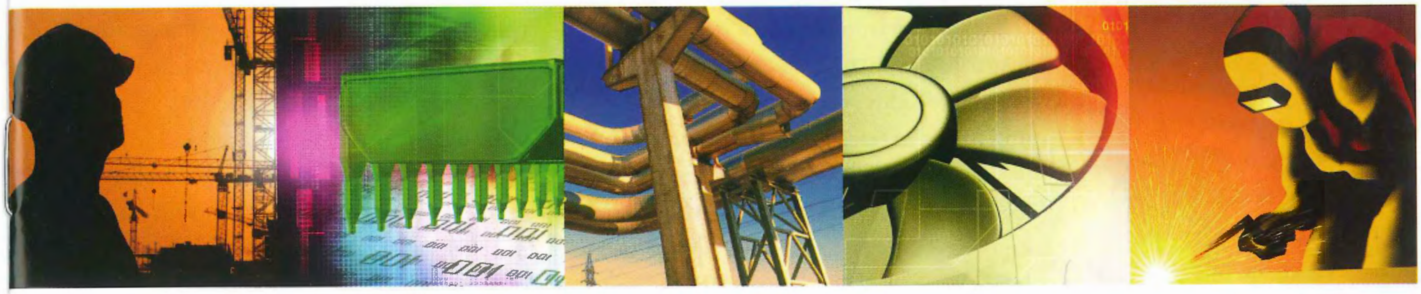

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Notes on Toroidal Fields

by Patrick R. Jenkins*

NDT practitioners, especially those working in aerospace, who perform magnetic particle inspection on ring or disk shaped parts may have an opportunity to use a method called *toroidal magnetization*. Because the use of a conventional bench type machine in the normal manner presents certain problems, including the possibility of arc burning or hazardous part handling operations, the use of a toroidal field presents a practical alternative. This article gives a description of how a toroidal field is generated and how it is used.

In mathematics, a *toroid* is a doughnut shaped object, such as an O-ring. In the NDT world, it describes the shape of the magnetic field encompassing a test piece during a specialized test method using certain types of coil. When a ring or disk shaped part is put into the field of the coil, the magnetic field flows in the direction defined by the *right hand rule*, a technique for visualizing the relationship between a flowing current and its induced magnetic field. When the right hand is closed in a fist and the thumb is extended in the direction of current flow, the coiled fingers represent the direction of the self induced magnetic field (ASNT 2008, 231). When the coil is suddenly de-energized, the field in the part quickly collapses, and this collapse generates a current that in turn generates a toroidal magnetic field surrounding the part (Fig. 1). The magnetic field is the result of the current flowing circumferentially through the test piece.

A coil can be thought of as a magnetic battery. The coil stores the energy of a magnetic field that has been converted to an electric current by a change in the field. As children, some of us may have created a simple electromagnet by wrapping numerous turns of wire around a nail or bolt and then touching the ends of the wire to the poles of a battery. The unpleasant shock we experienced upon disconnection from the power source was the result of the collapsing magnetic field and was far in excess of what the battery was capable of producing (Perkins 1896; Schwarz 1990, 198; Hayt 1981, 328).

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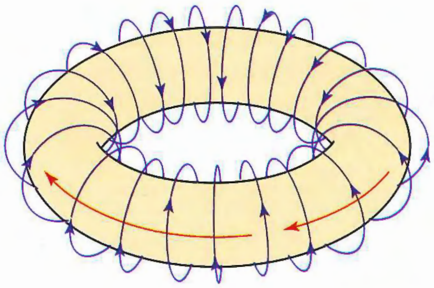

Figure 1. Toroidal magnetic field used in magnetic particle testing as noncontact means to reduce potential for arc burning.

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Purpose

In most cases, the purpose of using toroidal magnetization is to create a noncontact type of magnetic induction to eliminate the possibility of arc burning that may be produced by a direct contact shot. As a side benefit, inspection can often be performed in one step compared with other methods that might require multiple inspection steps, because the magnetic field is uniform and completely encompasses the part (assuming uniform part geometry).

Theory

With the above description in mind, it is important to note that although related, the primary magnetizing field produced by the coil does not actually create the toroidal field in itself. The toroidal field is created by the current produced when that coil field collapses. In simple terms, the sequence of events for developing a toroidal field can be described as follows:

1. Primary effect - magnetizing current (mag shot) produces a field surrounding the part.
2. Secondary effect - circumferential current flow is developed within the test piece by the collapsing field.
3. Tertiary effect - strong toroidal magnetic field is created as a product of the secondary current flow within the part.
4. Discontinuities perpendicular to the field direction within the part may now be detected.

This is a transformer technique in its simplest form (Schwarz 1990, 198; Hayt 1981, 328). Since direct current will not pass through a transformer, there must be a moving or time varying field to make this technique work. Because it happens quickly, almost instantaneously, it is the collapsing field that provides the time varying component. Without this, there is no secondary (eddy) current flow and no toroidal field. There must be a proper magnetic coupling between the primary winding and the effective secondary winding (test piece) to achieve this effect.

Figure 2 illustrates the dynamic condition that arises when a magnetic field moves or collapses in relationship to a ring. Without that collapse, there is no resulting secondary (eddy) current induced in the ring that is necessary to create the toroidal field shown in exaggerated form as the blue lines in Fig. 2 (Hayt 2001, 323). For simplicity, the magnet moving up and down (time varying) in Fig. 2 represents the primary effect in the example. However, we can just as easily substitute the flux field generated by the coil on our wet horizontal or mobile power pack as it collapses.

In order to concentrate the flux and make it perform more efficiently, we can insert a high permeability, low retentivity ferromagnetic laminated core through the part as shown in Fig. 3 (Lide 2002, 12-117). The laminated core holding the test sample is then placed within the coil. Note that the laminated core does not need to be centered within the coil or work piece and it is often preferable for it not to be centered due to the magnetic inverse square losses that can occur with distance. In this picture the laminated core is shown resting on the head and tailstock V rests, but that circuit is not energized.

The circulating current flows within the part and the core only during movement of the magnetic field. This is the sequence. When the coil is energized, a longitudinal field flows in the laminated core and to some extent in the part. When the coil is de-energized, this field collapses and induces a circumferential current into the part (red arrows, Fig. 1). This in turn induces a strong toroidal field surrounding the part in a radial direction (blue arrows, Fig. 1).

Alternate Fixture Types

One alternate choice to the use of an air core or machine coil is a simple transformer fixture. This type of fixture is often more desirable because it is easy to use and has lower current requirements. Most of the same application considerations apply, however these fixtures are generally more forgiving in usage. A typical example of the tabletop transformer fixture (Fig. 4) is usually connected to the wet horizontal machine's head and tailstock using a standard clamp block, making hookup easy and quick. The fixture also makes it easy to utilize the wet continuous method and can be removed from the machine when not needed. Larger freestanding transformer fixtures are available for use in special cases.

Figure 4 shows a side view of a tabletop (closed loop) transformer fixture with a

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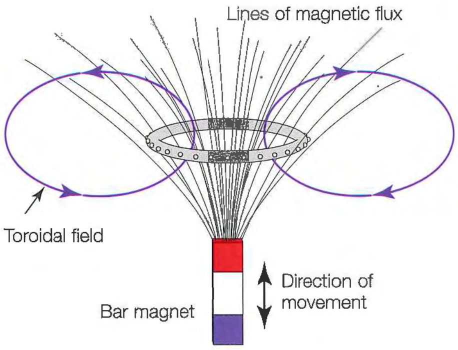

Figure 2. Secondary current is induced in ring only as result of movement of magnetic field of bar magnet in relationship to ring. Induced current in ring creates toroidal field (blue lines).

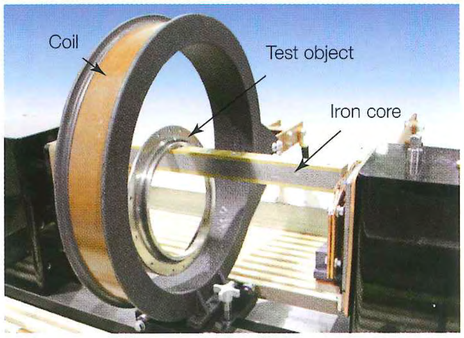

Figure 3. Magnetic flux during magnetizing pulse is concentrated in core inserted through test object.

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ring shaped part ready for inspection. Note that both the primary and secondary winding are in close proximity to the core. This allows tighter magnetic coupling than can be produced by an air core coil, thus increasing efficiency and reducing the amount of current needed. Usable alternating current produced in the secondary winding is the direct result of the changing magnetic flux within the magnetic core of the transformer (Schwarz 1990, 199). The flux path reverses 120 times per second when fed with a 60 Hz alternating current waveform. Without this time varying component no current will be induced into the secondary winding or part.

Equipment Application Considerations:

The following is a frequent comment. "My three-phase machine has a quick break feature, so I *have* a moving waveform." While it cannot be said that this statement is false, it is helpful to look a bit deeper into what the time varying component of the waveform actually is. The time varying component of the waveform is the collapse of the field at quick break. It is not the length of the magnetizing pulse. The collapse of the field at quick break is the only portion of the waveform that will create the eddy current flow. The graph in Fig. 5 illustrates an actual three-phase current waveform on a magnetic particle inspection machine obtained using a digital storage oscilloscope. This waveform represents the ideal conditions to be achieved; a rapid rise with no overshoot, stable output, and rapid fall conditions including the quick break pass condition. The graph is scaled so that each major division on the horizontal axis represents 100 ms, with a magnetizing value of 3500 amps direct current (average response). From a practical standpoint, the only real moving portion of this waveform is the ramp up, which allows the coil to store magnetic energy and the ramp down, (the quick break portion) which allows the stored magnetic energy to collapse into the ring, generating the eddy current and creating the desired toroidal field. This means the effective working time of the mag shot in this example is approximately 10 to 20 ms, no matter how long the actual pulse length.

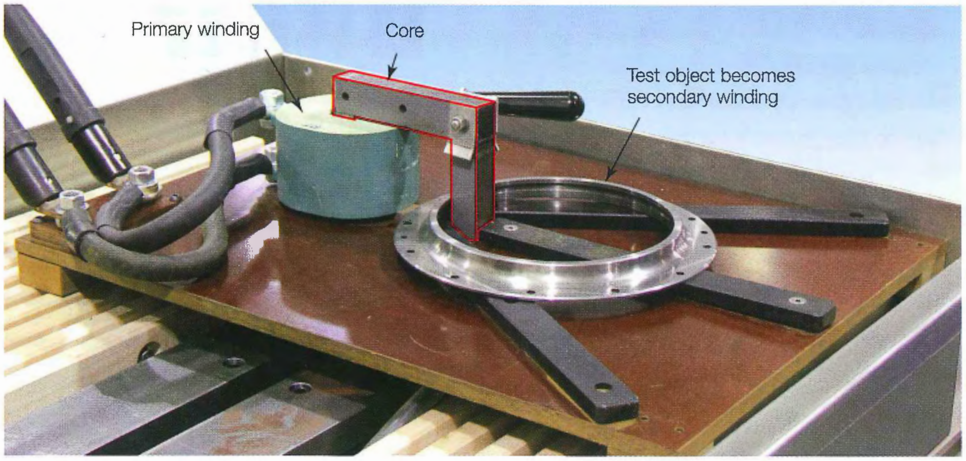

Figure 4. Table top, closed loop transformer fixture showing close proximity of primary and secondary (ring shaped test object) windings with core. Current and magnetic field within part illustrated in Fig. 1.

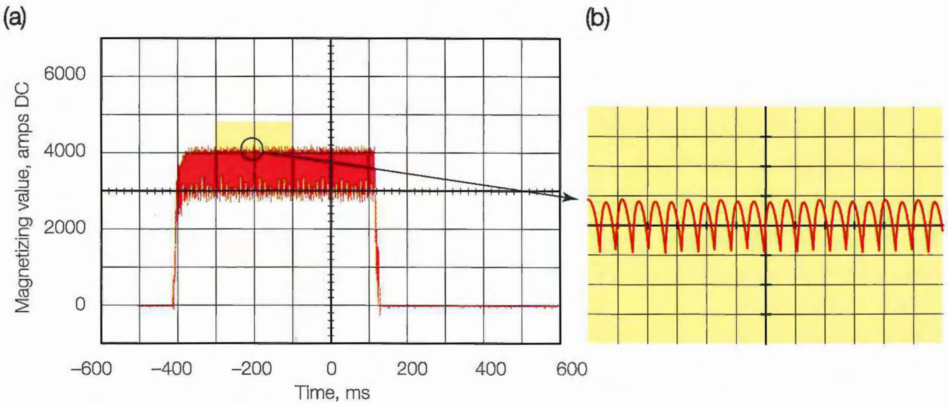

Figure 5. Ideal waveform conditions: (a) rapid rise, no overshoot, stable output, and rapid fall condition; (b) enlarged view of three-phase ripple on waveform peak with all phases in balanced load condition.

Technique Considerations

Due to the number of variables involved and differences in machinery, the technique should not be considered transportable to any other than the same make and model of equipment (and fixture style) on which the technique was originally developed.

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