Remanent Magnetism —A Cause of Arc Blow

Practical recommendations are presented on how to avoid arc blow attributable to the magnetization of different types of steel being welded

By E. HALMOY

From time to time, a welder will come across a workpiece that is strongly and permanently magnetized. Sometimes it is only a nuisance ; once in a while it is impossible to weld. The random occurrence of magnetized steel affects both quality and productivity. Efficient high quality welding is obviously unlikely when the welder has to struggle just to keep the arc burning.

Low carbon structural steel does not make good permanent magnets, but the remanent (i.e., residual) magnetic field evidently may be strong enough to deflect the arc. There are data available on the magnetic properties of the magnetically interesting alloys used in making transformer cores, strong permanent magnets, etc. As for the ordinary mild steels, however, there are very little reliable data.

In order to understand how a workpiece can be magnetized in practice, and how the problem can be avoided, it is useful to review the basic concepts of magnetization, demagnetization and magnetic circuits. Since there are hardly any data available, it has been necessary to measure the magnetic properties of some commonly used structural steels.

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Magnetic Arc Blow

A welding arc, like any other current carrying conductor, is subject to forces due to the magnetic field across the current path. This magnetic field may be due to the welding current itself, currents in other nearby circuits, or the sum of microscopic currents in a workpiece made of ferromagnetic materials such as mild steel.

The force per unit length of a conductor is proportional to the current times the magnitude of the magnetic field (i.e., the flux density) perpendicular to the current. The direction of the force is perpendicular to both the current and the magnetic field. If the polarity of either the current or the field is reversed, the direction of the force is also reversed.

When the forces are not symmetric with respect to the arc axis, they will tend to deflect the arc, which is a very mobile conductor. A magnetic field across a joint will tend to bend the arc forwards or backwards in the direction of welding depending on the polarities.

Magnetic Circuits

The magnetic field is only an abstraction used to account for the collective interaction of several currents It is visualized by means of lines of force that are always closed loops.

Figure 1A shows the familiar pattern of the lines of force around a short coil of N turns carrying a current I. A short permanent bar magnet would produce the same field pattern. If the coil is wound around a ring made of ferromagnetic material, the lines of force will follow the ring. This is a simple example of a magnetic circuit as in Fig. IB.

The number of lines of force which "flow" through the circuit is called the magnetic flux ϕ. The density of lines is B=O/A where A is the cross-sectional area of the ring. By consequence this quantity is called the magnetic flux density (measured in Tesla which equals 10,000 Gauss). The flux is "driven" by the ampere-turns NI, and the ability of the material to be permeated by

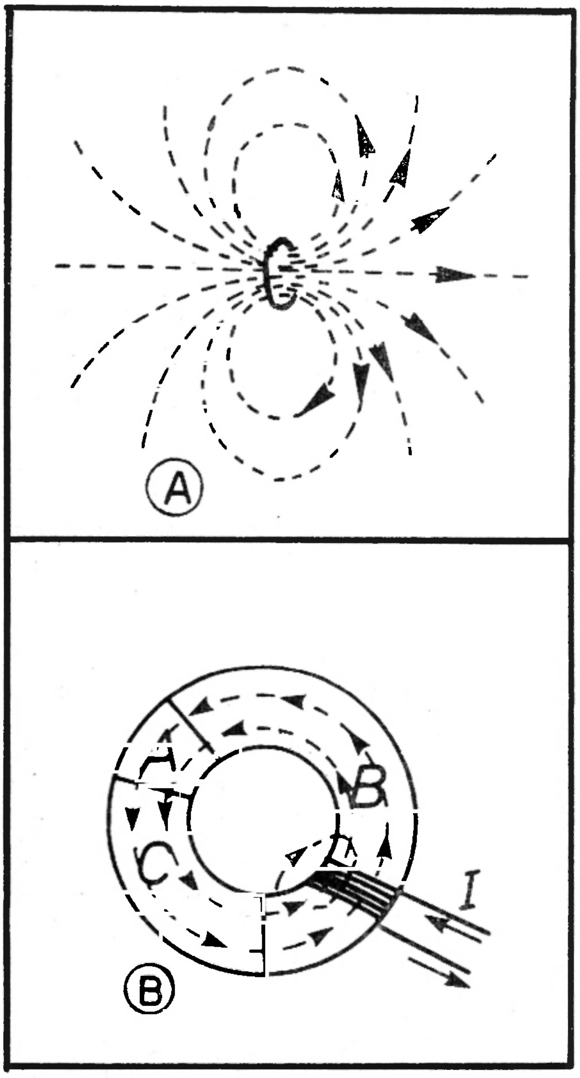

Fig. 1 Magnetic flux from a shortcoil A—in free space; B—through a magnetic circuit.

the flux is denoted by a quantity μ. This defines a new quantity $H=B/\mu$, which is called the magnetic field strength.

From the basic Ampere's law, one can derive an equation for the magnetic circuit in Fig. 1B, which is quite analogous to Ohm's law for an electric circuit :

$$\phi(I_A/\mu_A A_A + I_B/\mu_B A_B + I_C/\mu_C A_C) = NI$$

This is a powerful analogy that can be extended to more complex series and parallel circuits using the substitutions in Table 1.

The force is proportional to $B \times I$ and not $H \times I$. The names of B and H depend upon the author and year, which is very confusing. The notation used here agrees with the SI and, for the benefit of the practical engineer, clearly reflects the concept of a circuit.

Unfortunately, even a simple magnetic circuit is in reality much more complicated than the electric analogy. For one thing, there are no good insulators. Some leakage flux will always be present. Vacuum, air, and nearly all materials have a constant permeability $\mu=\mu_0$. In ferromagnetic materials $\mu=\mu_r \times \mu_0$. The non-dimensional factor μ_r is called the relative permeability and may equal several thousands. Unfortunately, μ_r is neither constant nor even single valued. It depends on the magnetic history of the material.

In practice, magnetic circuits are rarely simple rings. They may appear in the form of a frame, a stack of tubes, a workpiece in a fixture, etc. In such a circuit, the reluctance of an air gap of just 1 mm (0.004 in.) may be equal to that of several metres of steel. The flux density through the circuit generated by a current cable is, therefore, strongly dependent upon the absence or presence of small air gaps.

Table 1

Magnetic Force/Electric Circuit Analogues Equivalencies

Magnetic quantity	*Electric circuit analogy*
NI (magnetomotive force)	Applied voltage
ϕ (magnetic flux)	Current
B (magnetic flux density)	Current density
H (magnetic field strength)	Electric field strength
H.I (no name)	Voltage drop
μ (permeability)	Conductivity
$1/\mu A$ (reluctance)	Resistance

Magnetization and Demagnetization

The relationship between the magnetic field strength H and the flux density B for a particular steel is found experimentally by magnetizing a homogeneous ring of that steel. The field strength H=NI/I is simply proportional to the current. B is measured as described in the experimental section.

Starting with an unmagnetized ring, the B-H relationship will typically follow the dotted curve in Fig. 2, when the current is increased monotonically. This magnetization curve will flatten out as the material approaches saturation. When the current is reduced to zero, a B field of the same order of magnitude as the saturation value remains inside the ring. The flux density B_r which remains is called the remanence. It is necessary to reverse the current in order to force the B field back to zero. The corresponding value of H_c is called the coercivity.

By continuation, one can trace the familiar hysteresis loops of Fig. 2. By gradually decreasing the amplitude of the current reversals, the hysteresis loops will shrink towards the origin. This is one of two reliable ways to completely demagnetize a sample, The other way is to heat the whole sample to above 800°C (1500°F).

It is important to note that the remanence is always a very strong field and that it varies only by perhaps a factor 2 from one steel to another. On the other hand, the coercivity may vary by several orders of magnitude.

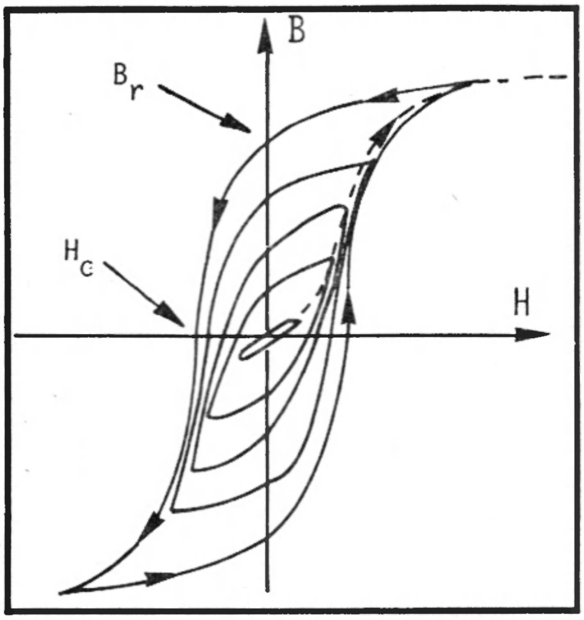

Fig. 2—Magnetisation curve and hysteresis loops.

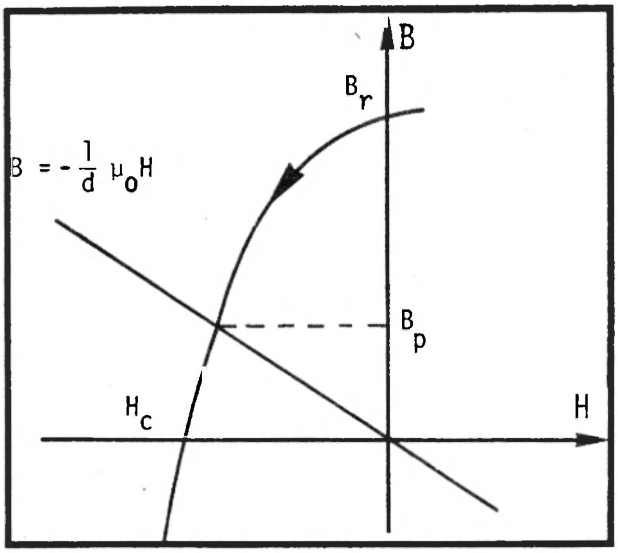

Fig. 3—Demagnetisation curve and line.

Fortunately for the welder, the remanent flux density is greatly reduced when an air gap of width d, like a welding groove, is cut across the ring. The B-H relationship drops along the second quadrant of the hysteresis loop, called the demagnetization curve. By using the magnetic Ohm's law, one can demonstrate that new values of H and B are given by the intersection of the demagnetization curve and a straight demagnetization line through the origin with the slope $-\mu_0 I A_A/dA_B$. This is illustrated in Fig. 3. A_A is the cross-sectional area of the air gap and A_B that of the steel ring. In this case $A_A/A_B \approx 1$, i.e., the slope is just $-\mu_0 I/d$. In SI units $\mu_0 = 4\pi \cdot 10^{-7}$.

In practice, the slope of the demagnetization line is small. It is, therefore, the width of the hysteresis curve, i.e., the coercivity, which determines the strength of the flux density across the air gap, and not the remanence. A material with a large value of H_c is called magnetically hard. A magnetically soft material has a low coercivity. A narrow hysteresis loop, i.e., a soft material, implies a steep magnetization curve, and vice versa. A magnetically soft material is, therefore, more easily magnetized than a hard material, but isn't as able to maintain the flux density across an air gap.

In the case just described, the magnetic circuit was closed while it was being magnetized, and the air gap was introduced afterwards. If the gap is present during the magnetization, it takes much more current to produce the same flux density, as shown schematically in

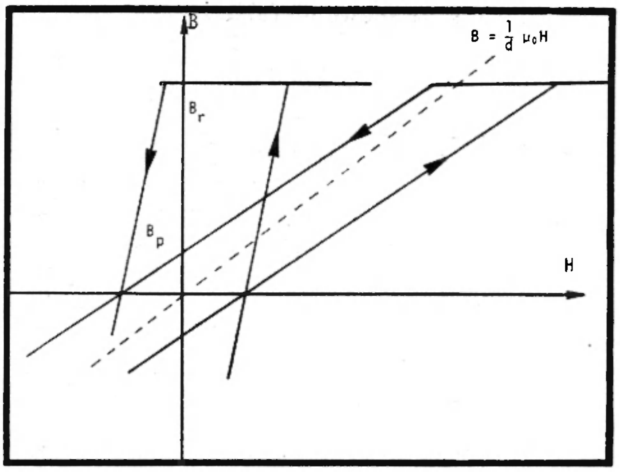

Fig. 4—Simplified hysteresis loop deformed by the presence of an air gap

Fig. 4. This simplified hysteresis loop is centered about a straight line with the slope $\mu_0 IA_A/dA_B \approx \mu_0 I/d$. The remanent flux density is given by the intersection of the demagnetization curve and the B-axis. Again, in practical cases the slope is very small ; this means that it is difficult to magnetize a magnetic circuit with a significant air gap, and the remanent field is greatly reduced by the presence of the gap.

Observations and Measurements

A number of actual cases of troublesome remanent magnetism are considered below. In addition, the magnetic properties of some typical steels as measured in the laboratory are presented.

1. Two 6 m (19.7 ft.) lengths of steel tubing with a 500 mm (20 in.) OD and 12 mm (0.5 in.) wall thickness were positioned for welding a butt joint using a V-groove with a 3 mm (0.12 in.) rootgap. Across the joint, there was a permanent magnetic field strong enough to hold sizable steelbolts, and welding was not possible. The magnetic field was measured to be approximately 400 Gauss in the root opening. The two tubes appeared to be magnetized like two bar magnets with stray fields of the order of 20-40 Gauss. The origin of the magnetization has not yet been traced.

The field was cancelled by means of a few turns of welding cable and a rectifier connected during welding. A number of other tubes were also magnetized but less so than this freak pair. They were welded with some difficulty without applying an opposing field.

2. The owner of an automobile repair shop was going to replace a 1 m (3.3 ft.) section of a chassis frame. The magnetic field was not measured but was obviously too strong for welding. With the aid of a battery charger, a counterfield was applied, and the job was finished. This man had welded a lot of frames in his life but had never seen any thing like this one.

3. A 10 cm (3.9 in.) wide ring was cut off a section of 36 in. (0.9 m) line pipe. The ring was cut in two halves which were tack-welded side by side forming a half ring with a V-groove and 1 mm (0.04 in.) rootgap along the mid-line. Thre was one tack-weld at either end of the half ring and one in the middle. A magnetic field of about 100 Gauss was measured across the root gap. It was assumed to be due to the tack-welding only.

As a demonstration, a GTA gun was held in the V-groove and a welding current of about 100 A was applied. The arc was strongly bent and the arc plasma blown along the groove. The metal in the groove was not melted at all.

4. Two 0.6 m (2 ft) lengths of 8 × 50 mm (0.31 × 2 in.) standard flat bar were tack-welded at both ends and in the middle to form a T-profile. Samples like this were used for experiments with fillet welding. After tack welding one could detect magnetic fields of the order of a few Gauss in the fillets of the T-bar. A rectifier was then connected to the ends of the crossbar of the T and a current of 450 A was passed along the profile for a few seconds. Afterwards a permanent magnetic field of about 40 Gauss was measured in the fillets, between the tacks.

5. Steel pipes that were to be welded and installed in an aluminium plant were strongly magnetized. Apparently it had happened when the pipes were transported close to the electrolytic cells. No measurements were made. The field was cancelled as in above case 1.

All measurements were made with a Bell 260 Hall effect Gauss-meter.

Coercivity Measurements

The hysteresis loops of three different ring shaped samples were traced in the following manner : More than 100 turns of twin lead lamp cord were wound around each ring. One lead was connected to a calibrated DC power supply. The voltage across a series resistor was connected to the X-axis of an X-Y recorder. The magnetic field strength then equalled H=NI/I. The second lead, acting as the secondary coil of a transformer, was connected to the Y-axis via an integrator/amplifier. The Y-input, which was proportional to the flux density B, was calibrated using a precision voltage supply.

The DC power supply was equipped with a current limit dial. The limit was initially set at a maximum value and the hysteresis curve was traced slowly (several tens of seconds) typically four times before an ink record was made. The current limit was then reduced, and a new curve was recorded in the same manner. Although the outer curves flattened off considerably, they were far from true saturation. The measured values of the coercivity H_c and the remanence B_r are, therefore, smaller than the maximum values. However, the difference is not important.

The three steels were samples from above case studies 1, 3 and 4. The last was a length of flat bar bent and welded in the shape of a ring. The other two were rings cut off the tubing. After recording the hysteresis curve of case 4, the ring was normalized, and a new set of curves was traced. A complete set of hysteresis curves is shown in Fig. 5 for case no. 1 only, the other being qualitatively similar.

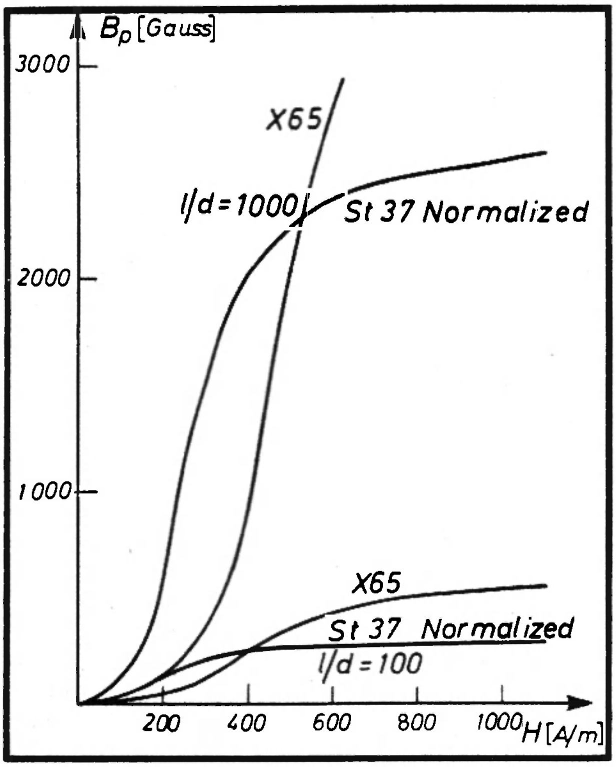

Fig. 5. Hysteresis loops of a St 52-3 steel.

The results are shown in Table 2.

Table 2

Coercivity (H_c) and Remanence (B_r) Measurements

Case No.	*Type of Steel*	*Carbon content, %*	*H_c, A/m*	*B_2, T*
1	St 52-3	0.20 max.	480	0.86
3	X 65	0.13	420	0.96
4	St 37	0.20 max.	328	0.86
(4)	(Normalized)	0.20 max.	250	0.95

Discussion

The only data relevant for comparison were found in ASM's *Metals Handbook* (Ref. 1) and are reproduced in Fig. 5. Here H_c is a function of carbon content. Our measurements are also plotted on the same diagram. Clearly, there is very little agreement. Other factors beside the carbon content must affect the coercivity of these steels. It is well known that small grain size leads to large coercivity (Ref. 2). The normalization experiment reported above also indicates that structural properties other than chemistry are important. Mcdern structural steels are apparently much better permanent magnets than expected.

What are the consequences of the increased coercivity ? A numerical example is shown in Fig. 6. Imagine an iron circuit of length 1 m (3.3 ft) with no air gap surrounding a welding cable carrying 575 A. The magnetization will then reach the point of the third largest loop. Now, if we introduce a large air gap of length 10 mm (0.4 in.), i.e., $1/d=100$, we end up with a permanent field of $B_p=360$ Gauss. An air gap of 1 mm (0.04 in.) gives a permanent field of $B_p=2900$ Gauss !

For low levels of magnetization, the softer materials may end up with a higher permanent magnetic field than the harder ones. By means of the same procedure as just described, the final values of B_p were plotted as a function of the magnetomotive force 1/1 for the magnetically hardest (case 3) and the softest steel (case 4, normalized). This is shown in Fig. 7 for two different values of air gap reluctance.

Studies of the magnetic deflection of gas-tungsten arcs (Ref. 3,4), indicate that applied magnetic fields of

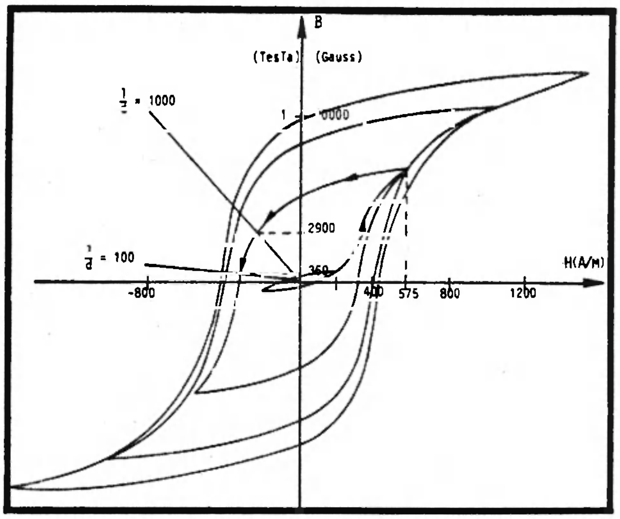

Fig. 6. Coercivity as a function of carbon content according to Ref. 1. Present results are indicated.

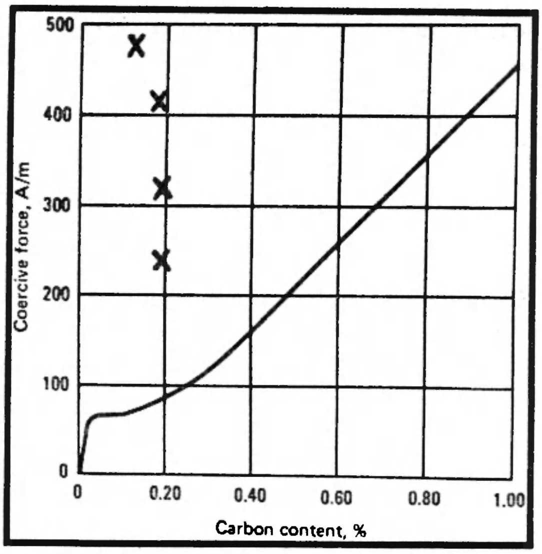

Fig. 7. Remanent flux density as a function of ampere-turns per metre for two steels and different air gaps.

the order of 10 to 100 Gauss produce very large deflections which strongly affect the bead shape. Clearly then, permanent magnetic fields of the order of several hundred Gauss are unacceptable.

In automatic welding, the existence of sporadic permanent magnetic fields will introduce an uncontrollable variable. In manual welding, a skilled welder may be able to produce an apparently sound weldment in spite of the magnetic field. In the off-shore construction industry today, however, the welder is obliged to adhere to very strict and sometimes very expensive procedure specifications. There is little reason to suppose that the welder can fulfill these when it is necessary to struggle just to deposit the metal. In that case either the weldment or the specifications are faulty.

Experience shows that strongly magnetized workpieces occur sporadically for no apparent reason. Our numerical examples show that, when there is no air gap, it takes no more than ordinary welding currents to produce unacceptable magnetic fields in good-sized magnetic circuits. However, it takes very little air gap to drastically reduce the initial magnetization caused by a given current. Normal variations in the length and area of air gaps occurring in stacks and fixtures may, therefore, explain the haphazard occurrence of magnetized steel.

What to do ?

Prevention is the best cure, because the magnetic field is hard to remove from large workpieces. Fortunately, it is not difficult to avoid closed magnetic circuits and magnetomotive forces if one is aware of the problem. This requires that people involved in the handling and transportation of steel should know the basics of magnetic circuits and the consequences of magnetization. Care should be exercised when using magnetic cranes, magnetic particle inspection, heat treatment by induction or electric furnaces, etc. Control and avoidance of magnetization ought to be included in any quality assurance system. If one reserves the right to reject a strongly magnetized item, the supplier might be more careful.

Once the damage has occurred, i.e., the steel is magnetized, the object is to remove or reduce the field across the gap—at least, while the welding is being done. To demagnetize large steel parts completely by either heating or running through the hysteresis loops is rarely feasible. Attempts to demagnetize limited areas of the steel part are likely to have either no effect or set up an even stronger magnetic field.

A permanently magnetized circuit cannot be "short-circuited" by bridging the gap with a piece of mild steel. The flux density close to the bridge may be reduced by 20-50 %, but this is insufficient.

The best procedure is to carefully apply an opposing field during welding. This can be done by loosely laying a few turns of welding cable on both sides of the joint forming one coil around the work piece. This coil is then connected to a rectifier. It is important to get the polarities right. Otherwise one can easily make things worse.

To find the direction and strength of the current without the use of expensive instruments, this simple method is suggested :

1. Place a small pocket compass close to the gap. The red (north) end of the needle will point in the positive field direction.

2. Grab the coil cable with the *right* hand in such a way that one's fingers are squeezed between the coil and the steel and pointing in *opposite* direction of the field. The thumb of the right hand then points in the proper direction of the current.

3. Increase the current until the compass needle changes direction.

4. Check the strength of the flux density by means of a paper clip, a piece of wire or other small piece of mild steel hanging in a piece of string. When one feels no magnetic pull in the gap, neither will the welding arc.

5. If the flux density varies significantly along the gap, it may be necessary to adjust the opposing field during the welding.

6. A simple way to fine adjust the flux density is to move the cable turns towards or away from the joint.

The maximum acceptable welding current should be used to increase the stiffness of the arc. Low voltage (i.e., a short arc) gives less deflection. Since the permanent magnetic field is independent of the welding current, the deflecting force on the arc will change direction when the welding current is reversed. AC welding may, therefore, be advantageous if otherwise acceptable.

Conclusion

Normal welding currents are sufficient to produce very strong magnetic fields if the workpiece is part of a closed magnetic circuit. The coercivity of modern steels are much higher than previous data would indicate. Consequently, the magnetic flux density across normal welding joints can be one or two orders of magnitude stronger than that which is used for deliberate arc deflection.

Strongly magnetized workpieces appear sporadically. Often, it is difficult to retrace the origin of the magnetic field. The best precaution is to avoid forming magnetic circuits and to be aware of the effects of welding cables and ground currents.

Remanent magnetism may be a serious uncontrollable problem in automatic welding. For manual arc welding it may render adherence to strict procedure specifications illusory.

A permanent magnetic field can be cancelled during welding by means of welding cable and a rectifier.

Acknowledgement

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