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Can We Use Induction Heating to Weld Steel as a Fusion Welding Process?

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Abstract: ***Using heat is very important for forming, joining, or treating most metals. Heat can be applied to metal by different processes, such as flame, ARC, friction, furnaces, and induction heating. This paper will focus on induction heating process, how it works, its advantages, applications, and if it can be used for welding steel as a fusion welding process? Using some sources is significant to buildup our point of view in this paper about using induction heating process for welding a steel as fusion welding.***

Keywords: Induction heating, steel, welding, and fusion

1. Introduction

Induction heating uses high frequency electricity to heat electrically conductive materials (usually a metal). Eddy currents are generated within the metal where the metal resistance leads to its heating. This is done by the effect of the electromagnetic induction. The heat is generated inside the work-piece, which is very efficient and a non-contact process. Therefore, using induction heating for welding is very useful and easy to use compared with other welding processes, while the main question is, can we use it for fusion welding to weld steels ? This will be shown in our research by using some academic resources to buildup our point of view and final result.

2. Working Principle

According to Faraday's Law, An alternating magnetic field is created when an alternating current flows in the primary coil of a transformer. An electric current will be induced in the secondary coil of the transformer if it is located within the magnetic field.

Figure (1) below, shows a basic induction heating setup. A power supply generates an alternating current (AC), which flow through an inductor (usually a copper coil). By placing the work-piece, which has to be heated, inside the inductor, it becomes a short circuit secondary. Where the inductor serves as the transformer primary. Circulating “Eddy Currents” (circular electric currents induced within conductors by changing magnetic field in the conductor. Also called Foucault currents) are induced within the work-piece when a metal part is placed within the inductor and the magnetic field [4].

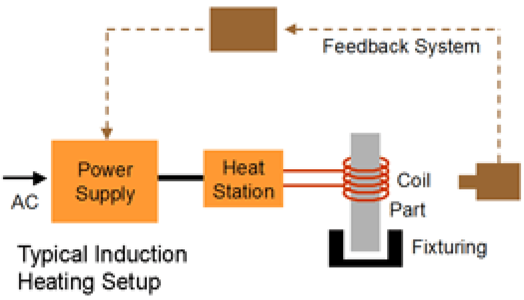

Figure 1: A basic induction heating setup [4].

In the next figure (2),it is showing the “Eddy Currents” (black arrows in work-piece) flow against the electrical resistivity of the metal work-piece. Without any direct contact between the metal part and the inductor, this generates a localized and precise heat .Both magnetic and non-magnetic parts can be heated in this way. This effect is related to the "**Joule effect**", a scientific formula expressing the relationship between heat produced by electrical current passed through a conductor [4].

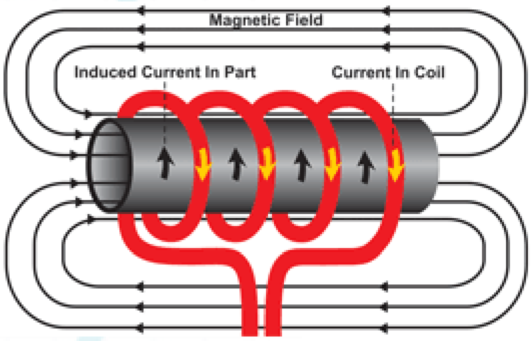

Figure 2: The flow of Eddy Currents [4].

Also, when magnetic parts pass through the inductor, internal friction is created and additional heat is produced within the magnetic parts. Due to the rapidly changing magnetic fields within the inductor, naturally, Magnetic materials offer electrical resistance which produces internal friction which in turn produces heat and helps to heat faster.

There is no contact between the part and the inductor during heating process, neither any combustion gases. That is one of the best advantages which can be offered in this process.

To get the best transmission of energy from the electrical conductor to the part needed to be heated, a sufficient intense magnetic field has to be created and the work-piece has to be positioned within the field’s center. To achieve this, the electrical conductor or coil need to be formed with one or more turns and the work-piece is positioned in the centre of the coil to concentrate the magnetic field onto the component. The electrical current is, then, forced to flow within the part. Both currents flow strength in the component and the coil are equal. The current flow in the coil must be very high, between 1000 – 10.000 amperes, to create enough strong magnetic field. Current that intense normally would melt the coil. Water cooled copper tubing coil is must be used, In order to avoid this problem.

Increasing the frequency of the current is another way to create a strong alternating magnetic field. Both household and industry electrical mains supply normally operates at a frequency of 50 Hz, i.e. the current will change direction 50 times / sec. An induction heating equipment operates at a frequency of 50 and 1 million Hz range, depending upon the application.

3. Induction Heating Applications

Heat Treating:
- Single Shot
- Normalizing
- Tooth-by-Tooth Gear Hardening
- Quench & Temper
- Seam Annealing

Tube & Pipe:
- Austenizing
- Coating & Galvanizing
- Pipe End Heating
- Seam Annealing
- Upsetting

Brazing & Joining:
- Wire Heating
- Brazing & Soldering
- Preheating

Forging & Forming:
- Bar End Heating
- Bending
- Twisting
- Fitting

Specialty Heating:
- Crystal Growing
- Shrink-Fitting
- Susceptor Heating (for non-conductive materials)

Advantages of Induction Heating:
- Obtaining very high power density due to the heating speed.
- Concentrated location heating.
- High temperatures.
- Adapted to medium-sized and mass production industrial requirements.
- Easy automation of equipment.
- No thermal inertia.
- Repeatability of operations.
- High heating efficiency.
- No pollution from the heating source.
- Energy saving
- Saving time
- Safe

Disadvantages of Induction Heating:
- Complicated device design.
- High initial cost.
- Limited applications
- Limited penetration heating depth.
- Requires A.C. power supply with high watts (hard to be portable).

Important Factors To Consider:
The efficiency of an induction heating system depends on several factors:
The characteristics of the material itself, the design of the inductor, the capacity of the power supply, and the amount of temperature change required for the application.

4. Characteristics of the Material

Electric Conductivity
Induction heating works only with conductive materials (metals). To heat plastics or any other non-conductive materials, we heat them indirectly by first heating a conductive metal, which called “Susceptor” where it transfers the heat to the non-conductive material, and it should be connected directly to the work-piece.

Magnetic or Non-Magnetic
Magnetic materials are easier to heat, because they produce heat through what is called the “Hysteresis Effect” (quick flipping of the magnetic domains which causes considerable friction that leads to generates heating inside a metal) , in addition to the “Eddy Currents” to induced heat. On the other hand, magnetic materials loses their magnetic properties when heated to a certain temperature, called the “Curie point”.

Curie point (temperature) is approximately 700°C, where the steel loses its magnetic properties if heated above this temperature, and there can be no heating due to “Hysteresis” losses. All heating on the steel above 700°C will be due to induced “Eddy Currents” alone.

Therefore, it’s a challenge for the induction heating systems to heat the steel above 700°C. Alloyed steels may have lower curie point. It’s also a challenge to heat Copper and Aluminum efficiently by induction heating. Both are non-magnetic and very good electrical conductors.

Thick or Thin
About 85% of the heating effect occurs on the surface (skin) of the conductive materials’ work-piece. As the distance from the surface increases, the heating intensity diminishes.

The smaller or thinner the parts the quicker it can be heated than large thick parts, especially if heating is needed all the way through in larger parts.

There is a relationship between the frequency of the alternating current and the depth of heating penetration. the higher the frequency, the shallower the heating in the work-piece. Frequencies of 100 to 400 kHz produce relatively high-energy heat, ideal for heating small parts or larger part’s surface (skin). Frequencies of 5 to 30 kHz is used to get longer heating cycles and it have been shown to be most effective for deep penetration as we will see in the upcoming table (1).

Table 1: The approximate frequencies to reach the highest temperature for both magnetic and non-magnetic steel depending on the diameter size (distance from metal's surface to be heated) [12].

Magnetic Steel Final Temp. 700°C	Frequencies Needed	Non-Magnetic Steel Final Temp. 1200°C
Ø in mm	Hz	Ø in mm
27 – 75	50	150 – 500
8 – 35	500	60 – 250
6 – 25	1K	40 – 175
3.5 – 14	3K	25 – 100
2.5 - 10.5	5K	20 – 85
2 - 8.5	10K	14 – 60
1.5 - 5.5	20K	10 – 40
0.7 – 3	60K	5 – 22
0.5 – 2	100K	4 – 17
0.2 -1	500K	1.8 – 8

Electric Resistivity

If two same size pieces of steel and copper are to be heated by the same induction heating process, we will get a different result. Steel with carbon has high electrical resistivity. Both strongly resist the flow of the current, therefore, heat builds up quickly. On the other hand, Copper, Brass and Aluminum take longer to heat and that's because of their low current resistivity. A very hot piece of steel will be more receptive to induction heating than a cold piece; so, Resistivity increases with temperature and helps to heat the metal faster.

Inductor Design:

Magnetic field in the induction heating system is developed through the flow of alternating current within the inductor as we have seen in the last figure (2) .So inductor design is an important aspect of the overall system. To get a proper heating pattern for your part and maximum efficiency of the induction heating power supply, the inductor has to be well designed, while still allowing the part's insertion and removal easily, in the same time.

Power Supply Capacity

The energy needed to be transferred to the work-piece must be determined. This depends on the mass of the material being heated, the specific heat, and the rise in temperature required for the material. We should also conceder, Heat losses from conduction, convection and radiation.

5. Degree of Temperature Change Required

The efficiency of induction heating depends on the amount of temperature change required. From all previous information, we can see that there are three major factors or conditions, which can directly affect the response of the metal with the induction heating process. These factors are fixed in the metal and strongly effect the possibility of the metal to be heated in order to reach the desired temperature. The three main factors or conditions that metal depends on to be heated, are actually called material's properties. These material's properties are electric conductivity, electric resistivity, and magnetic. The material which has these three properties with the highest rates, will be best fit to be heated in induction heating process rather than other materials. That leads us to one material which fulfills these three condition, and this is a steel.

Steel has a very good magnetic, electric conductivity, and electric resistivity comparing it with other materials. Therefore, we will focus on the steel to find out if it possible to use induction heating process to weld a steel as a fusion welding or it is not possible.

6. Effect of Frequency on Induction Heating

The induction heating process is influenced by the electrical frequency. The dimensions of the work piece, type of material, position between the part and the coil, and the penetration depth desired ,all to be considered to determine the desirable frequency range .The penetration of heat is decreased As the frequency increased. The normal range of frequency is 500 Hz to 10 kHz, and 100 kHz to 2 MHz. High range of frequency used for quick heating of small objects or the surface of large parts .Low frequency of 5-30 kHz is used to get deep heat penetration. This is clearly shown in the previous table (1). To prove the relation between the frequency and the heat penetration's depth and how do they affect each other, we have gathered some significant information about current density penetration and the frequency from some academic figures and equations, such as Dr. Valery Rudnev's paper as we will see next:

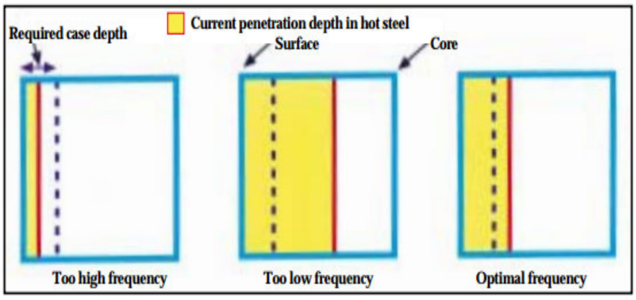

Figure (3): This figure showing the affection of the frequency amount used on the current density penetration depth from the surface of the steel [5].

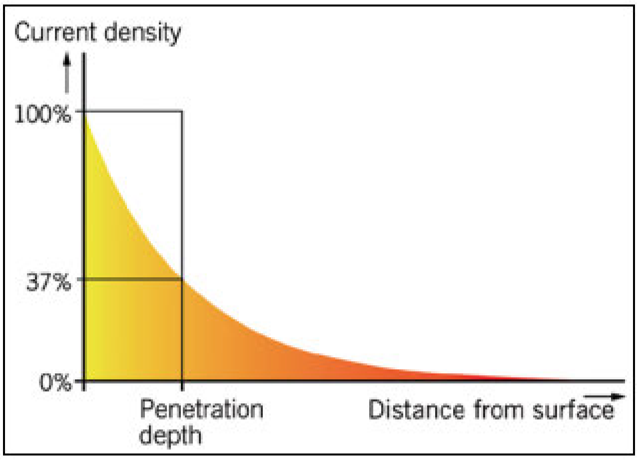

Figure 4: This figure showing concentration of the current density penetration affected by the distance from the surface [12]

In the figures (3 & 4), we can see that the penetration depth of the current density decreasing if we increase the desired distance to be heated from the surface as it shown in figure

(4), but in the same time in figure (3), the desired penetration depth of current density can be controlled by the amount of the frequency used. We can also prove that using some theoretic equations as we will see next:

$$I = I_{\circ} \times e^{(-y/\delta)} \quad \text{Eq. (1), [5].}$$

$$\delta = (503) \times \left((\rho/(\mu_r \times f))^{(1/2)} \right) \quad \text{Eq. (2), [5].}$$

First equation is to find (I), which is the density current (in Ampere per square meter) at the distance from the work-piece's surface (y) in (meter), with respect of current density at the surface ($I_{\circ}$) (in Ampere per square meter), and (δ) is the current penetration depth (in meter). While, equation (2) is for finding the current penetration depth (δ), where (ρ) is the electric resistivity of the metal (in Ω.m), (μ_r) is the relative magnetic permeability, and (f) is the frequency (in Hz). Therefore, from both equations, we can see that to increase the current penetration depth (δ), we need to decrease the frequency (f) as one can see in equation (2). Mathematically, increasing the depth of current penetration will increase the current density directly as it shown in equation (1). Also, At one penetration depth from the surface ($y = \delta$), the current will equal 37% of its surface value as we see in figure (4). However, the power density will equal 14% of its surface value. So from this, we can conclude that about 63% of the current and 86% of the induced power in the work-piece will be concentrated within a surface layer of thickness (δ) [5].

7. What is Induction Welding?

Induction welding is a form of welding that uses electromagnetic induction to heat the work piece. The welding apparatus contains an induction coil that is energized with a radio-frequency electric current. This generates a high-frequency electromagnetic field that acts on either an electrically conductive or a ferromagnetic work piece. In an electrically conductive work piece, such as steel, the main heating effect is resistive heating, which is due to magnetically induced currents called eddy currents.

In a nonmagnetic materials, such as plastics, can be induction-welded by formulating them with metallic or ferromagnetic compounds, as we mentioned before, it is called "Susceptors," that absorb the electromagnetic energy from the induction coil, become hot, and lose their heat energy to the surrounding material by thermal conduction.

Induction welding typically applies high frequencies in the range of 200 to 600 kHz and power from 50 to 1500 kw. The choices of frequency is crucial, as it determines the heat's penetration depth. Table (1) shows the approximate frequencies for heating steels (magnetic and non-magnetic).

From table (1), one can see that the frequency increasing when the diameter size of the steel is decreasing (distance of penetration from metal's surface). That showing the lower rate of frequencies per second can be used for deeper heat penetration, which is good for heating up thick material.

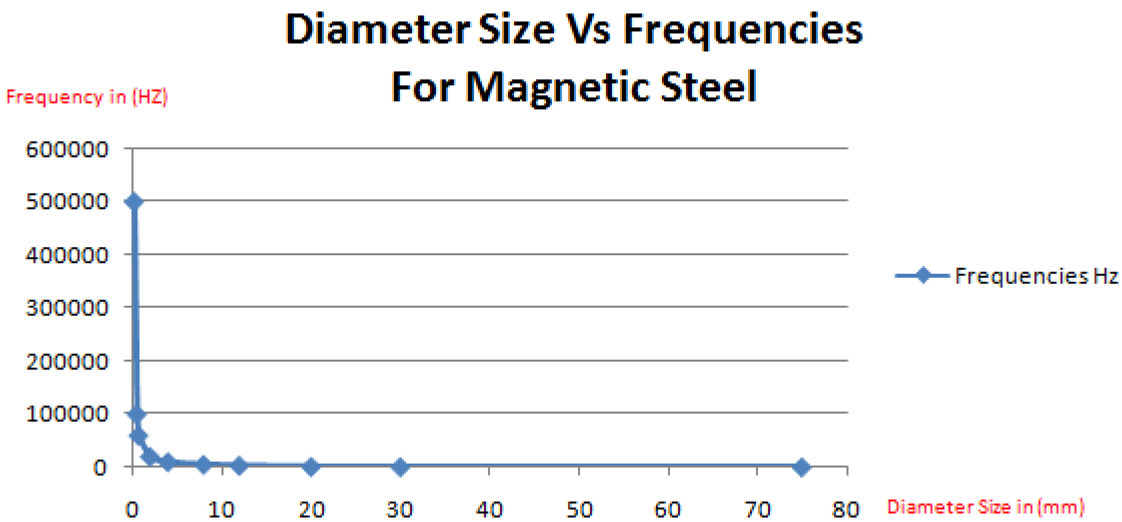

Figure 5: The relation between the diameter size (mm) (distance of penetration from metal's serface) and the frequency (Hz) used in induction heating for Magnetic Steel

The previous figure (5), showing us the trend of the relationship between the diameter size of a magnetic steel and the frequency needed to heat it up to (700°C). It is clear for the reader that to obtain deep heat penetration lower frequency is needed.

Can we use Induction Heating Method to Weld A Steel?
First, we have to check if the steel is capable to be induction welded/heated & fulfills all the conditions needed to be in any metal to be induction welded.

Since steel is a conductive material, one of the many conditions that must be in any material to be induction heated, then it's suitable for the induction welding.

Steel is magnetic. Magnetic metals are easier to be induction heated/welded than a non magnetic metal as we have discussed before.

Electrical resistivity .Steel has high electrical resistivity. Because steel strongly resist the current flow, heat builds up quickly. Low resistivity metals such as copper, brass and aluminum take longer time to heat. Resistivity increases with temperature, so a very hot piece of steel will be more receptive to induction heating than a cold piece.

Therefore, steel is capable to be induction welded only because it fulfills the requirements needed for a metal to be induction welded/heated.

Types of Steels and can Induction Heating/Welding Be Use To Weld Them as a Fusion Welding Process?

1) Low-Carbon Steel:
This type of steel contains a very low content of alloying elements and small amount of Mn (Manganese) and the percentage of carbon content is less than (0.25 weight % of C). This type of steel mostly called "Wrought Steel," and it's main desirable properties are ductile, malleable, tough, can be strengthen in cold working, and well known easy material to be welded. It was known as "Pure Iron," and its melting point temperature range is (1480-1590°C). It's main applications are sheets, wires, and pipes.

2) Medium-Carbon Steel:
This type of steel it has more content of carbon and manganese. The carbon content of this type of steel is between (0.25-0.60 weight % of C). It is mainly known as "Mild Steel," and has some desirable properties comparing it with the Wrought Steel such as, more strength, wear resistance, and sacrifice of ductility and toughness . The melting point ranges for Mild Steel is (1420-1540°C). Some of its main applications are railway wheels, gears, crankshafts, and other machine parts.

3) High-Carbon Steel:
This type of steel is designed to stay longer than standard Mild Steel. It has a carbon content between (0.60-1.40 weight % of C). It is usually containing vanadium, tungsten, molybdenum, and chromium. This combination makes this type of materials harder, high strength, and less ductility comparing it with Mild Steel. It is called "Hardox Steel" and it's melting point temperature range is (1425-1530°C). Its applications are razors, hacksaw blades, springs, and high-strength wire.

4) Stainless Steel:
The predominant alloying element for this material is chromium, with a concentration of at least (11 weight % of Cr) and more than (50 weight % of Fe). This type of steel can be divided to three main classes or grades depending on the phase constituent of microstructure austenitic, martensitic, and ferritic. The first two grades of this material are non-magnetic, while the ferritic can be consider as magnetic material. The Stainless Steel well known as excellent corrosion resistance and ultrahigh-strength steel under high temperature up to (1000°C) because of the high content of chromium. Stainless steel has a melting point range about (1380-1520°C). It's main applications are cooking equipment, high temperature steam boilers, heat-treating furnaces, and aircrafts.

5) Cast Iron:
This type of steel is a class of ferrous alloys which has carbon contents range is (2.14-6.70 weight % of C). It mainly classifies to four different types, Gray Iron, Nodular, Malleable, and Compacted Graphite Iron depending on the content of carbon and some other elements with some differences in the microstructures during the heat-treatment process. The main properties of Cast Iron are hard, high strength, high thermal conductivity, and generally it has a good thermal shock but difficult to weld. Melting point range is (1130-1220°C). Typically these types of steel are used for cylinder blocks, valves and pumps bodies, diesel engine blocks, gears, rollers, and exhaust manifolds [15].

From the melting temperatures of the most common steels that are used in welding, we found that cast iron has the lowest melting temperature (around 1130℃).

Now the question is, does induction heating/welding reaches the melting temperature of any kind of steel commonly used in welding?

According to the information in the previous table (1), that shows the approximate frequencies for heating some common materials depending on the size of the diameter, we can see that the maximum temperature which can be reached using heat induction to heat some common steels is 1200º C for a non magnetic steel mostly (Stainless Steel).

So, from the previous information about the types of steels that can be welded as fusion welding using any welding methods, we found that Cast Iron has melting point ranges about (1130-1220 ℃), which is the lowest melting temperature range among steels. So it's impossible to fusion weld it using induction welding, because as it showing in the table(1.1) induction heating/welding can reach only (700°C) for magnetic materials. Cast Iron is one of the magnetic steels, which has the lowest melting point range among all the steel's types as we have mentioned in the previous pages.

Another consequences of applying induction welding on a steel as a fusion welding is that, welding puddle which is a must to start and continue welding line. The induction technique uses a rod or coil to heat a wide area of the metal which means that the heat is not concentrated on a small area to form a welding puddle and control it to start the weld on a specific area on the surface. Therefore, it's very difficult, for now, to fusion the steel.

8. Result Discussion & Point of Interest

We have reached a point that we can't weld a steel as a fusion welding using induction welding method. But from what we have reached, we have found that a non-magnetic steel can reach higher temperature than a magnetic steel around (1200°C) by applying it to the induction heating. This leads us to a very important point, which is, losing magnetic property of the steel one of the main three condition of induction heating can be replaced by increasing the steel's electric resistivity, but not to reach the point to turn it to insulator. Where electric conductivity is very important for the material and can't be neglected, in order to apply it for induction heating. So, we leave the door open for other researchers to move on and continuing this research to find out, can the steel be melted by using induction heating process by using a "Susceptors," as what we do for plastics.

But we need a metal, which has a very high electric resistivity without focusing on magnetic property as a "Susceptors." This is a real challenge for researchers to find out a material which can be heated by induction heating process above (1400˚C) in order to use it as a "Susceptors" to weld a Cast Iron steel as a fusion welding, which has the lowest melting temperature among steels.

9. Conclusion

Induction heating is a common heating process used to heat metals. It's used in many applications, especially the applications involving heat such as, non-fusion welding (soldering and brazing), heat-treatment, and thermoforming (forging, straightening, and shrink fitting). The effect of heating depends on the Characteristics of the part used to be induction heated or welded and the parameters of the machine used.

So far, induction heating cannot be used to weld steel as fusion-welding process due to the main three conditions of induction heating/welding. For magnetic steel we have seen that the temperature can reach only (700˚C), and that because of, this type of steel will lose its magnetic property when heated above (700˚C) and this known as "Curie Temperature." By reaching this temperature the steel looses the magnetic property, will affect directly on (Hysteresis Effect), one important condition of induction heating/welding which we have mentioned before.

On the other hand, we have the non-magnetic steel, which mostly represents Stainless Steel in our research. This type of steel as we mentioned before, it has higher melting point with the range of (1380-1520˚C). Due to table (1), we found that the temperature which induction heating offers is only (1200˚C) and not enough to melt the Stainless Steel.

Therefore, we have came up with a conclusion of, the induction heating/welding process cannot be used as a fusion welding process for steel, because the temperature which we can reach is not enough to melt the steel. As we mentioned in the previous pages, that is happened because of losing one of three main conditions or factors of induction heating/welding . When we talk about the three main conditions or factors, we mean material's electric resistivity and magnetic property only, but not its electric conductivity. Materials with no electric conductivity, can't be heated directly by induction heating/welding without "Susceptors."

Losing magnetic property draws the heating temperature down for the steel. While, increasing the electric resistivity property of the steel leads to increase the heating temperature as what we have seen in table(1). Therefore, magnetic property of a metal is helpful to be heated by induction heating, but we can sacrifice it with increasing the metal's electric resistivity in order to reach higher temperature such as Stainless steel (the non-magnetic steel).

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