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INTRODUCTION TO MAGNESIUM

This chapter introduces magnesium as an energy-efficient material that has the potential to replace steel, aluminum alloys, and some plastic-based materials. This is possible for a design engineer as the specific strength and stiffness of magnesium exceeds that of most commonly used metals and some plastic-based materials. Serving engineering applications since 1920s, magnesium was not the material of choice for many applications due to its high cost till about two decades back. Interest in magnesium-based materials is recently revived primarily because of its gradually reducing cost and the resolve of the scientists, researchers, and engineers to cut down energy consumption and greenhouse gas emissions.

1.1. INTRODUCTION

Over the years, with the increasing demand for economical use of scarce energy resources, skyrocketing crude oil prices (see Figure 1.1) [1], and ever-stricter control over emissions to lower environmental impact, industries are constantly searching for new, advanced materials as alternatives to "conventional" materials. The spike in crude oil

Magnesium, Magnesium Alloys, & Magnesium Composites, by Manoj Gupta and Nai Mui Ling, Sharon

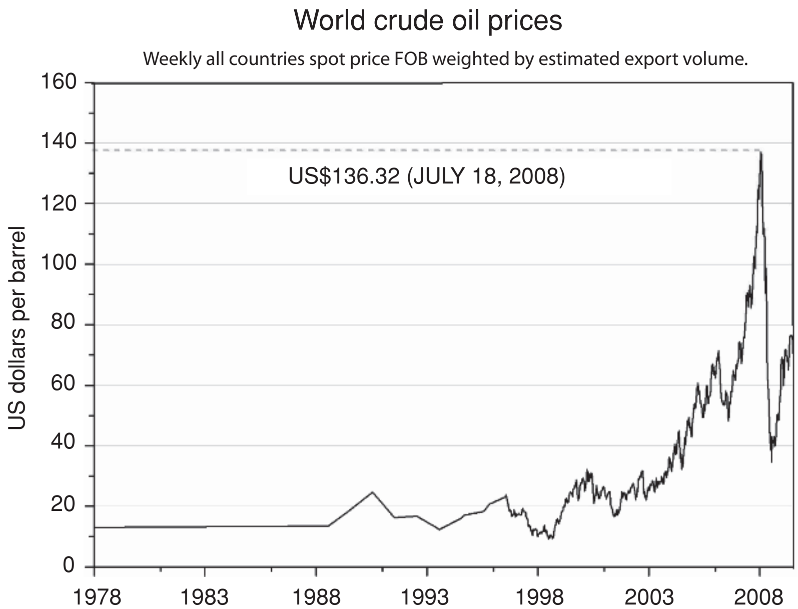

Figure 1.1. World crude oil prices. (Energy Information Administration, US)

price in July 2008 (see Figure 1.1) revealed the future trend of oil prices. Owing to this price rise, coupled with the depletion of energy resources with time, the choice of lightweight metals is the key and unavoidable solution for the future. Magnesium is one such promising lightweight metal, which is currently underutilized for engineering applications.

Magnesium is the sixth most abundant element in the earth's crust, representing 2.7% of the earth's crust [2]. Although magnesium is not found in its elemental form, magnesium compounds can be found worldwide. The most common compounds are magnesite ($MgCO_3$), dolomite ($MgCO_3{\cdot}CaCO_3$), carnallite ($KCl{\cdot}MgCl_2{\cdot}6H_2O$), and also seawater [3]. Magnesium is the third most abundant dissolved mineral in the

TABLE 1.1. Density of commonly used structural materials [7, 8].

Materials	Density (g/cm^3)
Steel (cast iron)	7.2
Titanium	4.51
Aluminum	2.71
Magnesium	1.74
Structural plastic[a]	1.0–1.7

[a]The density value is dependent on the type and amount of reinforcements.

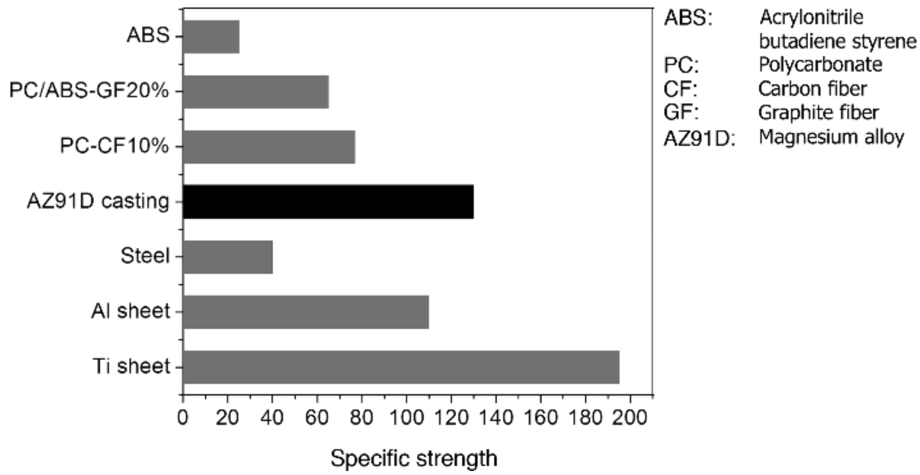

Figure 1.2. Specific strength of various structural materials. (Data extracted from [8].)

seawater (1.1 kg/m^3). Magnesium is the lightest of all structural metals. It has a density of 1.74 g/cm^3, which is approximately one-fourth the density of steel and two-thirds that of aluminum (see Table 1.1) [4–6]. Because of its low density and high specific mechanical properties (Figures 1.2 and 1.3), magnesium-based materials are actively pursued by companies for weight-critical applications.

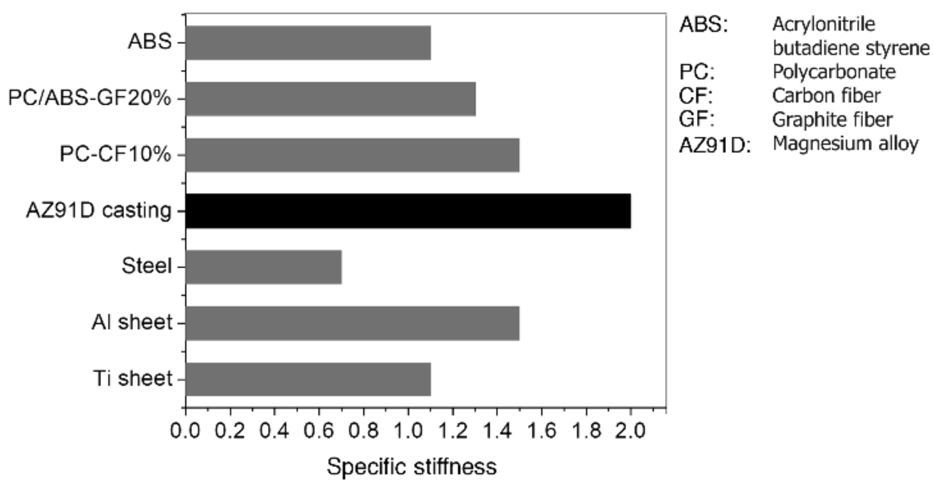

Figure 1.3. Specific stiffness of various structural materials. (Data extracted from [8].)

1.2. CHARACTERISTICS OF PURE MAGNESIUM [3]

1.2.1. Atomic Properties and Crystal Structure

Symbol	Mg
Element classification	Alkaline earth metal
Atomic number	12
Atomic weight	24.3050(6)
Atomic volume	14.0 cm^3/mol
Atomic radius	0.160 nm
Ionic radius	0.072 nm
Orbital electron states in free atoms	$1s^2, 2s^2, 2p^6, 3s^2$
Electrons per shell	2, 8, 2
Most common valence	2+
Crystal structure	Hexagonal close-packed (HCP)

1.2.2. Physical Properties

Density (at 20°C)	1.738 g/cm^3
Melting point	(650 ± 1)°C
Boiling point	1090°C
Linear coefficient of thermal expansion	
At 20–100°C	$26.1 \times 10^{-6}\ °C^{-1}$
At 20–200°C	$27.1 \times 10^{-6}\ °C^{-1}$
At 20–300°C	$28.0 \times 10^{-6}\ °C^{-1}$
At 20–400°C	$29.0 \times 10^{-6}\ °C^{-1}$
At 20–500°C	$29.9 \times 10^{-6}\ °C^{-1}$
Thermal conductivity (at 27°C)	$156\ W\ m^{-1}\ K^{-1}$
Specific heat capacity (at 20°C)	$1.025\ kJ\ kg^{-1}\ K^{-1}$
Latent heat of fusion	360–377 $kJ\ kg^{-1}$
Latent heat of vaporization	5150–5400 $kJ\ kg^{-1}$
Latent heat of sublimation (at 25°C)	6113–6238 $kJ\ kg^{-1}$
Heat of combustion	24.9–25.2 $MJ\ kg^{-1}$
Coefficient of self-diffusion	
At 468°C	$4.4 \times 10^{-10}\ cm^2\ s^{-1}$
At 551°C	$3.6 \times 10^{-9}\ cm^2\ s^{-1}$
At 627°C	$2.1 \times 10^{-8}\ cm^2\ s^{-1}$

1.2.3. Electrical Properties

Electrical conductivity	38.6% IACS
Electrical resistivity (polycrystalline magnesium)	
At 20°C	44.5 nΩ m
At 316°C	92.8 nΩ m
At 593°C	139.5 nΩ m

TABLE 1.2. Mechanical properties of pure Mg at 20°C [3, 9–11].

Pure Magnesium	Annealed Sheet	Hand-Rolled Sheet	Sand Cast	Extruded	PM-Extruded	DMD-Extruded
0.2% Compressive yield strength (MPa)	69–83	105–115	21	34–55	92 ± 12[a]	74 ± 4[b]
0.2% Tensile yield strength (MPa)	90–105	115–140	21	69–105	132 ± 7[c]	97 ± 2[d]
Ultimate tensile strength (MPa)	160–195	180–220	90	165–205	193 ± 2[c]	173 ± 1[d]
Hardness HB[e]	40–41	45–47	30	35	—	—

[a]PM: powder metallurgy method, extruded at 350°C, extrusion ratio 20.25:1 [9].
[b]DMD: disintegrated melt deposition method, extruded at 350°C, extrusion ratio 20.25:1 [11].
[c]PM: powder metallurgy method, extruded at 250°C, extrusion ratio 20.25:1 [10].
[d]DMD: disintegrated melt deposition method, extruded at 250°C, extrusion ratio 20.25:1 [10].
[e]Using 10-mm diameter ball, 500-kg load.

1.2.4. Mechanical Properties

Table 1.2 shows the room-temperature mechanical properties of pure magnesium processed under different conditions.

1.3. APPLICATIONS

1.3.1. Automotive Applications

In the 1920s, magnesium parts made their way into racing cars. However, it was not until the 1930s that magnesium was used in commercial vehicles such as the Volkswagen (VW) Beetle. The VW Beetle, back then, contained more than 20 kg of magnesium alloy in the transmission housing and the crankcase.

Over the past decade, the increasing environmental and legislative pressures on the automotive industry to produce lighter, higher fuel efficiency, and higher performance vehicles have resulted in the surge in the use of magnesium. Widely used conventional steel parts are being replaced by new advanced materials such as magnesium, aluminum, and metal matrix composites. Leading automobile makers such as Audi, Volkswagen, DaimlerChrysler (Mercedes-Benz), Toyota, Ford, BMW, Jaguar, Fiat, Hyundai, and Kia Motors Corporation have used magnesium-based materials in their automotive parts. Figure 1.4 shows some of the actual magnesium automotive components. Figure 1.5 shows the NUS-FSAE Car using Mg alloy in wheel assembly. This car is built by a group of mechanical engineering students from the National University of Singapore (NUS),

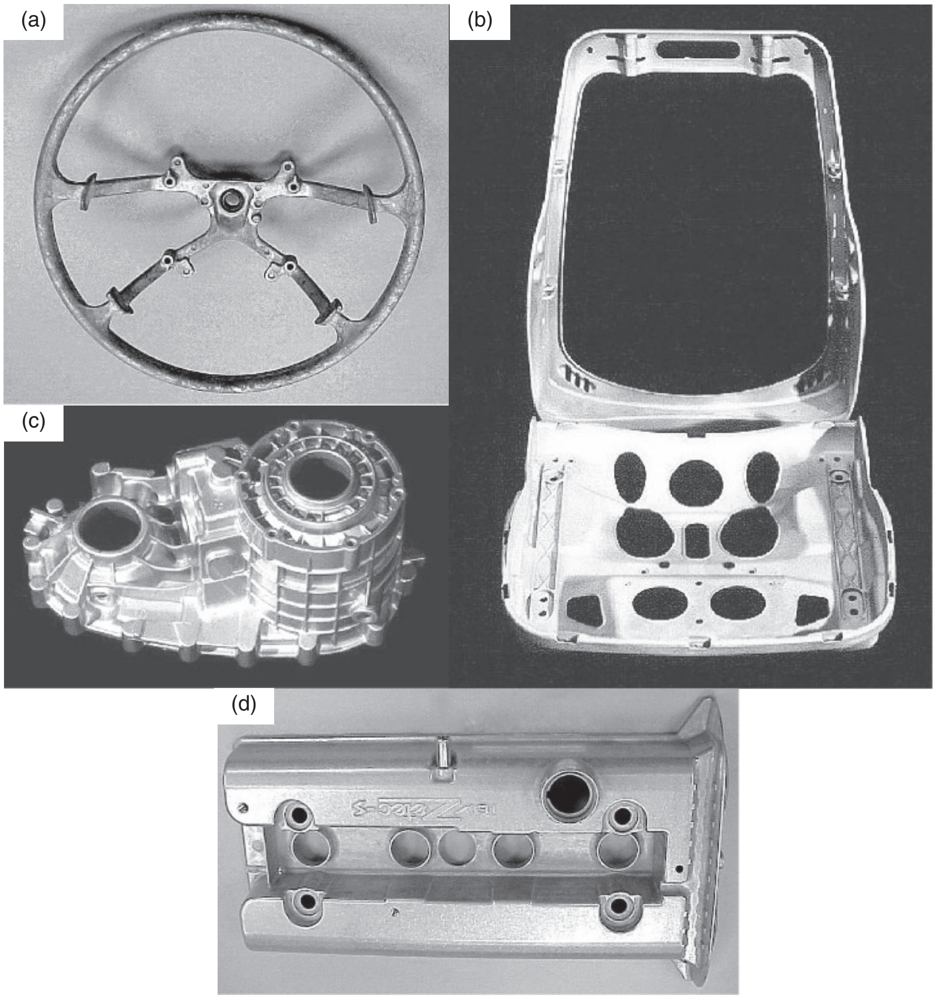

Figure 1.4. Magnesium automotive components: (a) magnesium steering wheel core for Toyota Camry weighing 0.75 kg, (b) seat support for Jaguar and Fiat models weighing 2.6 kg, (c) rear transfer case made from AZ91D weighing 2.7 kg, and (d) AZ91 magnesium alloy cam cover for Ford Zetec engine weighing 0.9 kg.

to participate in the FSAE (Formula Society of Automotive Engineers) competition in the United States.

In the VW Passat and Audi A4, magnesium parts are used in the gearbox housing [12]. In the Toyota Lexus, Carina, Celica, and Corolla, the steering wheels are made of magnesium [13]. In the Mercedes-Benz SLK, the fuel tank cover is made of a magnesium alloy. In Hyundai Azera (Grandeur) and Kia Amanti (Opirus), magnesium is also used in interior parts such as the seat frame, steering column housing, driver's air

Figure 1.5. NUS-FSAE Car using Mg alloy in wheel assembly. (Courtesy: Professor K. H. Seah, National University of Singapore.)

bag housing, steering wheel, and lock body [14]. Hyundai and Kia Motors Corporation project that the use of a magnesium seat frame translates to a 6 kg weight reduction per car (∼40% weight reduction by replacing steel with magnesium alloy). Thus, their annual consumption of magnesium was expected to increase from 670 tons in 2004 to 3700 tons in 2007 [14].

1.3.2. Aerospace Applications

In the aerospace industry, weight reduction is one of the most critical objectives due to the increasing need for emission reduction and fuel efficiency. The reduction in overall weight of the aircraft will result in fuel savings, which translates to savings in the total operational cost. Several weight reduction alternatives such as aluminum, fiber metal laminates, and low-density structural plastics have been introduced over the years. However, the limited advancement in the development of aluminum alloys has made further weight reduction a challenge. Fiber metal laminates are also high-cost materials and, hence, are only used for primary structures with the highest mechanical properties requirements. Moreover, low-density structural plastics have low impact and damage tolerance properties. They also exhibit inferior properties when subjected to temperature extremes. Thus, all these limitations have made magnesium an attractive alternative.

Magnesium-based materials have a long history of application in the aerospace industry. Over the years, magnesium-based materials are extensively used in both civil and military aircraft. Some applications include the thrust reverser (for Boeing 737, 747, 757, 767), gearbox (Rolls-Royce), engines, and helicopter transmission casings, etc. Military aircraft, such as the Eurofighter Typhoon, Tornado, and F16, also benefit from the lightweight characteristics of magnesium alloys for transmission casings.

There is also widespread use of magnesium in spacecraft and missiles due to the requirement for lightweight materials to reduce the lift-off weight. This is coupled with its high specific mechanical properties, ease of fabrication, and other attractive features such as its capability to withstand (i) elevated temperatures, (ii) exposure to ozone, and (iii) bombardment of high-energy particles and small meteorites. Large amount of magnesium (in the form of sheets) was used in the Titan, Agena, and Atlas intercontinental ballistic missiles [15].

1.3.3. Medical Applications

Magnesium alloys were first introduced as orthopedic biomaterials in the first half of the last century [16]. However, because of its low corrosion resistance, a large amount of hydrogen accumulates around the implant during the *in vivo* corrosion process, confining the widespread use of magnesium-based materials as biomaterials. Despite this, magnesium still possesses many attractive characteristics that make magnesium-based materials potential candidates to serve as implants for load-bearing applications in the medical industry.

Magnesium has a much lighter density than other implant materials (Table 1.3). It also has greater fracture toughness as compared to hydroxyapatite. Furthermore, as shown in Table 1.3, its elastic modulus and compressive yield strength values are more comparable to that of natural bone than the other commonly used metallic implants [17].

Magnesium is also present as a natural ion in the human body, whereby approximately 1 mol of magnesium is stored in a 70 kg adult human body and an estimated amount of half of the total physical magnesium is present in the bone tissue [17]. It also assists in many human metabolic reactions and is nontoxic to the human body. Magnesium

TABLE 1.3. Physical and mechanical properties of natural bone and some implant materials [17].

Materials	Density (g/cm^3)	Fracture Toughness ($MPa\ m^{1/2}$)	Elastic Modulus (GPa)	Compressive Yield Strength (MPa)
Natural bone	1.8–2.1	3–6	3–20	130–180
Ti alloy	4.4–4.5	55–115	110–117	758–1117
Co–Cr alloy	8.3–9.2	—	230	450–1000
Stainless steel	7.9–8.1	50–200	189–205	170–310
Magnesium	1.74–2.0	15–40	41–45	65–100
Hydroxyapatite	3.1	0.7	73–117	600

has good biocompatibility and it is biodegradable in human body fluid by corrosion, thus eliminating the need for another operation to remove the implant. All these desirable features make magnesium-based material a promising implant material [17–19].

In order to overcome the corrosion issues that limit the use of magnesium-based materials in orthopedics application, in recent years, much research efforts are focused to explore the use of different alloying elements in magnesium and surface treatments such as protective coatings on magnesium-based materials [17].

1.3.4. Sports Applications

In the sporting industry, it is important that the sports equipment matches up to the ever-increasing expectations of sports enthusiasts. The excellent specific strength and ability of magnesium alloys and magnesium composites to form intricate shapes resulted in many applications in sports-related equipment. For example, magnesium-based materials are used in the handles of archery bows, tennis rackets, and golf clubs (Figure 1.6).

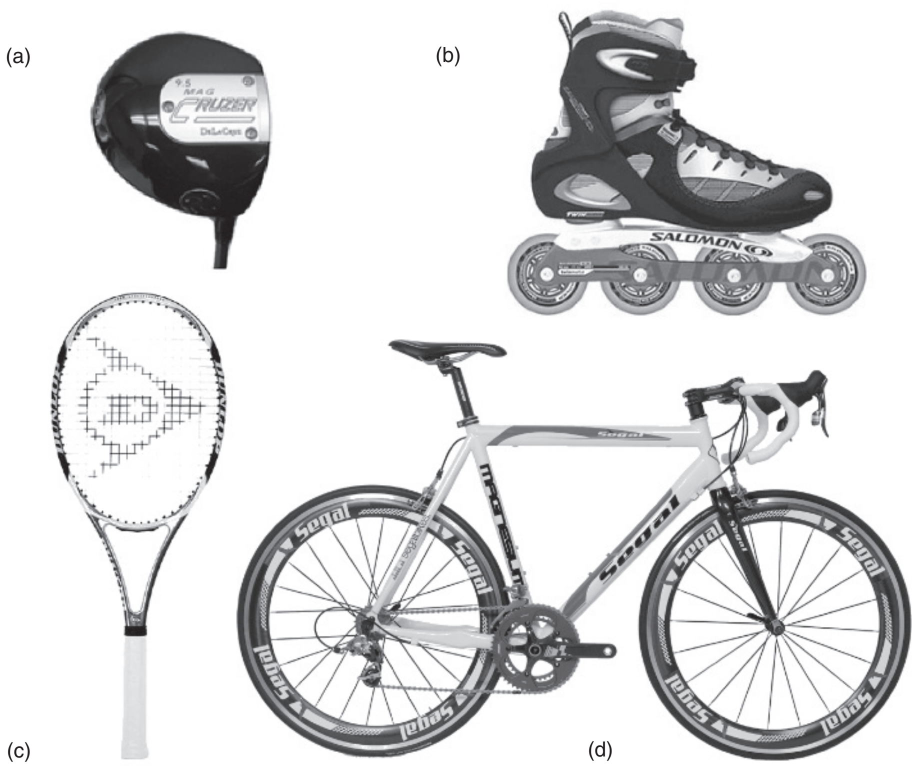

Figure 1.6. Magnesium sports equipment: (a) golf club head is cast from high-quality magnesium (courtesy of www.thegolfdome.ca), (b) in-line skates with magnesium chassis (courtesy of www.skates.com), (c) tennis racquet with magnesium head (courtesy of www.courtsidesports.com), and (d) bicycle with magnesium frame (courtesy of www.segalbikes.eu).

Figure 1.7. Laptop with magnesium alloy AZ91D casing.

The lightweight and excellent damping characteristics of magnesium-based materials have also made them a popular material choice in bicycle frames and the chassis of in-line skates (Figure 1.6). Bicycle frames made from magnesium alloys or composites are capable of absorbing shock and vibration [15], hence allowing the rider to exert less energy and enjoy a more comfortable ride.

1.3.5. Electronic Applications

The trend in the electronic equipment industry is to make products more personal and portable. Hence, it is important that the components that make up the equipment are lightweight and also durable. Magnesium-based materials meet the necessary requirements as they are as light as plastic, but exhibit great improvement in strength, heat transfer, and the ability to shield electromagnetic interference and radio frequency interference, as compared with their plastic counterparts [15]. Hence, as shown in Figure 1.7, magnesium-based materials are used in housings of cell phones, computers, laptops, and portable media players (such as the Apple iPod Nano magnesium case).

The ability to form magnesium alloys into complex shapes and the good heat dissipation and heat transfer characteristics of magnesium alloys also result in the use of magnesium alloys in heat sinks and the arms of the hard-drive reader [15]. Other examples of the use of magnesium include the housings of cameras (Figure 1.8) and digital image projection systems.

1.3.6. Other Applications

Optical Applications. Magnesium is commonly used to make the frame of eyewear because of its lightweight property. Other optical equipment that capitalizes on the

Figure 1.8. Magnesium housing of digital camera.

lightweight and optical stability attributes of magnesium includes the rifle scopes and binoculars.

Hand-Held Working Tools. In order to achieve higher working efficiency, it is desirable that the hand-held working tools are lightweight to allow greater portability. Hence, the low density of magnesium coupled with its resistance to impact and its ability to reduce noise and vibration makes it the material of choice for a wide range of hand-held working tools. Some examples include [15] the following:

(i) Magnesium chain saw housing
(ii) Magnesium housing and cylinder of pneumatic nail gun
(iii) Housings of gear and engine of hand-held tools
(iv) Handles of hand shears
(v) Housing of hand drills

1.4. SUMMARY

This chapter presents the potential of magnesium as an energy-efficient material. Its lightweight and high specific strength characteristics are favorable properties that have resulted in many applications in the automotive, aerospace, sports, and electronic industries. The future applications of magnesium-based materials are unlimited and depend on the vision and imagination of working engineers.

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