DOE

MARKET RESEARCH STUDY

U.S. FORGING INDUSTRY

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1.0 INTRODUCTION

The forging industry plays a vital and often unseen role in the global economy. "Forging" has been around for millenia and doesn't have the current cache of "augmented reality, cybersecurity or cryptocurrency." None-the-less forging is fundamentally important to key U.S. industries including the aerospace, automotive, defense, power generation, rail, and shipping industries. So, what is "forging" and why is the Advanced Manufacturing Office (AMO) of the Department of Energy (DOE) interested in the forging industry?

Forging is a metal working process that uses high temperatures to manipulate metals into desired shapes. Most commonly, the types of metals forged include steel (carbon steel, alloy steel, stainless steel) and titanium, as well as soft metals such as aluminum, brass and copper. Forging is said to produce some of the sturdiest manufactured parts available and uses a variety of methods such as **closed forging** (also referred to as impression die forging), **cold forging**, **open die forging** (also referred to as smith forging) and **seamless rolled ring forging.**[1] Others define the forging methods based on temperature.[2]

The demands on the forging industry fluctuate over time and continually require the integration of new technologies and processes as customer requirements change. Current predictions are that the forging industry must prepare for another growth spurt in order to meet the anticipated demand for the automotive, as well as aerospace and wind power markets. It is also anticipated that greater use of materials such as magnesium will be required to reduce weight while retaining the strength of the alloys used.[3] According to Grandview Research the global metal forging market valued in 2021 at USD 74.36 billion is projected to grow at a compound annual growth rate (CAGR) of 7.7% from 2022 to 2030.[4] Although there is concurrence on the size of today's global forging market, there is considerable variability regarding the predicted rate of growth.

The **Advanced Manufacturing Office (AMO)** — within the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy (EERE) — partners with manufacturers, not-for profit entities, universities, national laboratories, and state and local governments to address energy related manufacturing challenges through research, development, and demonstration (RD&D). How the United States applies our diverse and abundant domestic energy resources to manufacturing can be a critical factor in the economic competitiveness, energy security, and responsible environmental stewardship of the nation. Advancements in manufacturing impact the energy efficiency of products used throughout the economy. The AMO is the only technology development office within the U.S. Government that is dedicated to improving the energy and material efficiency, productivity, and competitiveness of manufacturers across the industrial sector.

1 Great Lakes Forge Inc. n.d. "*What are the different types of forging processes?*"; Forging Industry Association n.d. " Forging Facts."

2 Thomas, a Xometry Company. n.d. "What is forging?"

3 Anchor Harvey. n.d. "Magnesium forgings."; Papenberg, Nikolaus." Mg-Alloys for Forging Applications – A Review." *Materials*, 2020, 13(4).

4 Kubatzke, Kerry. " *How Forgings are Paving the Way for the Future of EVs*." Altenergymag.com, October 19, 2021.; Grand View Research. Metal Forging Market Size, Share & Trends Analysis Report by Raw Materials (Carbon Steel, Aluminum, Alloy Steel), By Application (Automotive, Aerospace, Oil& Gas) by Region, and Segment Forecasts, 2022-2030.

This report provides an overview of the evolution of the forging industry in the United States and highlights the industry's challenges between 2020 and the present. Also provided is a brief introduction to the global forging industry. Appendix A contains a listing of Universities that support the forging industry, as well as additional information about the Forging Industry Association (FIA).

Figure 1: Introduction to the Department of Energy's Advanced Manufacturing Office
Click to see video

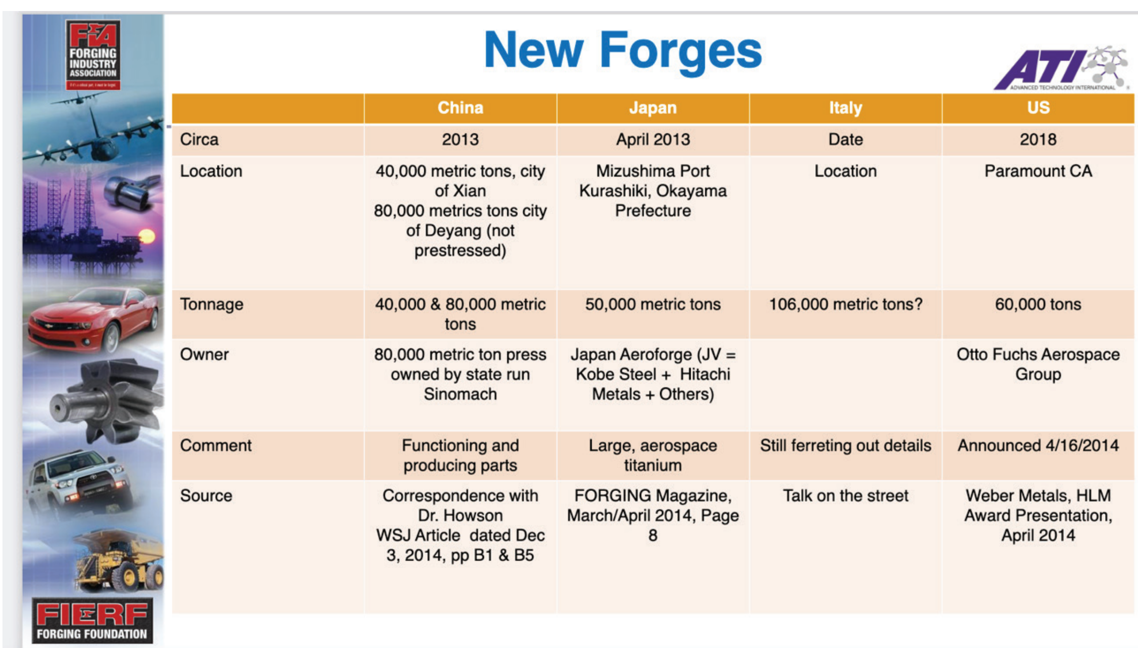
2.0 FORGING INDUSTRY OVERVIEW

The United States forging industry advanced greatly after World War II, having learned much from the three presses they received from Germany as part of the war reparations.[5] This type of press had enabled the German aircraft to have more advanced parts than the allies. The German forgings were lighter, stronger, and easier to produce. They also made great use of magnesium, a mineral of which Germany had a large supply.[6] In the 1950's, to compete with Russia during the cold war, the U.S. kicked off the **Air Force Heavy Press program**.[7] A total of ten presses were created: four forging presses, the waffle iron and six extrusion presses. These are among the most powerful presses ever made.

5 Maloney, Dan. "Retrotechtacular: The Iron Giants that Built the Jet Age." *HACKADAY*, September 1, 2018.
6 History of Magnesium Production, n.d. or author
7 Heffernan, Tim. "The Machines that Made the Jet Age." *Boingboing.* February 13, 2012; Heffernan, Tim. "Iron Giant." *The Atlantic. March 2012.*

Figure 2: America's Iron Giants
Click to see incredible video

In 2018, at the Forging Industry Technical Conference, a presentation was given on The Historic Heavy Forging Presses of the World. The presentation not only documents the advances made annually in forging presses between the 1930's and 2018, but also includes numerous photos and information on the evolution of the forging industry. For anyone interested in forging, this presentation serves as an outstanding introduction. The following figure is a global listing of new and planned presses as of 2018.



New Forges

	China	Japan	Italy	US
Circa	2013	April 2013	Date	2018
Location	40,000 metric tons, city of Xian 80,000 metrics tons city of Deyang (not prestressed)	Mizushima Port Kurashiki, Okayama Prefecture	Location	Paramount CA
Tonnage	40,000 & 80,000 metric tons	50,000 metric tons	106,000 metric tons?	60,000 tons
Owner	80,000 metric ton press owned by state run Sinomach	Japan Aeroforge (JV = Kobe Steel + Hitachi Metals + Others)		Otto Fuchs Aerospace Group
Comment	Functioning and producing parts	Large, aerospace titanium	Still ferreting out details	Announced 4/16/2014
Source	Correspondence with Dr. Howson WSJ Article dated Dec 3, 2014, pp B1 & B5	FORGING Magazine, March/April 2014, Page 8	Talk on the street	Weber Metals, HLM Award Presentation, April 2014

Figure 3: New Forges (Global)
Source: Tirpak, John[8]

8 Tirpak, John. "Historic Heavy Forging Presses of the World." Forging Technology Conference, September 11, 2018.

2.1 Typical Forgings, Per Application Sectors

Forging creates parts (called forgings) that are stronger than those manufactured by any other metalworking process. Forgings are almost always used where reliability and human safety are critical, such as to make components found in airplanes, automobiles, tractors, ships, oil drilling equipment, engines, missiles, and other kinds of capital equipment. Forged parts can be simple or highly precise. The following table serves to provide a perspective on the number of forged parts by application.[9]

Table 1: Introduction to Forged Parts by Application

Application	Benefits	Forged Parts
Aerospace	High strength-to-weight ratio and structural reliability improve performance, range, and payload capabilities of aircraft. Ferrous and non-ferrous forgings are used in helicopters, commercial jets, supersonic military aircraft, and others.	Many aircraft contain more than **450** structural forgings as well as hundreds of forged engine parts. Forged parts include bulkheads, hinges, engine mounts, brackets, beams, shafts, landing-gear cylinders, structs, arresting hooks and many other
Automotive	High strength-to-weight ratio and structural reliability	Cars and trucks may contain more than **250** forgings, most of which are produced from carbon or alloy steel. There are many forged engine and powertrain components. Forged camshafts, pinions, gears, and rocker arms offer ease of selective hardening as well as strength.
Defense	High strength-to-weight ratio and structural reliability	Used in tanks, gun tubes, US Navy's Aegis Class guided missile destroyer rudders, missile warheads, standard artillery shells
Power Generation	High strength-to-weight ratio and structural reliability	Pressure vessels; generator rotors; pump shafts; valve manifolds; valve bodies; turbine blades and rotors; pipes; and fittings are forged for nuclear (commercial and naval), land (including geothermal and biomass), and marine power generation equipment.
Wind Energy	High strength-to-weight ratio and structural reliability	Approximately 20 metric tons of forgings are used in a typical large wind turbine.
Railroads		Railcar and locomotive axels must be forged; as well as the traction gears and engine crankshaft

9 Forging Industry Association. Forging Facts. *No date - accessed July 13, 2022*

Medical	Strong, lightweight	Surgical tools and joint replacements
Sports	Forged clubs allow more efficient energy transfer	Forged golf clubs
Tools		Hammers and wrenches

FORGE magazine conducted a survey of its readership in October 2020 and released the results in December 2020, through the 2021 Business Outlook for Forging. Survey respondents were executives, plant and division managers, and operators at North American forging businesses.[10] When asked "which market offered the most promise to your company," the majority of companies (~29 percent) said **"Aircraft/Aerospace Components,"** followed by 21 percent that choose **"Other Automotive Components"** (which does *not* include "fuel efficient engines" and "lighter composites for transportation"). However, some forging companies do expect to find opportunity in the markets for "fuel efficient engines" (7.58 percent) and "lighter composites for transportation" (1.52 percent)[11] These companies may be forging light weight metals, such as aluminum, that can address EV light-weighting goals. *This is discussed in more detail in the electric transport section.*

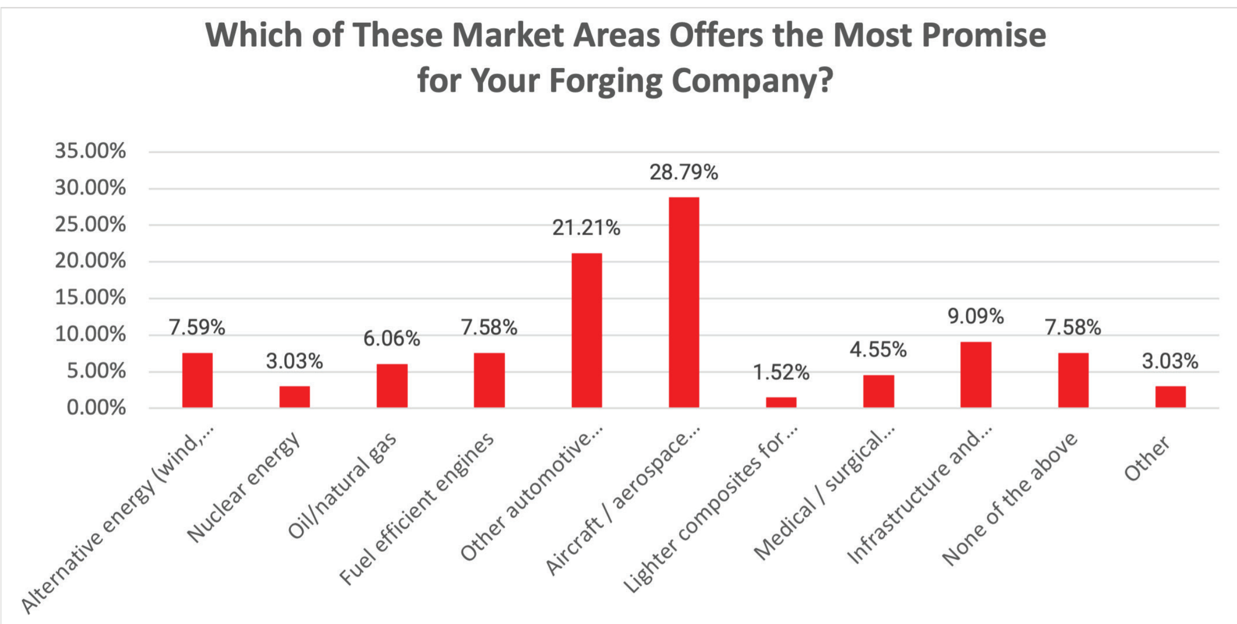


Figure 4: Most Promising Forging Applications
Source: 2021 Business Outlook for Forging survey results[12]

These findings are consistent with the predictions made by various market research firms regarding markets where demand for forged parts will be highest and continue to increase. For example, IndustryArc cited:

10 The number of respondents from the mailing list for FORGE was not provided. It is assumed that the sur vey contained multiple choice questions, as one of the answer categories was "None of the above". It is assumed, but not known that respondents needed to select one category.
11 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
12 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

"In November 2020, Boeing projected that China's airlines will buy US$1.4 trillion worth of 8,600 new aircraft and US $1.7 trillion worth of commercial aviation services over the next 20 years. According to Boeing's current business forecast, the Middle East would need 2,520 new aircraft by 2030. Also, according to Boeing India is expected to drive the demand for 2,300 aircrafts worth US $320 billion over the next 20 years. Considering the benefits associated with forged metals is expected to have great potential applications in aerospace. Hence, the increasing aerospace industry will act as a driver for the metal forging market."[13]

The key global suppliers are being ZF Friedrichshafen AG, Bharat Forge Limited, NTN Corporation, American Axle & Manufacturing, Inc., Meritor Inc., ThyssenKrupp AG, CIE Automotive, S.A., Dana Inc., Nanjin Automobile Forging Co., Ltd., and Ramkrishna Forgings.

According to GreyViews, the automotive segment of the global forging market is expected to grow from $33.5 billion in 2020 to $52.8 billion by 2028 with key global suppliers being ZF Friedrichshafen AG, Bharat Forge Limited, NTN Corporation, American Axle & Manufacturing, Inc., Meritor Inc., ThyssenKrupp AG, CIE Automotive, S.A., Dana Inc., Nanjin Automobile Forging Co., Ltd., and Ramkrishna Forgings.

2.2 North American Forging Industry Demographics

2.2.1 The Number and Location of North American Forging Companies

The tools needed to accurately size the number of forging companies within the United States based on either the number of employees, the value of shipments or on tonnage – simply do not exist. In a 2004 article, published in the New Equipment Digest, the problem with available data was clearly articulated. The U.S. government classifies plants according to the major end product, using the North American Industrial Classification system (NAICS). Therefore, job shops that make forgings are typically classified in one of two NAICS codes: (1) iron and steel forgings (332111) and (2) nonferrous forgings (332112). Captive forging departments that produce forgings for their own use are said to not be classified in either of these groups – but may be buried in other classifications such as motor vehicles, machine tools, hand tools and the like.

Today, the situation is more complex than described in 2004. If one looks at the NAICS codes used by Alcoa – the largest, U.S. forging company, they use NAICS 331318 – Other aluminum Rolling, Drawing and Extruding and NAICS 331523 Nonferrous Metal Die-Casting Foundries.

Given this situation, in the data provided in this section, the Forgings' circulation database is used as the basis for the annual census that the magazine conducts. The magazine also states that "We do not compare the data from year to year because some changes are due as much to better research as to any actual increase or decrease in numbers of forging units."[14] In 2004, which was the 12th year in which they conducted the survey, 398

13 IndustryARC. n.d. "Metal Forging Market Overview (2021-2026)"

14 Huskonen, Wallace. "Forging's 12th Annual Census of North America Forging Operations". *New Equipment Digest*. June 6, 2004

forging locations in the United States were included in their survey. The response rate is not cited.

According to a 2020 publication of the Forging Industry Association (FIA) at that time (2020) there were nearly 480 forging operations in 38 states, Canada, and Mexico,[15] the largest concentration is in the following states: Ohio (79), Pennsylvania (63), Illinois (54), Michigan (54), California (38), Texas (41), New York (16), Indiana (18), Wisconsin (17), Kentucky (13), Massachusetts (10), and South Carolina (9).[16] It is important to keep in mind that this number is based on the membership of the FIA and includes Canada, Mexico and the United States.

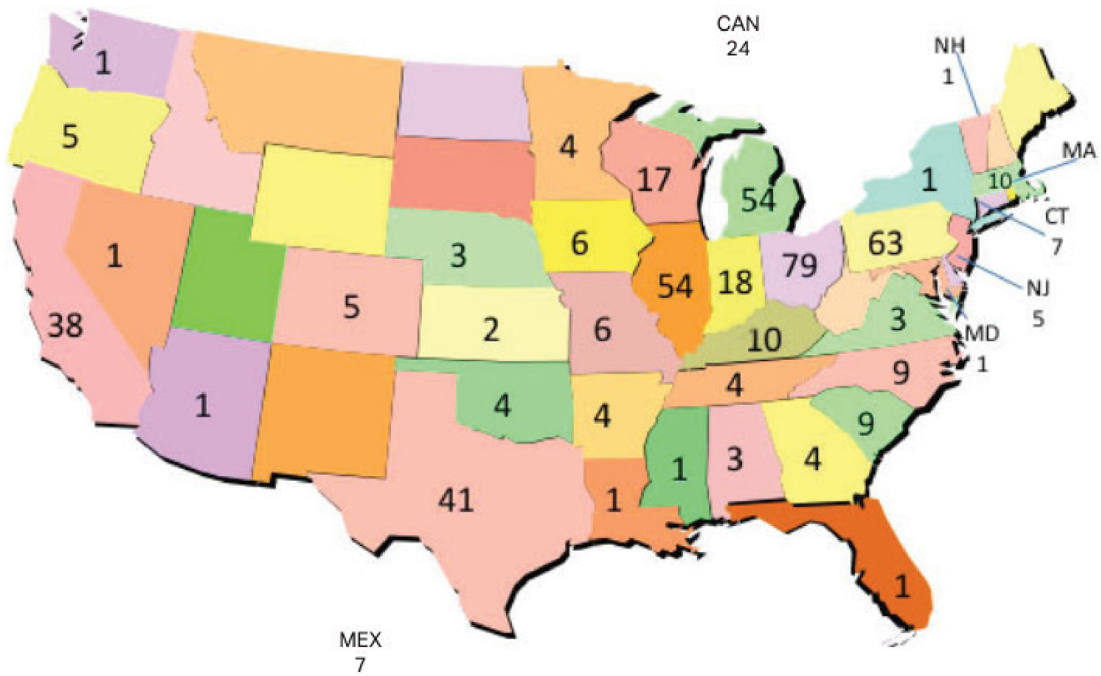


Figure 5: North America Forging Industry
Source: Forging Industry Association[17]

By contrast the [Forging Suppliers](#) database, includes 715 companies throughout the U.S. and Canada (most of which are forgings manufacturers) in its 2022 publication and can be used to search by company type, metal or process type, customer industry served, products produced, company size and ownership, location, or by company certifications. The method used by Thomas.net to include companies in this directory is not described. Thomas.net also includes a listing of the 14 Top U.S. Forgings Manufacturers with brief company profiles. A list of these companies follows, rank-ordered by approximate company sales as cited by Thomas.net. NAICS have been added.

Table 2: Fourteen Largest U.S. Forging Companies According to Thomasnet.com

15 Forging Industry Association. Forging Industry Fact Sheet. February 2020
16 Forging Industry Association. Forging Industry Fact Sheet. February 2020
17 Forging Industry Association. Forging Industry Fact Sheet. February 2020

Rank	Company Name	Year Founded	NAICS Used
1	Alcoa	1888	33138, 331523
2	American Axle & Mfg.	1993	332111
3	Angstrom Automotive Group	1993	33,336
4	ATI (Allegheny Technologies)	N/A	331110
5	Bula Forge	1973	332111
6	Coulter Forge Technology	1930's	331110
7	General Dynamics Ordnance & Tactical Systems	N/A	332993
8	Precision Castparts	1956	331512, 331529
9	Scot Forge	N/A	332111, 34629901
10	SWPC	1852	326199
11	Aichi Forge USA	1985	332111
12	Powers & Sons	1938	7699
13	Sypris Solutions	1927	334515
14	Ellwood Group	1910	332111

2.2.2 The Size of North American Forging Companies

The best source of statistics on the forging industry is the **Forging Industry Association**. FIA publishes its statistics on its website and also in a number of magazines including the New Equipment Digest, the Forgings and/or Forge magazine. It is important to note that the statistics reported reflect information provided by a subset of its membership that responds to an annual survey. The number of respondents is never cited and as noted in the 12th survey in 2004 changes over time may be "due as much to better research as to any actual increase or decrease in numbers of forging units."[18] With that caveat in mind, in 2020 which cites pre-COVID numbers from 2019, 30.4 percent of forging companies in North America employed 250 or more workers; 17.4 percent employed 100 to 249; 13 percent employed 50 to 99; 14.5 percent employed 20-49; and 24.6 percent had 20 or fewer employees.[19]

Most forging companies are small. Only nine percent of respondents to FORGING magazine's October 2020 survey reported shipping over $100 million annually.[20] The revenue breakdown for all the 2020 survey respondents:

- 16.7 percent of responding companies ship less than $1 million annually
- 13.6 percent ship $1 million- $5 million annually
- 15.2 percent ship $5 million-$10 million annually

18 Huskonen, Wallace. "Forging's 12th Annual Census of North America Forging Operations". *New Equipment Digest*. June 6, 2004

19 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

20 In the 2012 and 2014 surveys the % of respondents reporting over $100M in sales was 23%. However, in the 2011 survey it was 13%.

- 10.6 percent ship $10 - $20 million annually
- 13.6 percent ship $20 - $50 million annually
- 10.13 percent ship $50 - $100 million annually
- 9.1 percent ship more than $100 million annually[21]

In looking at articles that report results from FIA surveys conducted over time (2011, 2012, 2014, 2016 and 2020) the data reported do not allow a comparison of key variables. However, the following figure is an example of the data contained in the FIA 2014 North American Forging Outlook which includes actuals through 2013 and projections through 2019. The following figure plots Impression Die Sales dollars in purple and percent change from a year ago (growth rates) by the superimposed green line graph. Comparable charts can be found in this report for Open Die Sales and Rolled Ring Sales.[22]

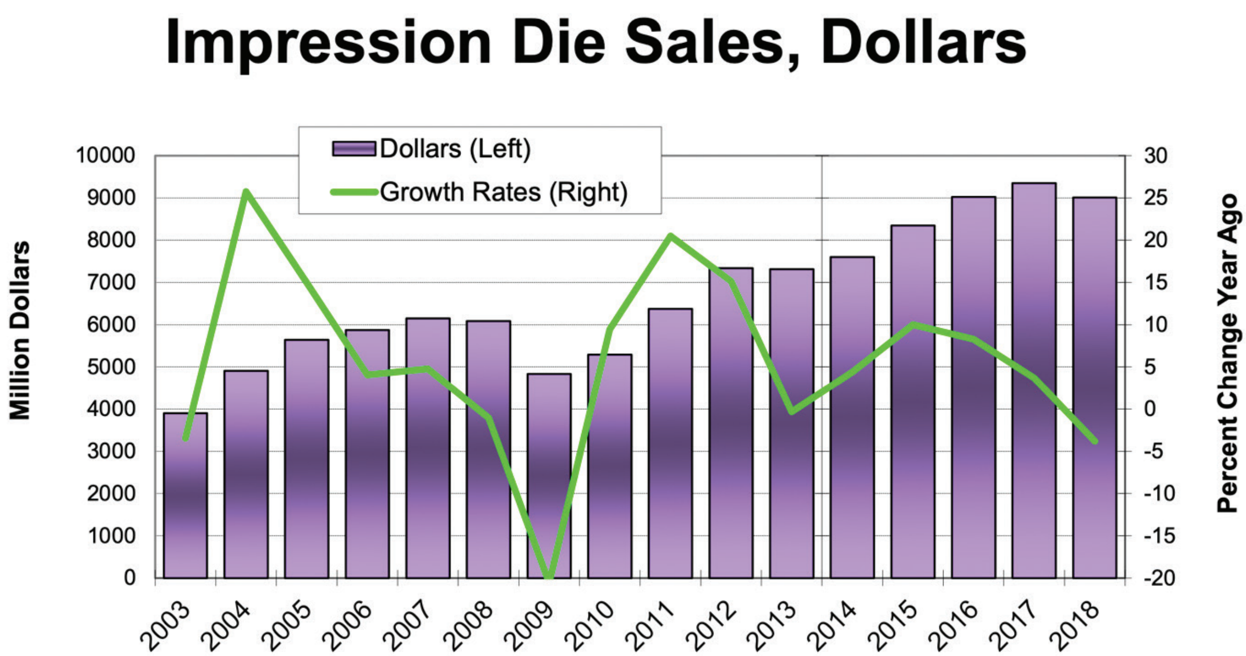


Figure 6: Impression Die Sales, Dollars and Percent Change
Source: IHS North American Forging Outlook

While several marketing firms provide global forging market revenues, none were found that provide the North American market size. FIA reports that the **North America forging industry generates revenues in the range of $13.5 – 15.5 billion, with custom forgings accounting for nearly $11 billion of sales** (the balance of sales is in standard (catalog) forgings and forgings created for use within the industry (captive forgings).[23]

With the impact of COVID-19, only 3 percent of forging companies reported operating at 100 percent capacity during 2020 and most forging plants operated below capacity. In terms of how 2020 forging revenues compared to 2019, results of the October 2020 FORGING magazine survey indicate that, while about 55 percent of forging companies

21 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
22 IHS North American Forging Outlook, 2014.
23 Forging Industry Association. Forging Industry Fact Sheet. February 2020

reported 2020 shipment revenue decreases compared to 2019, almost 35 percent reported 2020 revenues to be about the same as 2019 and about 10 percent reported increased revenues.[24] Also of note is that the FIA website now cites membership of 200 companies, which would imply a smaller pool of respondents than in 2004.[25]

2.3 Forging Industry Spending

According to FIA, in 2020, industry participants invested the most in these three areas: forge furnaces/billet-to-bar heaters; training/education; and forging machine rebuilds/control modernization. In 2021, these areas were expected to remain dominant, especially training and education.[26]

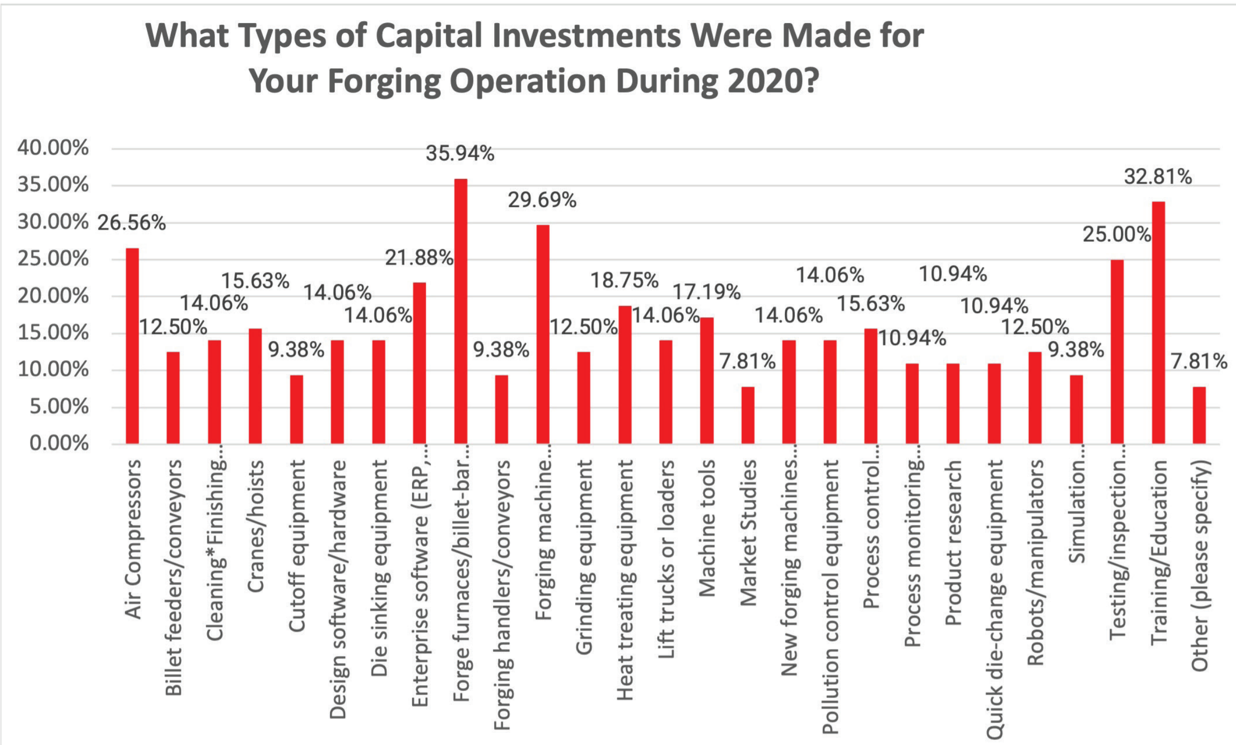


Figure 7: Forging Industry Capital Investments in 2020
Source: 2021 Business Outlook for Forging survey results[27]

24 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
25 FIA Membership Information, 2022
26 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
27 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

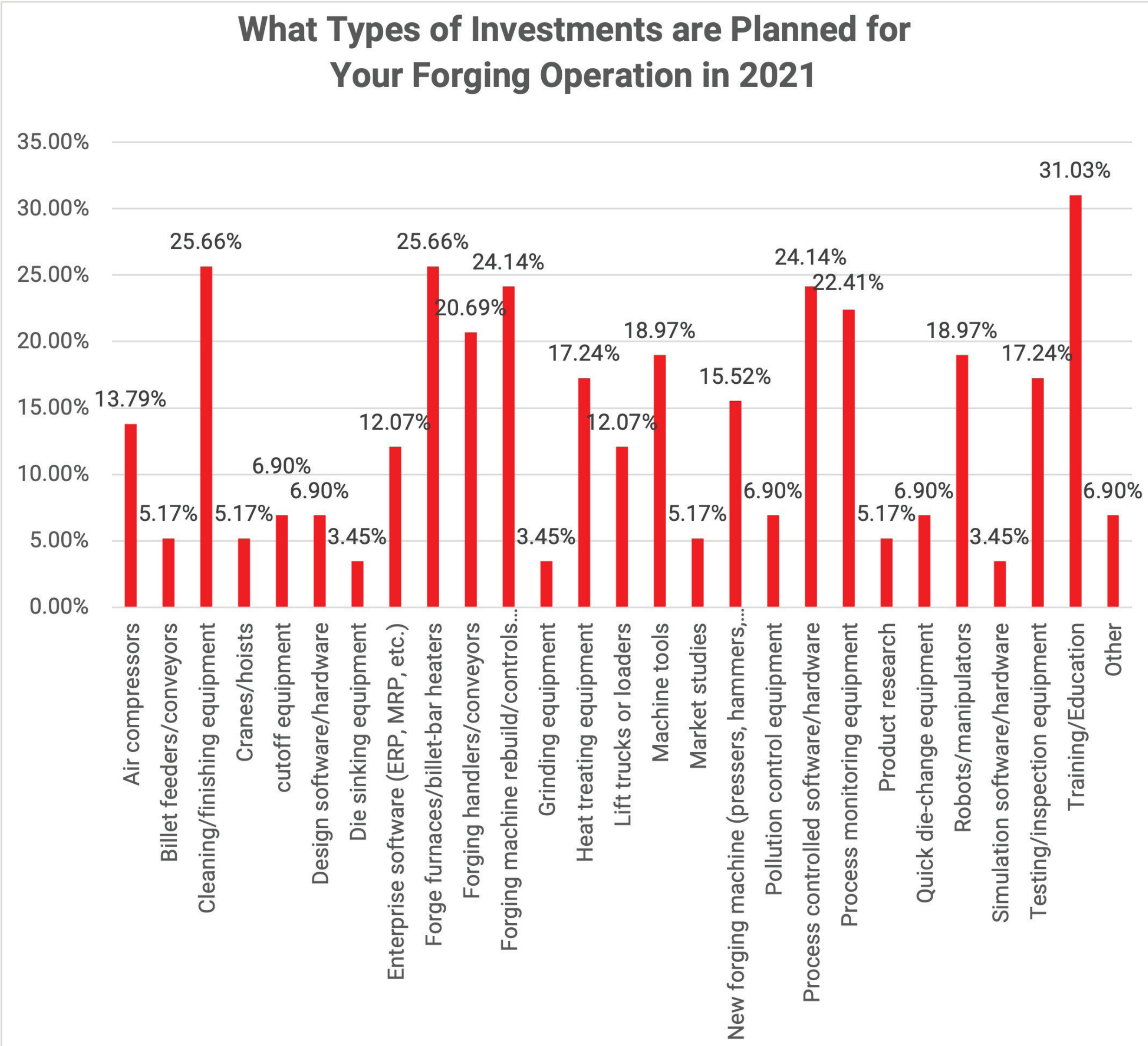


Figure 8: Forging Industry Capital Investments in 2020
Source: 2021 Business Outlook for Forging survey results[28]

In terms of equipment and plant expansion investments, almost 40 percent of survey responders had no plans to make capital expenditures in 2021.[29] In terms of increases in capital expenditures, in the 2011 and 2012 survey publications, 41% of the respondents indicated their intent to increase capital expenditures. In 2014 34.5% of the respondents indicated the intent to increase their capital expenditures, while in the 2020 publication which reported pre-COVID figures from 2019, 45.5% of the respondents indicated the intent to increase capital expenditures.

28 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
29 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

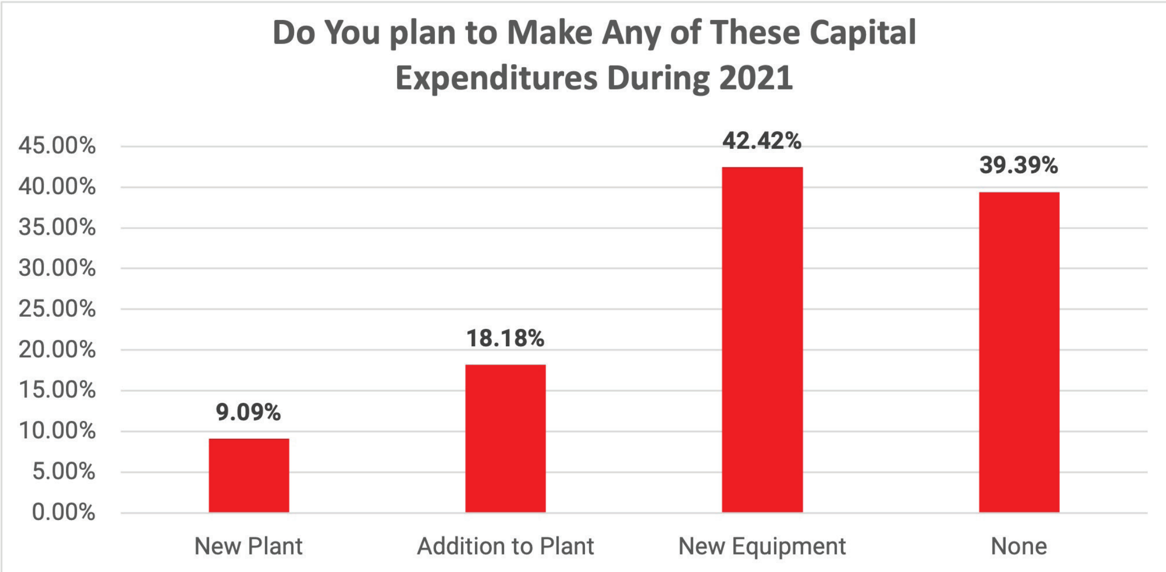


Figure 9: Capital Investments Planned for 2021
Source: 2021 Business Outlook for Forging survey results[30]

2.4 Metals Forged and Forging Processes

While just about any metal can be forged, the most common are carbon, alloy, and stainless steels; very hard tool steels; aluminum; titanium; brass and copper; and high-temperature alloys which contain cobalt, nickel or molybdenum.[31] According to the most recent *FORGING* Business Outlook Survey results, when asked to identify the **metals forged** at their operations (allowing multiple choices):

- 53 percent of respondents are forging alloy steel materials
- 49 percent process carbon steels
- 33 percent forge stainless steels
- 21 percent forge high-temperature alloy materials
- Per Nonferrous metals:
  - 31 percent work with aluminum alloys
  - 24 percent process brass and copper alloys
  - 24 percent work with titanium alloys.[32]

The respondents are engaged in all the typical forging processes, including:

- Open-die forging (54 percent
- Impression-die (closed-die) forging (49 percent)
- Ring rolling (17 percent)
- Impact extrusion (9 percent)
- Other operations named by the respondents include powder forging, hand forging, orbital forging, spin forging, flow forming, and cold forging.[33]

30 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
31 Forging Industry Association. Forging Facts. *No date - accessed July 13, 2022*
32 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
33 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

2.4.1 New Developments with Titanium and Magnesium

Titanium

Titanium is widely used in the aerospace industry. In fact, titanium alloys account for approximately 15% of the Boeing 787 airframe by weight. Titanium is also used in desalination plants, the production of power plant components and medical implants. The unique properties of titanium and titanium alloys make this a highly valued material. It is lightweight, has a high ratio of strength to weight, is corrosion resistant and can withstand high temperatures. For aerospace applications two additional features make this a prized material: (1) It is less likely to cause galvanic corrosion when joined with carbon fiber reinforced plastic (CRFP) parts such as body and wing panels and (2) the thermal titanium coefficients of expansion are similar to CFRP's. Owing to the fact that titanium alloys are difficult to machine, the preference is to use forging to create "near net shapes", thus saving both time and money.[34]

The VSMO-AVISMA Corporation, the largest titanium producer in the world, is located in Verkhnyaya Salda, Russia.

A new challenge is that the Titanium Supply Chain for the Aerospace Industry Goes Through Russia. In light of the on-going war in the Ukraine, the vulnerability of the titanium and titanium forgings supply chain is of concern. Russia is a dominant player in these markets. In fact, the VSMO-AVISMA Corporation, the largest titanium producer in the world, is located in Verkhnyaya Salda, Russia.[35] Given the importance of titanium alloys to Boeing, the company formed a partnership with VSMO and also established a joint venture called Ural Boeing Manufacturing, located on the site of the VSMPO factory. One of the JV buildings specializes in producing the rough machining of titanium forgings for all of Boeing's commercial programs including the 737 MAX, 787, and 777X.[36]

In 2019 the U.S. imported 95% of the titanium consumed. However, ATI Titanium LLC, a subsidiary of Allegheny Technologies is finishing construction of a large titanium sponge plant at Rawley, Utah, right next to the U.S. magnesium plant. This is the first, new titanium sponge plant built in the U.S. in more than 30 years.[37] Titanium sponge is an intermediate material, produced through the Kroll process in which titanium tetrachloride is reduced with magnesium metal.

34 Shih, Willy. *"The Titanium Supply Chain for the Aerospace Industry Goes Through Russia."* Forbes, March 6, 2022

35 Shih, Willy. *"The Titanium Supply Chain for the Aerospace Industry Goes Through Russia."* Forbes, March 6, 2022.

36 *"Ural Boeing Manufacturing launches second titanium production site in Russia."*

37 Tripp, Bryce. "*Great Salt Lake – The Titanium Connection*." The Utah Geological Survey

Figure 10: The Titanium Manufacturing Process
Click to see video

Numerous U.S. forging companies post blogs and articles about the challenges faced in forging titanium. New Equipment Digest reports that **some machine shops are adding advanced forging equipment** to complement their existing CNC (Computer Numerical Control) capabilities, **to be able to produce more cost-efficient precision titanium parts faster**.

> There are significant advantages to including forging in a machine shop's repertoire. With recent advances in the controls and automation of hydraulic forging presses, precision titanium parts can be forged to extremely tight tolerances, and at relatively high volume. Forging also significantly lowers titanium input costs by as much as 50%.[38]

Titanium alloys are considered difficult materials to forge, as it is challenging to fill dies with the alloy to obtain the desired shapes.[39] Companies such as Erie Press Systems integrate a Human-Machine Interface (HMI) which allows operators to see how the press functions and anticipate how it should be performing.[40] An overview of the methods that can be used to address the various challenges when forging titanium is also available.[41]

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38 Williams, Del. Using a Forging Press To Reduce the Cost of Titanium Parts. New Equipment Digest, April 11, 2022

39 Choda, Takashi et al. "Technologies for Process Design of Titanium Alloy Forging for Aircraft Parts." Kobe Steel. n.d.

40 "*Titanium Forging: Increase Revenues by Supplying Machine Shops with Near-Net-Shaped Parts.*" Manufacturing Tomorrow, n.d.

41 Zhao, Qinyang. *"High-strength titanium alloys for aerospace engineering applications: A review on melting-forging process."* Materials Science and Engineering. Volume 845, June 2022.

Magnesium

As noted in the introduction to this report, the addition of magnesium (Mg) to alloys enables the construction of light weight parts, a highly desirable feature of both the automotive and aircraft industries. Reducing the weight of vehicles is an efficient way to save energy and reduce CO2 emissions. In 2021 alone, there were over 4,000 papers published on the topic of magnesium alloys with 40% of the research being conducted in China. In the U.S. researchers from **Northeastern University**[42] and **Northwestern Polytech University**[43] were among the most prolific.[44]

> Magnesium alloys, being the lightest construction materials and showing good heat dissipation and vibration damping, are found to have more and more applications in the automotive industry. They are used to produce elements for operation at ambient temperatures, such as brackets, covers, or casings of modern cars. The vast majority of products made of magnesium alloys are obtained mainly in extrusion and stamping processes and, less frequently, in rolling and forging processes. However, forged products made of magnesium alloys deserve special attention due to their homogeneous microstructure and improved mechanical properties compared to elements made of cast alloys. Due to their properties, the products obtained in the forging process are also attractive to such industries as: shipbuilding, aviation, space, and electronics.[45]

According to the International Magnesium Association (IMA) a number of automotive manufacturers including Audi, Daimler, Ford, Jaguar, Fiat and Kia have already replaced steel and aluminum with magnesium in various parts. The IMA has a 3D demonstrator on their website which displays the parts manufactured with magnesium. The site also includes information on the value of using magnesium, apart from weight reduction.

The **United States Automotive Materials Partnership (USAMP)** published its Magnesium Vision 2020 for expanding Potential Automotive Applications of Magnesium. This 46-page document presents the challenges and/or suspected technical problems associated with increasing the use magnesium; presents R&D proposals to address these challenges; suggests solutions and provides a vision to expand potential automotive magnesium applications.

42 Professor Teiichi Ando from Northeastern university publishes a great deal on magnesium alloys
43 Professor Jianghua Shen from Northwestern Polytechnical University conducts research on magnesium alloys
44 Song, Jiangfeng et al. "Research Advances of Magnesium and magnesium alloys worldwide in 2021." *Journal of Magnesium and Alloys.* 10 (2022) 863-898.
45 Banaszek, Grzegorz et al. Investigation of the Influence of Open-Die Forging Parameters on the Flow Kinetics of AZ91 Magnesium Alloy. Materials (Base), July 2021

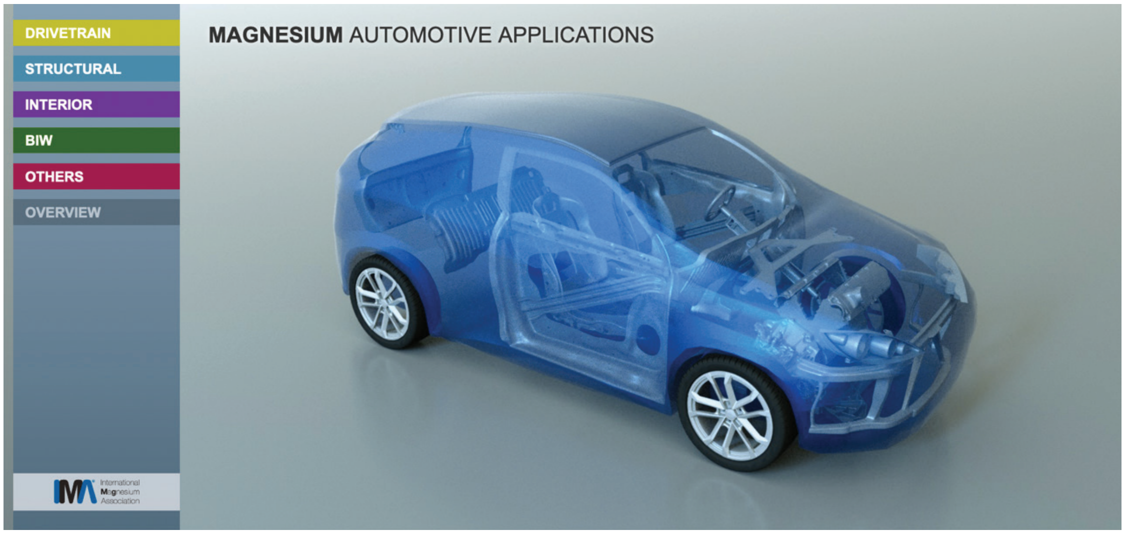

Figure 11: Magnesium Automotive Applications Demonstrator
Click to use demonstrator

While interest in magnesium alloys is increasing, the world-wide supply of magnesium is decreasing. Globally, the largest supplier of magnesium is China which produces 69% of the global demand. However, according to the Energy Industry Review, the flow of magnesium to Europe in 2022 has come to a stand-still. The largest reserves of magnesium are found in Russia (27%), China (20%) and North Korea (18%).[46] Although the U.S. has a domestic supply of magnesium from the electrolysis of water taken from the Great Salt Lake in Utah,[47] others wonder if there will be a "magnesium-shortage tsunami" that will increase the pricing of U.S automobiles.[48]

3.0 INDUSTRY CHALLENGES AND RESPONSES

3.1 Defense Customer Issues

The Department of Defense has prioritized four areas in which critical vulnerabilities pose the most pressing threat to national security, and one of the four is the Casting and Forging (C&F) industry supply chain.[49] DoD has deemed it critical to build more resilience into the C&F supply chain. In its February 2022 report, Securing Defense-Critical Supply Chains, DoD discusses the challenges that the C&F industry faces in trying to meet the needs of the military, such as concerns about non-standard technical data packages, complex contracting processes, burdensome accounting system requirements, small and unreliable demand, and a slow Government sales cycle.[50]

46 *"New Crisis in the Automotive Industry: Magnesium."* Energy Industry Review, January 14, 2022
47 Daigle, Brian and Samantha De Carlo. "Magnesium Price Spike; A Flash in the Pan?" United States International Trade Commission, April 2022.
48 *"Is a magnesium-shortage tsunami about to slam the automotive industry*? DSM, 2021
49 Securing Defense-Critical Supply Chains, Department of Defense. February 2022
50 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

The U.S. C&F industry faces challenges related to capability and capacity, workforce, and U.S. Government policies. Like all businesses, domestic producers need predictable demand, costs, and returns to compete successfully for global market share. In some cases, DoD product needs involve specialized, often low-density requirements that can only be addressed by a small portion of the casting and forging market. Furthermore, the variability of DoD funding (timing and amount) creates challenges for businesses trying to satisfy DoD needs. Industry currently prefers to pursue commercial work. Obstacles to expanding DoD's sources of supply in this area lie in the complex Federal contracting process, the need for improved technical data requirements, and the requirement to modify plant capabilities to support the manufacturing of products that meet military specifications.[51]

Low-volume work driven by U.S. Government and DoD procurement practices incurs high startup costs and produces limited profits. Many small and medium sized manufacturers find it challenging to create sustainable businesses or production lines in this space. Although many trade policy actions are conducted pursuant to specific authorities and designed to remedy injury to domestic industry and respond to unfair or unreasonable foreign trade practices, participants in DoD industry listening sessions reported that tariffs on raw materials used in U.S.-made C&F parts made U.S. products significantly more expensive than parts made in China, driving U.S. suppliers out of business.[52]

The Military, in turn, has challenges in working with the U.S. C&F industry. Multiple U.S. sources have told DoD that China and other foreign suppliers can often deliver a completed item for the same cost that a U.S. forge will pay for the raw materials needed to produce the parts of an item.[53] DoD adds:

The Military Services have experienced casting and forging capability and capacity challenges that can be attributed in part to the impacts of offshoring and waves of industry consolidation since the mid-20th century.

As domestic capacity and overall market share erode, fewer U.S. and allied firms can afford improvements to equipment and processes. Limited access to capital for America's small and medium size producers has hindered their ability to invest in the necessary technologies. This includes the adoption of innovative processes and complementary technologies such as additive manufacturing, robotic automation, and digital engineering to support reverse engineering of aging parts. [54]

Although some suppliers have updated equipment over time in an attempt to meet the Services' needs, many commercial and OIB C&F plants have aging equipment or are limited by existing facilities, infrastructure, and, for commercial firms, state and federal operating permits. For example, the Army recently invested over $65M to upgrade a critical rotary forge at Watervliet Arsenal, NY.[55] [*Organic Defense Industrial Base (OIB): The OIB includes government-owned government operated (GOGO) and government-owned contractor-operated (GOCO) facilities that provide specific goods and services for the DoD*].[56]

51 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

52 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

53 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

54 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

55 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

56 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

As a result of these challenges, DoD reports that it currently counts on foreign countries, including sometimes China, for very large cast and forged products used in some defense systems and many machine tools and manufacturing systems in which DoD is reliant.[57] DoD also is challenged by vendor control of technical data for C&F parts, which limits availability and competitive pricing.

> Vendor control of detailed technical data for C&F parts can constrain DoD's ability to acquire affordable replacement parts, especially for long-lived systems. This is especially true if the original vendor no longer has the capability or desire to manufacture the part. It also makes it difficult for DoD to enable new manufacturers to produce replacement parts using specific geometries, materials, and manufacturing methods that can be constrained by lack of technical data or data rights.[58]

To address this, DoD is exploring creating Government-developed technical data. Efforts at Oak Ridge National Lab's Manufacturing Demonstration Facility indicate that this can:

- Expand the supplier base by licensing on a non-exclusive basis to as many manufacturers as needed, resulting in more competitive pricing

- Increase speed and reduce the cost of first-part certification and acceptance (requires the IP to include a manufacturing recipe which manufacturers must follow scrupulously). This reduces barriers to entry for new and smaller suppliers, increasing the supplier base that can afford to compete for defense work, thereby reducing prices and vendor lock

- Contribute to development of a creative, competent workforce able to deliver next-generation solutions efficiently.[59]

DoD has developed a recommended plan of action to address these C&F supply chain challenges, starting with the development of a cross-service C&F strategy, to be published no later than the end of Q2 of FY 2023. This strategy will make recommendations concerning the following:

- **Establishing C&F centers of excellence.**
- **Identifying other specific measures to improve the OIB's capabilities.**
- **Prioritizing DoD research into:**
    - New C&F processes.
    - Alternatives to C&F, such as new subtractive and hybrid methods.
    - Expanding use of additive manufacturing and digital production capabilities as a tool to enhance traditional methods, such as 3D printing sand cores, and for direct manufacturing.
    - Identify specific opportunities requiring the development of Government-owned technical data.[60]

57 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

58 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

59 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

60 Securing Defense-Critical Supply Chains, Department of Defense. February 2022

Based on the finalized strategy, DoD then plans to:

- Invest in the C&F industrial base, creating a working group that will address sub-tier supplier and workforce development, competition to enable affordable production, and designs and procurements that optimize synergies within the DIB.
- Expand its existing partnerships (such as ORNL) and develop new interagency and organization relationships, such as with the American Metalcasting Consortium and the Forging Defense Manufacturing Consortium
- Identify and develop allied and partner nations' C&F capabilities
- Engage the NIST's Manufacturing Extension Partnership to expand its understanding of industry's perspectives on building commercially viable domestic capacity.[61]

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3.2 Forging Industry's 2nd Biggest Current Concern: Labor

Due to the impact of COVID-19 on the world market in late 2020, lack of orders was the dominant concern of forging companies, going into 2021.[62] Labor issues was a close second – both the lack of skilled labor, as well as higher labor costs. 34 percent of forging survey respondents indicated that a general shortage of skilled labor has been a problem for their operations. Almost 33 percent of companies reported investing in training and/or education for their workers in 2020 and 31 percent of companies expected to invest in training and education services in 2021. Some respondents expressed concern over a lack of training programs, internships, and scholarships, and a lack of continuing education opportunities. When asked what would be the most effective at encouraging professional growth, industry participants vastly agreed that companies involvement with trade associations and colleges, as well as adding additional or alternative training programs at colleges and trade schools, would be most effective.[63]

61 Securing Defense-Critical Supply Chains, Department of Defense. February 2022
62 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
63 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

The third pain point has been raw material lead times, although the percentage of companies that voiced this concern dropped from 32.79 percent in 2020 to 28.33 percent going into 2021.[64]

3.2.1 Robotics/Automation to Bridge Labor Gaps

In addition to the training solution, automation is expected to play a key role in bridging the labor gap for the forging industry. According to the recent survey results, this is especially true for Tier-2 metalworking shops, competing with larger OEMs, and Tier 1 shops competing for the small talent pool of skilled workers.[65]

Erie Press Systems reports that 90 percent of their press customers request equipment with an automation component.

Some of the tasks that were once performed manually can now be done with a "mechanical hand" using robot technology, and automated tooling changes can be completed "with the push of a button." By automating forging operations, productivity can increase from several hundred pieces per hour to up to 3,000, depending on the type of products being forged.[66] One study that implemented robotization into a hot die forging process concluded that robotization had several tangible benefits, beyond just replacing human labor. While simple components are made by cold forging, the hot forging process is required to make complex parts.[67]

> Implementing robotization into one of the most difficult production processes aimed at replacing the role of a human by transferring the competences from the operator of the die forging process onto a supervising person, where all the activities are realized automatically, thus eliminating the effect of the human factor on the quality of the manufactured product. Additionally, the robotization of the [hot] forging process brought a lot of tangible **benefits, such as stability and repeatability of the process (reduction of reject rate), as well as increased efficiency and quality of the forgings**.[68]

Bill Goodwin of Erie Press Systems reports that 90 percent of their press customers request equipment with an automation component.[69]

3.2.2 Foreign Competition Issues

FORGE editor Dean Peters cites theft of IP and currency manipulation as ways that foreign competitors have unfairly hurt the North American forgers.[70] FIA, to counter what it calls unfair trade practices, recently established a political action committee, ForgingPAC, to

64 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
65 Williams, Del. Skilled Forging Labor Shortage: Automation Can Bridge the Gap. New Equipment Digest, February 9, 2022
66 Williams, Del. Skilled Forging Labor Shortage: Automation Can Bridge the Gap. New Equipment Digest, February 9, 2022
67 Mewada, Shivial et al. Smart Diagnostic Expert System for Defect in Forging Process by Using Machine Learning Process. Journal of Nanomaterials, May 23, 2022
68 Hawryluk, Marek and Rychlik, Marcin. An implementation of robotization for the chosen hot die forging process. Archives of Civil and Mechanical Engineering Volume 22, Article number: 119, May 6, 2022
69 Williams, Del. Skilled Forging Labor Shortage: Automation Can Bridge the Gap. New Equipment Digest, February 9, 2022
70 Peters, Dean M. The Acceleration of Change. FORGE, February 2, 2022

give a political voice to the industry's key issues. Megha Patel, FIA's new government affairs specialist, recently described how foreign competition has negatively impacted The North America forging industry:

> You might be wondering why a greater advocacy push is necessary? **Unfair trade has had devasting effect on the North American forging industry**. Our updated **plant closings** list shows **241 plant closures since 1979 and 25,000+ lost jobs**. Companies are **losing millions of dollars** and **cannot compete with such low-cost parts** even with the tariffs. It puts our national security at risk as plants close and the United States relies on foreign countries for forgings. Not to mention the job losses that come with these closures.[71]

New Equipment Digest reports that the imposition of **tariffs on steel and aluminum imports has "roiled" the North America forging sector** — "limiting raw-material sources for some forgers, initiating retaliatory actions by foreign governments against many of the forging sector's most dedicated suppliers, but limiting competition for a certain number of forgers that produce their own (mainly steel) raw materials."[72]

However, when asked what effect tariffs had on their forging business during 2020, 50 percent of survey respondents reported no effect, and only 20 percent maintained that imported forgings "remain a competitive factor." 7.8 percent reported that imported forgings are becoming less of a competitive factor, and 4.7 percent revealed that their business has actually developed its own export business.[73]

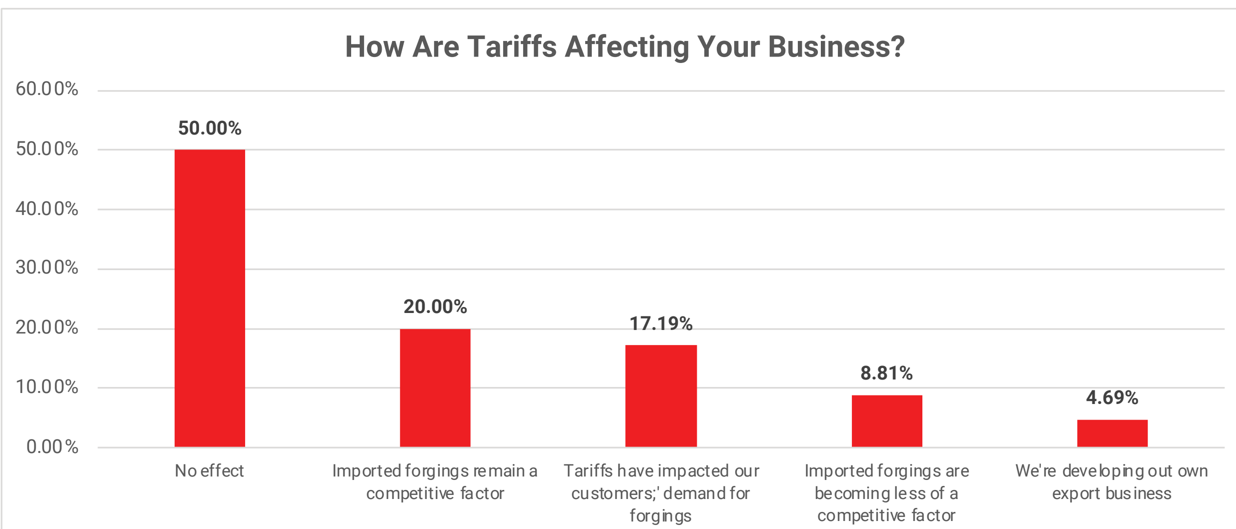

Figure 12: Impact of Tariffs on Forging Industry in 2020

Source: 2021 Business Outlook for Forging survey results[74]

71 Patel, Megha. Increased Focus on Advocacy and Government Affairs, FIA Magazine, May 2022. Accessed at https://www.forging.org/fia/fia-magazine/magazine-may-2022-volume-4

72 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

73 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

74 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

3.3 Electric Transport's Impact

In the short term, recent forging market reports cite growth in the automotive industry as a key factor creating a positive outlook for the global forging market.[75, 76] However, in the future, as E-mobility trends up, this technology will present challenges to the traditional forging industry, but also some opportunities.

When asked "which market offered the most promise to your company" in the October 2020 industry survey, only 7.58 percent said "fuel efficient engines" offered them the most promise; and only 1.52 percent said "lighter composites for transportation" offered them the best opportunity.[77] This is no doubt because EVs require fewer forged parts, and many traditional automotive forgings present weight issues – a major pain point in the E-mobility sector.

3.3.1 EVs Require Fewer Forged Parts

How and why will the growth of the electric vehicle (ev) market impact the forging industry? Will it upend the automobile manufacturing industry as some are predicting? In an article written by Tom Lefaivre, the President and CEO of **Anchor Harvey**, the author explains why fewer forged parts will be required

1. The transmission in an electric vehicle is less complex than the transmission in an internal combustion (ic) engine. Less complexity… requires less forged parts.

2. Temperature regulation is also another major difference. Internal combustion engines run hot and require forged parts for the cooling system. Electric vehicle motors generate far less heat and therefore require less forged parts for the cooling system.

3. The powertrain of the two vehicles is also significantly different. Internal combustion engines require over 2,000 forged parts, while electric vehicles require less than 100.

The rate at which the transition from internal combustion engines to electric vehicles will take place is anyone's guess. However, there are a number of trends which may be seen in the forging industry in the decades to come: contract bidding, consolidations, diversification and demand changes. [78] Of particular interest in this article is the concept of consolidation. Currently more than half of the components for the Chevrolet Bolt's components are sourced from LG Electronics in Korea. This type of consolidation to a single source could happen in the U.S. with the forging industry in order to simplify the supply chain.

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75 https://www.imarcgroup.com/metal-forging-market
76 https://www.digitaljournal.com/pr/north-america-forging-market-to-reflect-tremendous-growth-potential-with-a-cagr-of-5-2-by-2027-business-market-insights
77 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
78 Lefaivre, Tom. How New EV Tech is Changing the Forging Industry. Industry Today, March 26, 2021

Other U.S. manufacturers such as the General Motors Company and Ford Motor Company have publicly committed to sell only zero-emissions models by 2035.

> General Motors Co. has vowed to sell only zero-emissions models by 2035. Ford Motor Co. said it expects 40% of its global vehicle sales volume to be electric by 2030 and Stellantis NV, the successor to Fiat Chrysler, has said it is targeting over 70% of sales in Europe and over 40% in the U.S. to be "low emission vehicles," meaning either electric or hybrid, by 2030.[79]

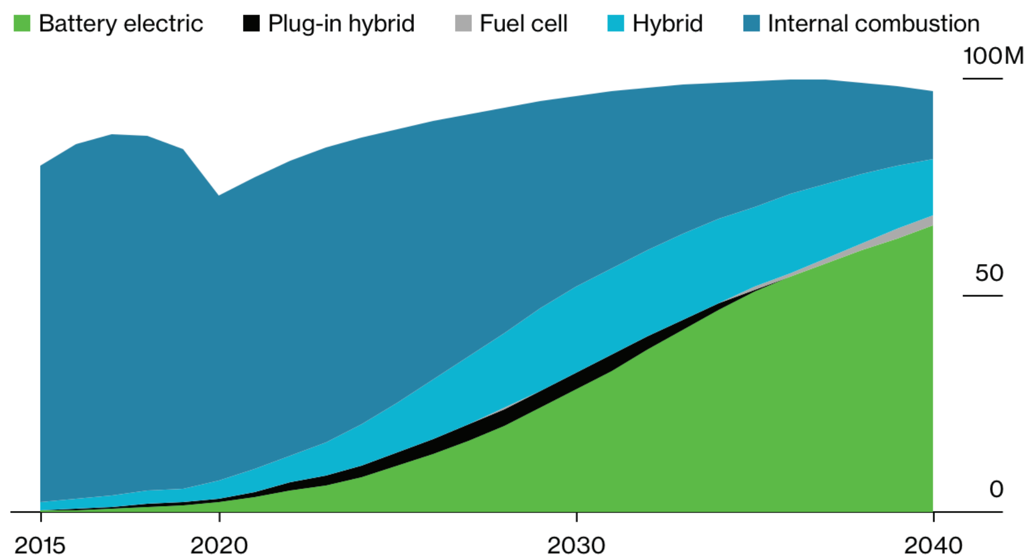

Figure 13: U.S. Passenger Vehicle Sales By Drivetrain
Source: Bloomberg News[80]

Some current suppliers of ICE forgings are looking at ways to replace the unneeded parts by switching to other products, such as hand tools, as well as exploring whether existing parts they make, like D-rings, can be repurposed to hold EV batteries. The U.S. forging industry has more time to adjust than their counterparts in France, Britain, and China, as currently only 2 percent of vehicles sold in the U.S. are EVs and the government has not set a date for banning ICEs, as France (2030), China (2040) and Britain (2040) have.[81]

The industry acknowledges that a fair amount of forging jobs may be lost, but other jobs will be created by electrification of transportation. The new jobs will require different skills, so retraining will be necessary. The United Auto Workers (UAW) union has estimated the shift to electric could result in the loss of 35,000 union jobs (not just forging jobs). The union is embracing the change but pushing to make sure that the new jobs created are located in the U.S., at comparable wages and benefits.[82]

79 Natter, Ari and Laing, Keith. The Coming Electric Car Disruption That Nobody's Talking About. Bloomberg US Edition, October 22, 2021

80 Natter, Ari and Laing, Keith. The Coming Electric Car Disruption That Nobody's Talking About. Bloomberg US Edition, October 22, 202

81 Natter, Ari and Laing, Keith. The Coming Electric Car Disruption That Nobody's Talking About. Bloomberg US Edition, October 22, 2021

82 Natter, Ari and Laing, Keith. The Coming Electric Car Disruption That Nobody's Talking About. Bloomberg US Edition, October 22, 2021

3.3.2 EV Opportunities for Aluminum and Magnesium Forgers

The EV industry is currently dealing with two pain points: the power-to-weight ratio; and expensive component supply issues.[83] Anchor Harvey's Tom Lefaivre and Kerry Kubatzke, the Lead Sales Manager for the company see strong opportunities for forgers to address these EV challenges by offering aluminum forged parts to replace steel forgings. The light weighting of EVs is essential to reducing the EV "range anxiety" that is currently a restraint on EV adoption. According to Anchor Harvey, compared to steel, aluminum forgings are equal in strength, while lower in weight and one-third the density. Anchor Harvey (AH) formed an **Electric Vehicle Workgroup** in 2021, working in partnership with name-brand OEMs, niche producers, and new EV startups to design and produce high-strength, lightweight forged aluminum EV components (such as steering knuckles, control arms, suspension components, structural nodes, etc.) for EV air and land vehicles.[84] Per AH EV forgings:

> Advanced logistics, process monitoring technology, and an **entirely domestic supply chain**, enable Anchor Harvey to provide partners with new tool and product lead times that are 3-4 times faster than the industry average.[85]

Global supply-chain issues have led to very high prices in steel and other staple manufacturing materials.[86] Kubatzke, in a May 2022 article, discusses how forgers, using domestically sourced aluminum to forge EV components, can help solve some of the EV industry's cost and supply issues. The company has enhanced its capabilities in precision-forged components over the hears by adding cutting-edge data acquisition systems, digital monitoring processes, and preventative and predictive maintenance services.

Anchor Harvey also forges magnesium, which is stronger than steel or aluminum, making it another choice metal for EV light weighting.[87] Per AH:

Magnesium Advantages:

- Magnesium weighs 75% less than steel
- Magnesium weighs 50% less than titanium
- Magnesium weighs 33% less than aluminum
- High dent and impact resistance
- Excellent stiffness and advanced damping
- Easily machined and widely recyclable[88]

Of note, unlike Europe, which gets 90 percent of its magnesium from China, in the U.S. there is some domestic production of magnesium (which could be increased) and the U.S. can also import magnesium from Canada, Mexico, and Israel, according to the U.S. International Trade Commission.[89]

83 Kubatzke, Kerry. Forging the Future of Transportation. Industrial Heating, May 9, 2022
84 Lefaivre, Tom. Anchor Harvey Electric Vehicle Workgroup EV Guidebook Forge Forward. No date. Accessed at https://www.anchorharvey.com/EV
85 Lefaivre, Tom. Anchor Harvey Electric Vehicle Workgroup EV Guidebook Forge Forward. No date. Accessed at https://www.anchorharvey.com/EV
86 Kubatzke, Kerry. Forging the Future of Transportation. Industrial Heating, May 9, 2022
87 https://www.anchorharvey.com/capabilities/magnesium-forgings/
88 https://www.anchorharvey.com/capabilities/magnesium-forgings/
89 Daigle, Brian and DeCarlo, Samantha. Magnesium Price Spike: A Flash in the Pan? U.S. International Trade Commission (USITC), April 2022

4.0 METAL ADDITIVE MANUFACTURING (AM) AND THE FORGING INDUSTRY

There are seven different types of additive technology acknowledged by ASTM Standards; some of which are used in metallurgy. These include:

- Laser-based Powder Bed Additive
- Metal Binder Jetting
- Sheet Lamination
- Directed Energy Deposition

What all "metal additive manufacturing" approaches or "metal 3D printing" share is the use of a heat source such as a laser or electron beam to heat the metal in powder or wire form so that it consolidates to form an object. AM can be confusing, as each AM process has multiple alternative names.

Directed Energy Deposition (DED) can be used to fabricate near-net-shape parts . For certain components DED can reduce die, machining and materials costs.

The question is often asked "Is additive manufacturing a threat to the forging industry?" To gain a perspective on this question a number of articles were reviewed that were written by subject matter experts from the forging industry. One author suggests that to answer this question you must first revisit the unique benefit of forging. Forged parts have physical strength due to the fact that the internal grain structure deforms to follow the general shape of the part. The result is that a forged part is stronger than cast or machined parts. The materials used in the forging process (commonly steel or iron) are usually less expensive, but the dies can be costly and secondary processes may need to be applied to achieve final tolerances. Forging is also more commonly used on less complex parts that need to be manufactured in a repeatable way. As a result of these benefits forging is ideal to use in making bulk heads, axle beams and shafts for automotive parts, artillery parts and engine mounts.[90]

Directed Energy Deposition (DED), one of the metal additive manufacturing approaches, has advantages when the material is expensive, when a low volume is needed and when the shape is complex. Use of this technique can be used to fabricate near-net-shape parts and for certain components DED can reduce die, machining, and material costs. When part strength is important, directed energy deposition may not be the method of choice as "DED components experience large thermal gradients during the deposition process that result in residual stresses that can lead to distortion and negatively affect the overall of the part." The author views these methods as complementary rather than competitive – as each has benefits depending on the situation.[91]

Illinois-based Scot Forge, in its May 10, 2022 article, *Additive Manufacturing - Innovations in Forging*, champions the **benefits of the diffusion bonding AM process**, while citing the

90 Molitch-Hou, Michael. *"Is 3D Printing a Threat to Forging?"* 3Dprint.com. March 6, 2020
91 Molitch-Hou, Michael. *"Is 3D Printing a Threat to Forging?"* 3Dprint.com. March 6, 2020

advantages and drawbacks of the ultrasonic additive, metal extrusion, and sintering AM processes:

> Metal extrusion … is reliable for creating small intricate pieces for noncritical applications … Unlike metal extrusion, the solid-state weld produced by the ultrasonic process provides a reliable way to join different metals without creating brittle metallurgy, as the bonding temperature is below their melting temperature … Selective Laser Sintering creates intricate parts through micro-welding powdered metal layer by layer. While ultrasonic additive, metal extrusion and sintering have significant capability in part complexity, they are severely limited by size as parts cannot be larger than the machine's build platform, and these processes face scalability issues. Materials for metal extrusion manufacturing and sintering can be limiting for manufacturers since only a small variety of metals can be used in these applications.[92]

For further discussion of diffusion bonding, see the May 2020 *3D Metal Printing* article: Diffusion Bonding Builds Complex Metal Parts with Internal Passageways.

4.1. AM in Valve Production

In a recent article, Valve Magazine's Margo Ellis discussed **AM advantages and disadvantages in valve production**:

> This method of building geometries layer by metal powder layer from a digital model (instead of through subtractive methods such as machining) is driving change in how valves and related components are produced … Compared with traditional production methods, there are numerous advantages of AM, including innovative and custom design, complex geometries, lighter weight, part consolidation, waste reduction, shorter supply chain, inventory control and faster everything: prototyping, setup, design adjustments, production, testing, assembly, turnaround and delivery.
>
> Despite all the enthusiasm for AM, however, some of the disadvantages yet to overcome are corollaries of the benefits: gaps in design knowledge and skills, high production costs (metal powder material, although partially offset by reduced machine time), size limitations, product quality, machine suppliers and a lack of both testing procedures and structural regulations.[93]

Ellis reports that some valve manufacturers, including Emerson and Neles, are in various stages of either field testing metal 3D printed valves (Neles), or in full-fledged production and distributing self-certified AM assembly components to customers (Emerson). Industry standards for 3D printed valves are under development and the regulatory process is ongoing, with industry engineers providing guidance for standardization.[94]

Emerson's Claire Belson reports that Emerson's valve components produced using Powder Bed Fusion (PBF) "exhibit material properties the same, if not improved in comparison to cast or wrought materials, even rivaling forgings."[95] Emerson is producing titanium valve

92 Scot Forge Company. Additive Manufacturing - Innovations in Forging. May 10, 2022
93 Ellis, Margo. Metal Additive Manufacturing: The Evolving Road to Adoption and Standardization. Valve Magazine, January 11, 2022
94 Ellis, Margo. Metal Additive Manufacturing: The Evolving Road to Adoption and Standardization. Valve Magazine, January 11, 2022
95 Ellis, Margo. Metal Additive Manufacturing: The Evolving Road to Adoption and Standardization.

bodies via PBF technology, with many currently in service across the globe. They recently received a Canadian Registration Number (CRN) for approval and sale in Canada, specific to boilers, pressure vessels or fittings that operate at a pressure greater than 15 psig.[96]

Jacob Nuechterlein, president of Elementum 3D, says the oil and gas sector has been slower to embrace AM for several reasons:

> “There’s a huge barrier to entry for (valve) manufacturers, but as the capabilities improve to where printing is faster and parts can be larger, the business case can be made for greater adoption, and eventually associated costs will come down as they’re amortized,” he states. In describing the business case measures, he described familiar themes of creating novel and complex products that are otherwise impossible and perennial logistical benefits like reducing the need for spare parts and warehousing them. When one-off replacement parts or components can be produced in as little as several days, there’s a huge upside for manufacturers and their customers.[97]

4.2 AM Benefits to Custom Forging

For custom forgings, traditional production methods commonly have high first article costs. According to Siemens Digital Industries Software’s Ashley Eckhoff, additive manufacturing, combined with CAD, can support cheaper and faster mass production of custom products.[98]

Valve Magazine, January 11, 2022

96 Ellis, Margo. Metal Additive Manufacturing: The Evolving Road to Adoption and Standardization. Valve Magazine, January 11, 2022

97 Ellis, Margo. Metal Additive Manufacturing: The Evolving Road to Adoption and Standardization. Valve Magazine, January 11, 2022

98 Ellis, Margo. Metal Additive Manufacturing: The Evolving Road to Adoption and Standardization. Valve Magazine, January 11, 2022

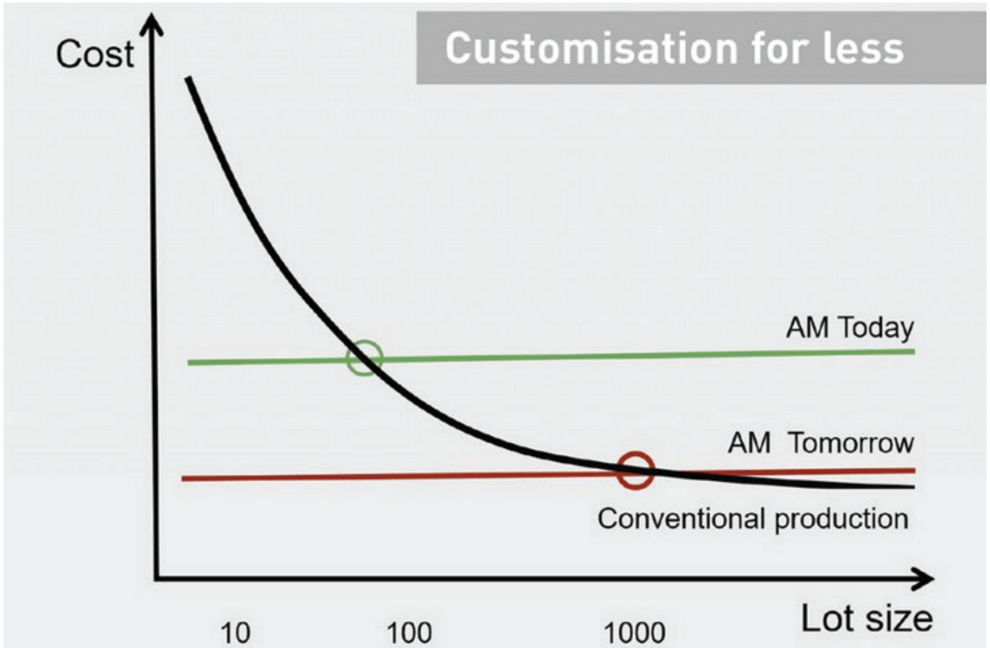

Figure 14: AM Reduces First Article Costs
Source: METAL AM/Siemens[99]

4.3 Opportunity of Additive Friction Stir Deposition (AFSD) Forging

Additive Friction Stir Deposition (AFSD) is an emerging forging-based additive process that allows some of the size and shape advantages found in casting, while increasing strength and decreasing impurities. AFSD **allows the manufacture of very large parts, much faster than traditional forging or casting**.[100]

MELD Manufacturing Corporation invented AFSD and has partnered with Virginia Polytechnic's Yu Research Group (led by Assistant Professor Hang Yu) to further research this technology's potential, with funding from the U.S. Department of Defense, the National Science Foundation, and Ford Motor Co. Yu expects AFSD will have a big impact on aluminum forging, such as in repair of high strength aluminum used by the defense department. His group is also exploring using the AFSD process with copper, steel, and titanium. Yu lab's Jake Yoder, who also works part time at MELD exploring how AFSD might be used on high-value materials like titanium, says there's no restriction on which metals you can print, and so far, no technical limit on how fast the process can print.[101] Per Meld Manufacturing:

> **The MELD process is capable of printing large metal parts at a scale not yet seen in the metal additive market**. The key enabler of this unprecedented leap in scalability is that, unlike traditional additive processes, MELD is not restricted to small powder beds or

99 Eckhoff, Ashley. Forging a process for mass customisation via metal Additive Manufacturing. METAL AM, Vol. 7 No. 2, Summer 2021
100 Moxley, Tonia. Research and industry partnership helps forge 21st century metallurgy. Virginia Tech, March 25, 2022
101 Moxley, Tonia. Research and industry partnership helps forge 21st century metallurgy. Virginia Tech, March 25, 2022

> costly vacuum systems. The MELD process is an open-atmosphere process and is not sensitive to the operating environment or material surface condition; making it an ideal candidate for real-world manufacturing.[102]

MELD founder and CEO Nanci Hardwick notes that clients needing large metal parts, which are currently made by traditional forging or casting, are experiencing long wait times for orders. The company is working with the Army to build a machine big enough to print tank components. It will be capable of printing parts up to 12 feet tall, making it one of the largest metal printers operating today.[103]

4.4 PM/AM Preform Forging Applications

The Powder Metallurgy (PM) additive manufacturing (AM) process can result in inherent voids and microstructural discontinuities, limiting factors for attaining the strength and durability needed in critical structural components.[104] Ohio-based Queen City Forging (QCF) discusses how **using AM to make forging *preforms* can help increase the strength and durability of components made with the PM process**:

> The use of AM in making forging preforms combines the flexibility and efficiency of near-net-shape manufacturing with the strength and durability properties of wrought manufacturing processes. The controlled deformation of the forging process removes porosity and voids in the PM preforms, also adding directional properties for strength, ductility, and resistance to impact and fatigue that wouldn't be possible with AM alone. In many alloys, deformation energies help drive dynamic recrystallization in subsequent thermal treatment … This preforming process has been used successfully by Federal-Mogul to manufacture steel connecting rods and brackets in "green form", with the forging process used to densify and improve mechanical properties. Arconic is also using AM preforms to manufacture titanium wing spars. Through powder blends of preforms, the subsequent forging process is reducing component input weight by one half to two thirds for critical structural aerospace components. Other non-ferrous uses of powder metallurgy or additive manufactured preforms include aluminum applications, where forging is a faster alternative to Hot Isostatic Pressing to achieve reduced porosity, increased density, and true wrought properties in aluminum metallurgy.[105]

QC Forge is working with PM manufacturers to develop preform processes for forging larger aluminum impellers that traditionally would be forged using steel, with the goal of reducing the weight and cost of impellers used in microturbine power generation systems or small aero engines.[106]

102 https://meldmanufacturing.com/technology-overview/
103 Moxley, Tonia. Research and industry partnership helps forge 21st century metallurgy. Virginia Tech, March 25, 2022
104 Queen City Forging blog: Forging Process Innovations: Advantages of Preforming with Additive Manufacturing. *Undated*
105 Queen City Forging blog: Forging Process Innovations: Advantages of Preforming with Additive Manufacturing. *Undated*
106 Queen City Forging blog: Forging Process Innovations: Advantages of Preforming with Additive Manufacturing. *Undated*

5.0 CHALLENGES TO IMPROVING ENERGY EFFICIENCY

The forging industry is a large consumer of energy. In an increasingly green economy, it too is taking measures to address energy consumption, which is also a large contributor to its expenses.[107] In the 2020 Forging Industry study which has been referenced throughout this report, 18 percent of survey respondents reported such costs to be a significant problem for their operation, and, going into 2021, 20 percent expected energy use to be a significant problem.[108] At current (2022) energy prices, energy use is an increasing pain point.

5.1 Using Induction Heating to Reduce Energy

Induction heating or "induction forging" refers to an alternative to conventional furnace heating that relies on fossil fuels. **Trenton Forging**, a Michigan based steel forging company, uses induction heating instead of a conventional furnace. Trenton describes this technology and its benefits:

> Induction heating is a process that uses alternating electrical current to produce alternating magnetic fields within a coil. The resistance that occurs induces heat from within the material located in the coil. While induction heating is not a new technology, it is a more eco-friendly option when compared to heating via gas-fired ovens and furnaces ... induction heating is an environmentally friendly process because it doesn't rely on fossil fuels (coal, crude oil, and natural gas)[109] … Induction heat offers a number of benefits for our forging services:
>
> - Convenient setup
> - Low-cost heating/produces less waste heat
> - Consistent temperatures
> - Clean energy
> - Easy installation or retrofitting[110]

The industrial engineering company Fives Group, which provides Induction Forging systems, explains that these systems save energy by applying heat only to the parts of the metal being shaped.

> Induction forging is a simple, fast, and efficient way to heat metals prior to forming. Heat can be applied specifically to the parts of the metal being shaped. This allows not only much greater control, but also increased efficiency. No energy is wasted heating parts that don't need forming. And, likewise, the metal that is not being shaped is left alone. This ensures there is no loss of integrity, which could reduce the metal's quality or performance. Another advantage of induction forging over a conventional furnace is the speed at which the metal is heated. This enables much higher productivity, whether you choose static or line heating for your application ... Our power converters are designed with very wide impedance ranges enabling heat continuity to be maintained, even beyond the Curie point.[111]

107 He, Fei et al. *"Study on Material and Energy Flow in Steel Forging Production Process."* IEEE Access. January 22, 2020
108 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
109 https://trentonforging.com/sustainability-in-forging-through-induction-heating-and-more/
110 https://trentonforging.com/forging/induction-heating/
111 https://www.fivesgroup.com/es/induction/forging

Trenton Forging has also reduced its energy consumption by utilizing a passive cooling system in its new press facility. The passive cooling systems uses cross-ventilation and stack ventilation. What makes this system unique, is that it relies on a smart, energy-efficient building design, and not on mechanical or electrical devices, like fans. Thus, it reduces heat gain and encourages cooling without using any energy at all.

5.2 Compressed Air System Retrofits to Save Energy

In the pneumatic operated forging industry, the major share of energy consumption is by the compressor units that are used to provide compressed air to the hammers.[112] Canada's **PC Forge** recently re-engineered its compressed air system to save energy and production efficiency, using funding from an Ontario Government incentive program, as described in this recent Compressed Air Best Practices Magazine article: Re-engineered Compressed Air System Scores Perfect "10" at PC Forge.

6.0 OTHER TECHNICAL ADVANCES USED IN THE FORGING INDUSTRY

This section provides a brief introduction to the variety of technologies that are being used by the forging industry including computer simulation, human machine interface (HMI) and artificial intelligence. As in earlier parts of this report, reference is made to data collected by the Forging Industry Association.

6.1 Computer Simulation in the Forging Industry

In the 2020 survey results of its membership, the FIA reported that a third (34.38 percent) of forging companies reported not using computer simulation in the design or analysis of their forging process. Of the 65.63 percent that did use computer simulation, 13.64 percent reported only using it to perform analysis after the fact, if process problems occurred on the shop floor. The major reasons cited for not using computer simulation were costs and lack of experienced personnel.[113]

112 Sankar, Shanmugasundaram. Energy Efficient Management of Compressed Air Systems in Forging Industries. Nehru College of Engineering and Research Centre (NCERC), July 2015

113 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020

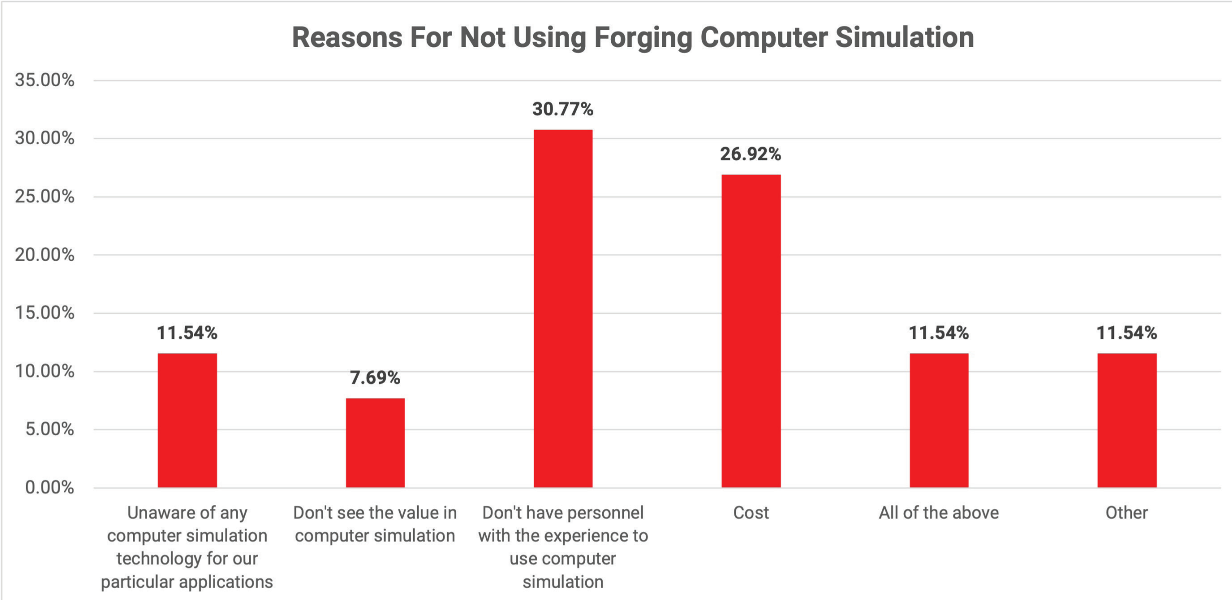

Figure 15: Reasons for Not Using Forging Computer Simulation
Source: 2021 Business Outlook for Forging survey results[114]

6.2 Increasing Press Size to Compete

In response to what it calls "ever-increasing competition from off-shore companies" **Trenton Forging,** a Michigan based steel forging company that has traditionally focused on meeting the needs of the low volume/job shop market, is in the process of expanding and modernizing, by erecting a new facility and **increasing press capacity** by gradually adding three state-of-the-art, fully automated 2500T press forging lines between 2022 and 2026. This addition will enable the company to forge larger components. Trenton also expects to add about 40 skilled professionals to its team to support this expansion.[115]

> "For over 50 years, we have relied on air-lift, gravity-drop hammer technology to manufacture steel forgings for a variety of industries," says Dane Moxlow, Vice President. "As our industry faces ever-increasing competition from off-shore companies that benefit from various state subsidy programs, we need to modernize our manufacturing processes to ensure company competitiveness and sustainability." This investment will allow Trenton Forging to add capacity, achieve higher output rates, manufacture higher volume programs, forge larger components, compete with offshore manufacturers, and alleviate labor shortage issues. "We will continue to run our existing hammer lines simultaneously … This way, we still meet the needs of the low volume/job shop market while also offering a high-quality, local solution to North American companies in need of a reliable supplier for high-volume projects," says Chelsea Lantto, President.[116]

114 New Equipment Digest. 2021 Business Outlook for Forging. December 8, 2020
115 FIA Staff (Press release). Trenton Forging Expands Capacity & Capability with Fully Automated Press Forging Line. FIA Magazine, August 11, 2021
116 FIA Staff (Press release). Trenton Forging Expands Capacity & Capability with Fully Automated Press Forging Line. FIA Magazine, August 11, 2021

6.3 AI/ML Use in Forging

Artificial intelligence (AI) and machine learning (ML) may help reduce energy use in the forging industry, along with other benefits. Globally, there is ongoing research into the potential benefit of using AI and ML to detect defects, improve quality, and save resources during the forging process. Hot forging processes present unique challenges to modeling and controlling in high temperature metal manufacturing. [117]

> Big data and AI are not yet widespread in the forging industry since its manufacturing processes are far more complex than those in other industries. In order to protect the environment, conserve resources and secure technological development, it is necessary to rely on the latest AI technologies …[118]

6.4 Human Machine Interface (HMI) and Forging

A Human-Machine Interface (HMI) is a user interface or dashboard that connects a person to the machine, such as a forging system. Bill Goodwin of **Erie Press Systems** reports that HMIs are becoming popular in the forging industry and that next-level HMIs are not only enabling operators to see how equipment is functioning but also to anticipate how it should be performing.

> "Instead of spending days trying to locate the right technical documentation and reading through data sheets or wiring schematics that can be 100 pages long, the data is searchable and immediately available to operators ... For example, at a dynamically animated schematic screen on the HMI, the operator can hover over the device to find the exact manufacturer's part number or click on the device to access its specific datasheet," explains Goodwin.[119]

6.5 Traceability Technology in Forging

To avoid major recall campaigns, at least one company, **SMS group**, has developed technology to track the manufacturing data of every forging throughout its lifetime. **iForge Traceability** allows for the digitalized and smart tracking of every single forged part. This type of technology could allow a forge to narrow a quality issue down to just a few individual forgings and pinpoint the cause. **iForge Traceability also allows for the ability to verify the carbon footprint for every forging with a precise CO2 value**, of value to OEMs, such as automotive manufacturers which increasingly need to calculate the carbon footprint for their products to provide verifiable emission values for their components.[120]

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117 Castillo, Vic et al Modeling and Controlling High-Temperature Manufacturing Processes with AI. FORGE Magazine, May 19, 2022; Mewed, Shivial et al. Smart Diagnostic Expert System for Defect in Forging Process by Using Machine Learning Process. Journal of Nanomaterials, May 23, 2022; Forging Processes Receive Intelligent Support. Know Center. October 10, 2021; Thore, Andreas et al. RI.SE Smart Forge – AI can help the industry to reach the climate goals. n.d

118 Forging Processes Receive Intelligent Support. Know Center. October 10, 2021

119 Williams, Del. Next-Level Forging Equipment Enhances Production Uptime and Control. New Equipment Digest, July 6, 2021

120 Scholles, Martin and Rossbach, Axel. iForge Traceability: Tracking Capability for Every Single Forging. FIA Magazine, May 2022. Accessed at https://www.forging.org/fia/fia-magazine/magazine-may-2022-volume-4

7.0 SUMMARY AND CONCLUSION

This report introduces an important and often over-looked section of the U.S economy – the forging industry. One of the major objectives of this report was to gain a perspective on changes in the number of businesses participating in the forging industry. However, the tools needed to truly address this challenge are not available. The Forging Industry Association (FIA) has consistently conducted surveys of its membership over the past 30+ years and provides the best insight available on what is happening in this industry. However, as the FIA points out, the tools needed to conduct a true census of this industry are lacking. A wide variety of NAICS codes are used by the Federal government to classify companies working in the forging industry. Large entities with captive forging may not identify, forging as a specialty. Looking at additional data from the Bureau of Labor Statistics and the International Trade Commission did not shed more insight on these numbers. FIA appropriately cautions that as the number of respondents may vary from year to year, they don't report trend data, but provide an annual glimpse of the challenges of their membership at that time. A comprehensive census is needed.

The American Iron and Steel industry accounts for more than $520 billion in economic output and is an important and vibrant part of the U.S. economy.[121] The focus on titanium and magnesium in this report does not minimize the importance of traditionally forged metals and alloys, but is highlighted due to concerns regarding the supply chain for these materials used in the automotive and aerospace market. Both China and Russia are producers of these materials, which are used by global economies. The impact of COVID and the war in the Ukraine on the supply of titanium and magnesium is accelerating on the markets they serve. The U.S. is said to have its own supply of these critical materials. However, currently both are also imported. According to Forbes, the U.S. imported 95% of the titanium that it consumed in 2019.[122]

Industry challenges were reviewed with a focus on the needs of the emerging electric vehicle market. Concerns regarding labor shortages and the need to incorporate a changing mix of capabilities was also addressed. The integration of additive manufacturing into the tool kit that forging companies use was an important part of this discussion. The forging industry appears to be taking the measures that it can to sustain its growth and incorporate new capabilities. More dialog between leaders in the forging industry and the Department of Energy is recommended.

121 "The Economic Impact of the American Iron and Steel Industry." American Iron and Steel Institute, (2018).
122 Shih, Willy. *"The Titanium Supply Chain for the Aerospace Industry Goes Through Russia."* Forbes, March 6, 2022

APPENDIX A: UNIVERSITIES THAT SUPPORT THE FORGING INDUSTRY

FIA reports the following academic members of the Forging Foundation (FIERF).[123]

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123 Academic Members, Forging Industry Association, accessed July 14, 2022
124 https://www.fierf.org/industry

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At FIERF's Professor Summit on August 17, 2022, at Cuyahoga Community College in Cleveland, OH, forging academics will hear from forging industry professionals on the state of the industry, as well as learn how to prepare the next generation of forgers, learn about Forging Foundation programs, and network with other professors. This is a no cost, registration required summit from 9:30 to 2 pm. See details.

Contacts (names, emails, phone numbers) for each FIA industry member can be found in the 2022 FIA Membership Directory, starting on page 27. The Directory also sorts producer members and supplier members by state/province, starting on page 150 and 166, respectively. The academic members included in the above section can also be found in this directory, along with all FIA officers, staff, and committee chairs.