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Powder Metallurgy Part Manufacturing Concentrated in North-Central Pennsylvania

ARTICLE

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ABSTRACT

The powder metallurgy parts manufacturing (PM^2) industry is a significant part of the history of the economy and technology of Pennsylvania. Powder metallurgy parts manufacturing is a process for forming a metal part by compacting metal powder in a die and then heating the compacted powder just below its melting point (called 'sintering'). Powder metallurgy parts manufacturing producers purchase specialized metal powders, lubricants, binders, additives, tooling, process equipment, and industrial gases. Powder metallurgy parts manufacturing producers in north-central Pennsylvania sell most of their PM^2 parts to the automotive industry for use in internal combustion engines. However, the PM^2 industry is adapting its processes for part production in electric vehicles and non-automotive sectors. The small number of specialized suppliers combined with a customer base centered on the automotive industry creates a highly competitive environment among PM^2 firms clustered in the small, rural three-county region of north-central Pennsylvania. Powder metallurgy parts manufacturing in the United States is highly concentrated in this region.

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INTRODUCTION

Powder metallurgy (PM) is a generic term including techniques for producing solid metal-based products from powders. Powder metallurgy part manufacturing (PMPM, or PM²) forms metal parts by sintering metal powders compacted in dies under pressure (James, 2015). 'Sintering' is the process of heating a so-called 'green compact' metal powder that was die-pressed into a shape (Rahaman, 2015). Sintering heats a green compact part just below its melting point in a furnace with a controlled, gas-enriched atmosphere to produce a finished metal part.

BACKGROUND

The history of applying PM² principles extends back as far as ≈3000 BCE (Adams, 2015), although commercial production of PM² accelerated in the late 1800s. In 2022, PM² accounted for only 6.5% of revenue generated by the United States (US) metal stamping and forging industry (Haupt, 2022, p. 18), of which PM² is a part. However, PM² has historically been the most profitable product segment of the metal stamping and forging industry (Haupt, 2022, p. 12).

The PM² industry is a significant part of the history of the economy and technology of Pennsylvania. Powder metallurgy part manufacturing in the US is highly concentrated in the north-central region of Pennsylvania. The history and performance of this geographic concentration of PM² offer examples of how a geographic cluster of human, natural, technological, and capital resources can establish a niche in the national economy and exert technical leadership globally. Although small, PM² holds a significant position in the history of metal part manufacturing in the US.

North-central Pennsylvania PM² is rooted in the late 1800s production of pressed carbon in St. Marys, Pennsylvania, to make metal graphite brushes for the then-emerging electric power industry. Carbon pressing techniques developed to make these parts were modified to make carbon electrodes for deployment in electric arc steel furnaces in Pittsburgh. Then, inspired by porous carbon bearings exhibited at the 1932 World's Fair in Chicago, carbon producers began exploring the growing possibilities of PM² after World War II. After gaining on-the-floor experience, employees of these producers spawned their own companies for PM². As production expanded, technology advanced, and PM² expertise clustered around St. Marys. North-central Pennsylvania began branding itself as the 'Powder Metallurgy Capital of the World.'

Scope of our perspectives

In the remainder of this article, we offer perspectives on the nature and operations of the PM² industry. First, we explain common processes for PM². Next, resource and product markets for PM² are described. Then, US Census Bureau data are analyzed to document the dense concentration of PM² in north-central Pennsylvania. Also delineated are some forces affecting the competitiveness of PM² in the US.

Our reflections about technology practices in PM² are based on interviews, meetings, and collaborative research activity with almost every PM² firm in north-central Pennsylvania, suppliers and customers for PM², and industry trade groups in the US and internationally.[1] Our process for gathering information followed the close-knit—in many cases, family-centered—community of PM² in north-central Pennsylvania, where PM² often is viewed more as a craft than as science or engineering. Not surprisingly, little formal guidance has been diffused from this tight community to integrate PM² into the industrial design of products. Powder metallurgy part manufacturing also is often neglected in the education of engineers. For instance, engineering students at Penn State receive approximately one-half hour of lecture devoted to PM² during their undergraduate experience.

PROCESSES

Conventional pressing

A process, diagrammed in Figure 1, known as press–and–sinter is the core, conventional PM² process. Custom–blended metal powders are fed into a die, compacted by a punch into the desired part, ejected from the die, and then sintered in a controlled atmosphere furnace at a temperature below the melting point of the base material. Press–and–sinter processes offer relatively low manufacturing and tooling costs and produce close tolerances in the finished parts.

General attributes of the PM² process include elimination or minimization of machining; reduction of scrap and waste due to 'net shape' processes; close dimensional tolerances; relatively low energy use (e.g., metal need not be melted); and ability to produce complex shapes. However, ejecting the pressed green compact part from the die imposes certain part design constraints. For example, parts with undercuts, grooves, threads, knurls, reverse tapers, or orifices at angles to the direction of pressing are ill-suited for PM². A green compact part resembles the greenware stage of ceramics production, so the part ejected from the die must have enough structural integrity to withstand handling and transportation. Sufficient radii of inner and outer flanges and the overall thickness of parts are required to maintain the integrity of a green compact part before sintering. Gear design for PM² is another example of a design constraint. An adequate modulus of gear teeth is necessary to allow powder to fill a die and to maintain sturdiness before sintering. As a result of these and other constraints, attention to part design is essential.

Metal powders are elemental or alloyed metals mixed before pressing with binders, lubricants, deflocullates,

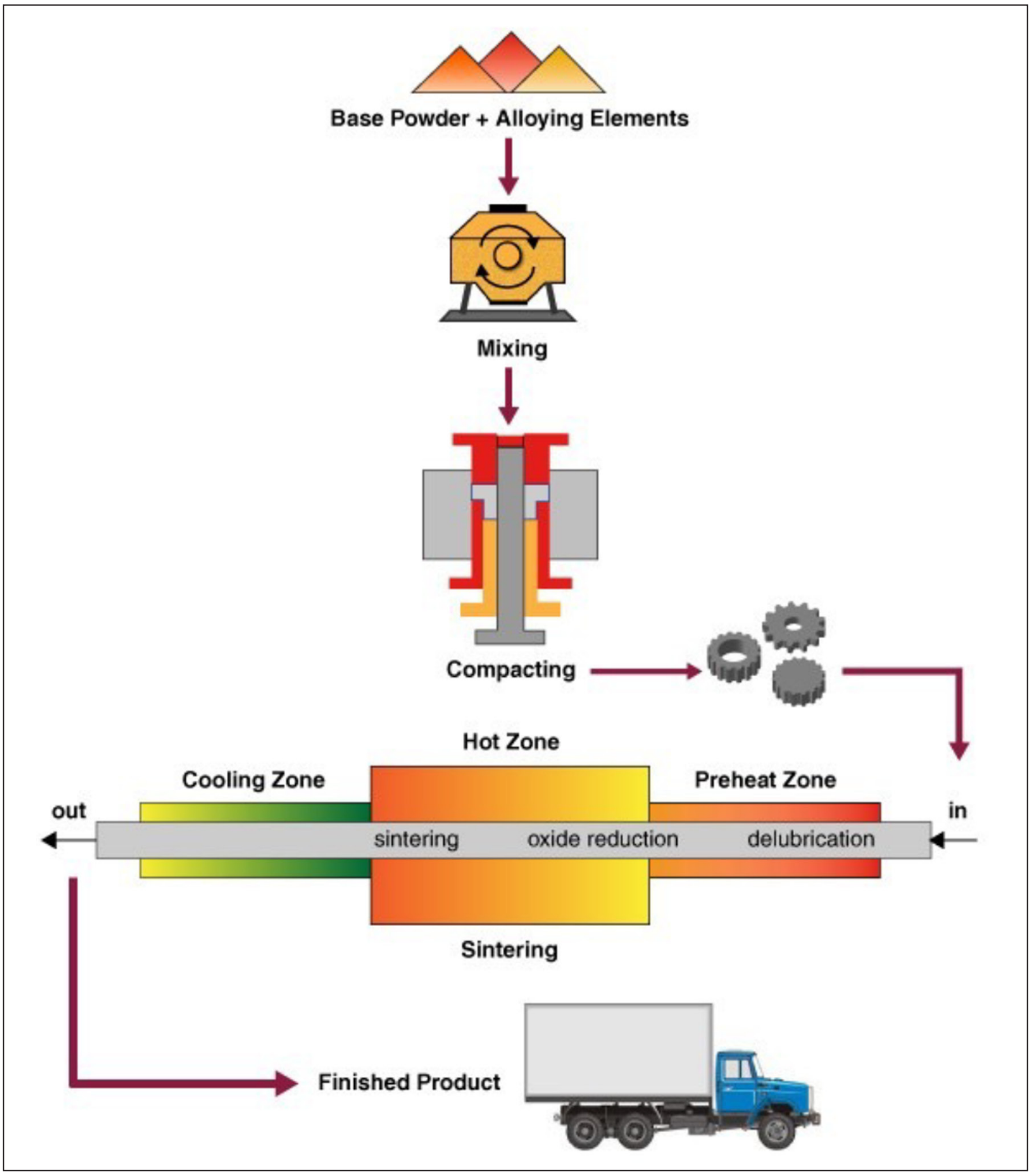

Figure 1 Conventional powder metallurgy process from metal powder to finished part.
Note: Used by permission from the Metal Powder International Foundation.

and additives. A binding mixture consolidates the loose powder. Lubricants are necessary because clearances between punches and dies used for powder pressing typically are less than 0.001 inches. Deflocullates stop the metal powder from clumping. Introducing additives can improve PM^2 part machinability, wear resistance, or lubricity.

The force necessary for pressing for most parts typically varies between 10,000 lbs/in^2 (70 MPa) and 120,000 lbs/in^2 (800 MPa). Parts for this type of manufacture are mostly small (under 5 lbs), and press requirements are under 100 tons typically. Presses with capacities of several thousand tons sometimes are used for work requiring more force. Double action presses, with opposing top and bottom punches, are common to reach the level and distribution of powder desired for compaction. The pressure the press can deliver dictates the upper limit of the size of a part. Increasing the speed of pressing enhances productivity, but pressing too fast can trap air that can prevent the part from compacting properly.

In 2019, press-and-sinter processes produced approximately 93% of the volume of worldwide PM^2 industry output. However, other PM^2 processes are emerging, some of which can add high market value but have correspondingly high production costs. In *metal injection molding*, metal powder is conventionally injection molded to produce a green compact for sintering. *Isostatic pressing* confines metal powder inside a flexible membrane surrounding a mold which acts as a barrier between the metal powder and a liquid or gas pressurizing medium. Isostatic pressing is adapted especially to relatively large, complex-shaped parts. *Powder forging* compacts metal powders into a 'preform' shape in a die. The preformed shape is sintered. The sintered preform is coated with a lubricant and is closed die forged. Forging causes plastic flow, resulting in a dense, non–porous, dimensionally–precise, low–waste part that possesses desirable mechanical properties. *Spray forming* is used to produce semi-finished mill products in the form of billets, tubes, and sheets through high–rate deposition of atomized powder metal layer-by-layer onto a substrate to form, after their solidification, a bulk product or thick coating. An innovative PM^2 process generating considerable attention is *additive manufacturing*, a group of fabrication processes through which three-dimensional parts are constructed by adding layers of materials on point, line, or planar surfaces (Hassanin & Jiang, 2015)—i.e., 3D printing using fine-grade metal powders. Metal injection molders are researching potential manufacturing marriages with additive manufacturing processes.

Sintering

Sintering creates metallurgical bonds between the powder particles, adding desirable mechanical and physical properties to the part. Sintering occurs in a sintering furnace in a controlled atmosphere that can enhance PM^2 part properties by, for instance, regulating oxidation, reduction, and carbon content, making heating and cooling uniform, producing a uniform microstructure of the product, and adding corrosion resistance. Since the late 1970s, a nitrogen/hydrogen mix has become the atmosphere of choice for most PM^2 sintering.

The typical sintering furnace contains a continuous mesh belt moving through three operating zones: (a) a pre-heat zone that burns off binders and lubricants added at the pressing phase and increases the temperature of the green part; (b) a hot zone in which the part raised to 70% to 90% of its melting point; and (c) a cooling zone, in which the part's temperature is gradually lowered. Post–sintering processes also can occur, such as machining, repressing (for decreased porosity and increased hardness), impregnating with oil or resin (to produce a self–lubricating part), infiltrating with another metal (to remove residual porosity and enhance part strength), plating, coating, deburring, welding, steam treating (to oxidize surfaces for strength and density improvement), or furnace brazing with other parts. However, an efficiency feature of PM^2 is that most finished parts require little or no secondary machining operations, such as are necessary for most stamped or forged parts.

A practical and distinguishing metallurgical feature of PM^2 processes is that parts for sintering are not subject to Gibbs' phase rule (Verret et al., 2020, p. 227) that would apply if these metals were alloyed by melting. This feature means that PM^2 does not face many of the same chemical, thermal, and containment restraints placed on materials alloyed by melting due to intersections and disjunctions of their various liquid and solid phases.

MARKETS

For resources

PM^2 purchases many of the inputs to processes from suppliers, just as most complex manufacturing operations do. PM^2 producers purchase two critical sets of supplies. One set of inputs includes metal powders, lubricants, binders, additives, and other raw materials that go into making finished parts. Another set comprises tooling, process equipment, industrial gases, and related services. Some PM^2 producers might choose to outsource post-sintering product finishing.

Metal powder is a unique and essential input to PM^2 processes. In north-central Pennsylvania, ferrous metal powder is dominant in production. Ferrous powder accounted for 89% of the global volume share of metal powder purchased in 2019. Atomization is the most popular method of metal powder production. Molten metal is forced through a nozzle, where it is atomized by an inert gas jet. This inert gas jet separates the molten metal into small metal dimples. These dimples solidify to produce metal powder. The powder can vary by shape, porosity, flow and friction characteristics, surface chemistry, and bulk density and is mixed before packing to include lubricants, binders, deflocculates additives, and additional materials.

Tooling is another critical input to PM^2 processes. A close fit of a punch with a die is necessary so that pressed metal particles do not become stuck in the clearance between the punch and die. Most punches and dies are made from hardened tool steels, the surfaces of which are ground and polished or lapped in the direction of tool movement. Tungsten carbide is used---- to make punches and dies for more powerful powder-pressing operations. These features demand high tolerance production of machine tooling and dictate careful tool use and maintenance.

Many PM^2 suppliers—gas furnace fabricators, gas suppliers, machine shops—are proximal to PM^2 producers in the north-central Pennsylvania region. Metal powder is typically supplied from outside the region (until recently, Scandinavia).

For products

The global PM^2 market was valued at $7.49 billion (US) in 2020 and is projected to reach $12.63 Billion by 2028, growing at a compound annual growth rate of 6.77%. The increasing demand for PM^2 parts in manufacturing automotive components is a significant factor in this global growth, particularly in China and India. The automotive industry is the customer for most of the PM^2 parts produced in north-central Pennsylvania.

According to the Metal Powder Industries Federation, the typical US light-duty vehicle contains about 37 pounds of PM^2 parts. Pickup trucks average about 60–95 pounds, depending on the configuration. The standard US passenger sedan averages 20 pounds. More than an estimated 1.5 billion PM² forged connecting rods have been made for light-duty vehicles produced in the US, Europe, and Japan. Commercial aircraft engines contain 1,500–4,400 pounds of PM² per engine.

The automotive industry and its consumers are moving quickly away from the internal combustion engine in favor of fully electric vehicles and hybrids, however. Increased sticker prices have made new vehicles less affordable for some consumers. Not surprisingly, the average income of a new US. vehicle buyer was $124,000 in 2021. And, with global supply disruptions and rising inflation, the number of vehicles sold in the United States in early 2022 plummeted. Consequently, the demand for PM² connecting rods, main bearing caps, and other internal combustion engine components is likely to decline.

The PM² industry hopes to leverage its extensive experience in supplying the automotive industry experience to supply electric vehicle producers. For instance, some firms are innovating to respond to the increasing demand for a stable supply of permanent magnets, which are vital components of electric vehicle motors. Fiodin and Kianan (2021), based on a teardown of a Tesla vehicle, found that the use of PM² parts in transmissions of electric vehicles could lower manufacturing costs by approximately 20% (p. 50).

In the future, the PM² industry must evolve if it is to meet changing market demands. Shifts from vehicles powered by internal combustion engines to electric vehicles and hybrids will require a creative design response from the industry to maintain PM² market shares in the automotive manufacturing industry. Limiting this effort will be the lack of information and experience about PM² among vehicle design teams, even though automotive manufacturing teams have long integrated PM².

Other markets are emerging to which PM² in north-central Pennsylvania might transfer its expertise from the manufacturing of automotive parts. For instance, the demand for PM² parts for aerospace and defense industries is an increasing share of the PM² market, even overtaking the vehicle market for PM² parts in many regions. Almost all PM² firms in north-central Pennsylvania produce steel parts, although markets untapped in the region exist for brass, copper, titanium, and aluminum alloys. Innovative uses of PM² processes are emerging using ceramics rather than metals, especially for small pieces with intricate designs in medical applications such as inner ear bone replacements.

CONCENTRATION IN NORTH-CENTRAL PENNSYLVANIA

Employment and wages in PM² in the United States are highly concentrated in just three rural counties in north-central Pennsylvania: Jefferson, Elk, and Cameron (See Figure 2). The Economic Research Service of the

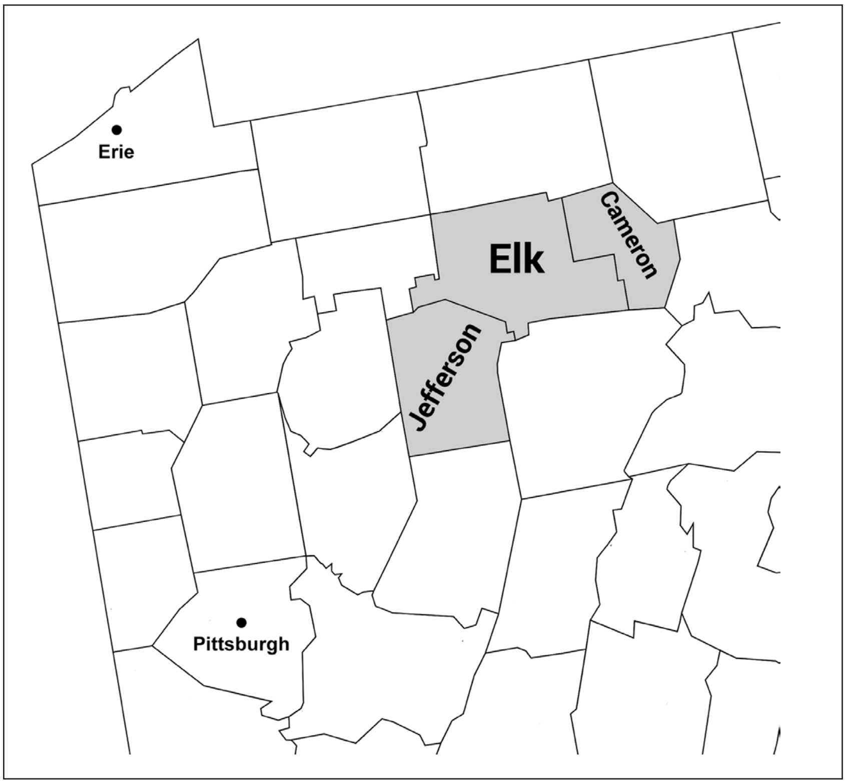

Figure 2 Rural Jefferson, Elk, and Cameron Counties in Pennsylvania contained 38% of establishments, employed 38% of workers, and paid 36% of wages in PM² (NAICS 332177) in the US, 2021 4th Quarter.

Note: Shares of establishments, employment, and wages were calculated using data from Bureau of Labor Statistics (2022). NAICS 332177 is a six-digit code used by the Bureau of the Census (2022) for classifying PM² industry activity and output within the US economy.

US Department of Agriculture classifies these three counties as rural due to relatively low population density and distance from metropolitan areas. Our analysis of Economic Research Service data sets (USDA ERS, 2022) revealed that two counties (Jefferson and Cameron) experience moderately high household poverty levels. Twenty percent of the population of these two counties have completed high school only. All three counties have experienced long–term population declines. These socioeconomic conditions accent the importance of PM^2 activity for the economic well-being of residents in the three-county region.

Documented in Table 1 is the high concentration of employment and wages in PM^2 in north-central Pennsylvania. The PM^2 industry makes up a much larger share of Pennsylvania's employment total than it does for the nation. The concentration of PM^2 employment and wages in Pennsylvania is more than 13 times the concentration of employment and wages for PM^2 in the US workforce.

Even more remarkable are the extraordinarily high concentrations of PM^2 employment and wages in the three counties—i.e., concentrations of employment and wages between 758 and 7,833 times higher than in the nation. These very dense employment and wage concentrations indicate the dominance of PM^2 in north-central Pennsylvania in the national PM^2 industry. Jefferson, Elk, and Cameron counties in Pennsylvania contained 38% of establishments, employed 38% of workers, and paid 36% of wages in PM^2 in the US during 2021.

High industry employment and wage concentrations in PM^2 within the region, relative to the nation, highlight the importance of the industry for exports from the north-central region. An exporting industry not only meets the demand for its products, but also produces enough so it can sell outside the region. A location quotient greater than 1.0 indicates that the economy is self–sufficient, and may even be exporting the good or the service of that particular industry. Industries such as PM^2 sell exports outside a region to contribute to the region's economic base. Economic base theory (explicated in Munroe & Biles, 2005) suggests that the means for strengthening and growing a local economy is to develop and enhance the exporting sectors (Klosterman, 1990, p. 115). In this way, PM^2 is a driving 'engine' for the north-central Pennsylvania economy.

Competitive forces

We analyzed competitive forces affecting PM^2 in north-central Pennsylvania using techniques specified by Porter (1998). The analysis drew on information from structured face–to–face and telephone meetings, gleaned during plant tours and over informal lunches, and captured in confidences revealed in unstructured personal conversations. Competitive forces identified were summarized around five themes: the threat of entry of new competitors; bargaining power of customers; bargaining power of suppliers; the threat posed by substitute products; and the nature of competitive rivalry within the PM part manufacturing industry. We conclude that the environment for PM^2 in north-central Pennsylvania is highly competitive.

The threat of entry of new competitors

The potential of profitable markets can draw firms to the region's PM^2 industry either through acquisitions and mergers or through start-ups. New entrants can

REGION	ESTABLISHMENTS[A]	DECEMBER EMPLOYMENT	TOTAL WAGES[B]	EMPLOYMENT LOCATION QUOTIENT[C]	WAGES LOCATION QUOTIENT[D]
US Total	167	8,702	$130,033	1.00	1.00
Pennsylvania	63	4,622	$64,025	13.56	13.18
Pennsylvania Counties					
Cameron	5	388	$8,014	3,882.58	7,833.02
Elk	32	2,276	$30,685	2,899.67	3,838.84
Jefferson	6	655	$8,377	758.76	996.84

Table 1 PM^2 Establishments, Employment, Wages, and Employment and Wages Location Quotients in the US, Pennsylvania, and Selected Pennsylvania Counties, 2021 4th Quarter.

Source: Bureau of Labor Statistics (2022).

[a] An establishment is generally a single physical location where business is conducted or where services or industrial operations are performed (Bureau of the Census, 2022). [b] In thousands of nominal US dollars. [c] Employment Location Quotient = local concentration/national concentration, where local concentration = local PM^2 employment/local all-industry employment, and national concentration = national PM^2 employment/national all-industry employment. [d] Calculated same as Employment Location Quotient, but substitute total wages for employment in calculations. Refer to Bureau of Labor Statistics (2021) and Wheeler (2005) for additional detail about calculation and interpretation.

affect the competitive climate in many ways. For example, new entrants can bring additional capacity to the PM^2 industry in the region, capture market share from incumbents, bid down industry prices, or inflate incumbent's costs, and, in these ways, effectively affect the profitability of incumbents in the north-central region of Pennsylvania.

Bargaining power of customers

The sizeable automotive industry is the primary customer for PM^2 parts from north-central Pennsylvania. These PM^2 customers enjoy strong bargaining power for PM^2 part prices. In some cases, customers drive the industry's prices down, bargain for more or better service at the same or lower prices, and pit PM^2 firms against one another. PM^2 firms in north-central Pennsylvania produce standard, undifferentiated PM^2 parts almost with the same features as commodities, so buyers face low costs of switching among PM^2 producers.

Bargaining power of suppliers

A small number of metal powder and gas furnace fabricators, gas, and machine shop suppliers affect the PM^2 industry in north-central Pennsylvania. For example, suppliers can raise prices in response to changes in their own markets or reduce the quality of their products without lowering prices. At the extreme, some suppliers refuse to work with a firm (due to *sub rosa* agreements with other PM^2 firms) or charge excessively high prices for unique resources. Because few suppliers are available, few substitutes for supplies exist, and costs to the PM^2 firms for switching suppliers are high. As such, suppliers hold strong bargaining power.

The threat of substitute products

Substitutes for PM^2 parts increase the propensity of customers to switch to alternative products in response to price increases. High elasticity of substitution for some PM^2 parts by product alternatives limits the potential returns in the PM^2 industry by capping price changes. Attractive price/quality substitutes for PM^2 parts place a tight lid on PM^2 firm profits in north-central Pennsylvania.

Competitive rivalry within the industry

North-central Pennsylvania is home to a close community of PM^2 firms. Rivalry among firms is a significant factor in the PM^2 competitive climate in the region. Rivalry for advantage in product and resource markets often occurs along price dimensions, not quality dimensions (which are dictated by customers in the integrated automotive industry). Regional rivals also compete aggressively on non–price dimensions such as innovation, marketing, branding, and public recognition, often fueled by long-standing PM^2-producing family rivalries.

CONCLUSIONS

The PM^2 industry is a small niche within the metal stamping and forging industry in the US PM^2 firms in north-central Pennsylvania hold a large, highly competitive and concentrated portion of that small niche. PM^2 in the region depends mainly on the automotive industry for demand for press-and-sinter parts for internal combustion engines, although the rapid movement toward hybrid and electric vehicles will require PM^2 firms to adapt and innovate with new products and materials to maintain their market share in automotive manufacturing.

The PM^2 industry cluster in north-central Pennsylvania is an example of a regional agglomeration of unique manufacturing activity over the previous 150 years that resulted in regional economic advantage and technological leadership. Advantages and leadership emerged from a cauldron of competition. The threat of new firms entering the market and the threat of products that could substitute for PM^2 products heighten competition among firms in the region. Also, the competitiveness of PM^2 firms is moderated by the strong bargaining power of PM^2 suppliers and customers. Parts manufactured are treated as commodities, so competition in pricing is limited. Rather, PM^2 firms in the region have strong competitive rivalries along non-price dimensions.

NOTE

1 The PM^2 research literature published in refereed journals focuses on physics, chemistry, engineering, and metallurgy applications to PM^2 processes that go well beyond an introductory discussion of PM^2. Few textbook resources are available about PM^2, primarily because PM^2 receives such scant attention in the education of engineers. Information about the organization, economics, and finances of PM^2 resides primarily in a vast gray literature not published in academic books or refereed journal articles. This gray literature is found in industry market reports sitting behind paywalls and in non-refereed conference presentations, audiovisual works, occasional papers, blogs posted on company websites, and in the literature distributed by professional associations. Passmore (2023) supplements the information offered in this article by listing, classifying, and citing some of this PM^2 gray literature.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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REFERENCES

Adams, J. P. (2015). History of powder metallurgy. In P. Samal & J. Newkirk (Eds.), *ASM handbook: Powder metallurgy, 7*. ASM International. DOI: https://doi.org/10.31399/asm.hb.v07.9781627081757

Bureau of Labor Statistics. (2021). *QCEW location quotient details* (Bureau of Labor Statistics, Quarterly Census of Employment and Wages). Retrieved from https://www.bls.gov/cew/about-data/location-quotients-explained.htm

Bureau of Labor Statistics. (2022). *Private, NAICS 332117 powder metallurgy part manufacturing, all counties in Pennsylvania 2021 fourth quarter, all establishment sizes.* (Bureau of Labor Statistics, Quarterly Census of Employment and Wages). Retrieved from https://data.bls.gov/cew/apps/table_maker/v4/table_maker.htm#type=2&st=42&year=2021&qtr=4&own=5&ind=332117&supp=1

Bureau of the Census. (2022). *Frequently asked questions: What is an establishment?* (Bureau of the Census, North American Industry Classification System). Retrieved from https://www.census.gov/naics/#q2

Fiodin, A., & **Kianan, B.** (2021). Tesla teardown: Identifying potential uses for PM in electric vehicle transmissions. *Powder Metallurgy Review, 10*(4), 45–52. https://www.pm-review.com/wp-content/uploads/2021/11/PM-Review-Winter-2021.pdf

Hassanin, H., & **Jiang, K**. (2015). Net shape manufacture of freestanding ceramic micro-components through soft lithography. In Y. Qin (Ed.), *Micromanufacturing engineering and technology* (2nd ed., pp. 239–256). William Andrew Publishing. DOI: https://doi.org/10.1016/B978-0-323-31149-6.00010-4

Haupt, N. (2022). *Metal stamping and forging in the US* (IBISWorld Industry Report 33211). Retrieved from IBISWorld proprietary database https://www.ibisworld.com/

James, W. B. (2015). Powder metallurgy methods and applications: Abstract. In *ASM Handbook*: Powder Metallurgy (volume 7). ASM International. Retrieved from https://dl.asminternational.org/handbooks/edited-volume/22/chapter/311363/Powder-Metallurgy-Methods-and-Applications. DOI: https://doi.org/10.31399/asm.hb.v07.a0006022

Klosterman, R. (1990). *Community analysis and planning techniques*. Rowman & Littlefield Publishers. Retrieved from https://archive.org/details/communityanalysi0000klos/page/n7/mode/2up

Munroe, D. K., & **Biles, J. J.** (2005). Regional science. In K. Kempf-Leonard (Ed.), *Encyclopedia of social measurement* (pp. 325–335). Elsevier. DOI: https://doi.org/10.1016/B0-12-369398-5/00365-0

Passmore, D. L. (2023, May 14). *Selected gray literature for the powder metallurgy part manufacturing industry*. Retrieved from https://osf.io/v354c

Porter, M. (1998). *Competitive strategy: Techniques for analyzing industries and competitors*. Free Press.

Rahaman, M. N. (2015). Sintering theory and fundamentals. In P. Samal & J. Newkirk (Eds.), *ASM handbook: Powder metallurgy, 7*. Retrieved from https://dl.asminternational.org/handbooks/edited-volume/22/chapter/312542/Sintering-Theory-and-Fundamentals. DOI: https://doi.org/10.31399/asm.hb.v07.a0006117

USDA ERS. (2022). *County-level data sets*. Economic Research Service, Department of Agriculture. https://www.ers.usda.gov/data-products/county-level-data-sets/

Verret, J., Qiao, R., & **Barghout, R. A.** (2020). *Foundations of chemical and biological engineering I*. BCcampus Open Education. Retrieved from https://pressbooks.bccampus.ca/chbe220/chapter/gibbs-phase-rule/

Wheeler, J. O. (2005). Geography. In K. Kempf-Leonard (Ed.), *Encyclopedia of social measurement* (pp. 115–123). Elsevier. DOI: https://doi.org/10.1016/B0-12-369398-5/00277-2

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