Zay Jeffries

1888–1965

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
William D. Nix

NATIONAL ACADEMY OF SCIENCES

ZAY JEFFRIES

April 22, 1888—May 21, 1965

Elected to the NAS, 1939

Zay Jeffries

By William D. Nix

In the nearly five decades since Zay Jeffries' death, his seminal ideas about the relationship between materials' microstructure and their mechanical properties—and the improvement of these properties through processing—have become accepted as the basic paradigm for the field of materials science. It is hoped that this review will serve to remind current and future generations of materials scientists of the brilliance of our field's forefathers and the contributions they made.

Because members of the National Academy of Sciences and other authorities in physical metallurgy and materials science who knew Jeffries personally have now left the scene, we are left to base his biographical memoir on written records that remain. The 1973 biography of Jeffries written by W. D. Mogerman at the request of the American Society for Metals (now ASM International) has been invaluable in this task.[1] Another important reference is the book *Men of Metals,* written by S. L. Hoyt, which contains an especially informative account of Jeffries' role in the development of the cemented-carbide cutting-tool industry and the trials and tribulations that he faced in that endeavor.[2] Jeffries' 1924 textbook *The Science of Metals*, coauthored by R. S. Archer, is another valuable source that especially reveals the clarity of thought that Jeffries brought to the understanding of materials.[3] The author of this memoir also received useful information about Jeffries'efforts during World War II from his grandson, Justice John W. Kittredge of the Supreme Court of South Carolina.

A succinct summary of Jeffries' most important scientific work is found in the official citation prepared by the American Society for Metals as it awarded the first ASM Gold Medal to him in 1943. ASM President Herbert J. French read this citation at the annual ASM dinner that year:

> *Zay Jeffries, recognizing the practical importance of the grain size in metals, devised procedures for its measurement and control. His utilization of these concepts and methods has resulted in: generally beneficial improvements in the manufacture and application of tungsten wire; the clarification of the mechanism of the hardening of steel; and a better understanding of the significance of grain size...to the properties and fabricating characteristics of metals at elevated temperatures.*
>
> *Zay Jeffries established the importance of the time factor in diffusion reactions in coarse structures. This led him to the development and commercial application of heat-treatable aluminum casting alloys. His elucidation of the effects of the various constituents on the forgeability and strength of aluminum alloys brought about the discovery of commercially workable alloys, which are the basis of the present aluminum forging industry. The metallurgical principles indicated were combined in the general slip interference theory of the hardening of metals, which has inspired widespread and profitable metallurgical research.*
>
> *Zay Jeffries' belief in the potential need for better cutting materials and the latent possibilities of hard carbides prompted his perseverance in the organization of a sound development program, the pursuance of which matured into the present commercial utilization of these materials in the metalworking industry.*

In these three paragraphs one finds reference to the seminal scientific works that led to Jeffries' election to the National Academy of Sciences some four years earlier, in 1939. The first paragraph refers to the importance of grain size in controlling the mechanical properties of metals and alloys and Jeffries' role in developing related techniques. The second refers to the critical role that time and temperature play in the annealing of technical alloys, especially aluminum alloys, and also to Jeffries' slip interference theory of the hardening of metals, which became the basis for developing strong alloys in the middle of the 20th century. The last paragraph refers to Jeffries' role, primarily as a manager and executive, in the development of the cemented-carbide cutting-tool industry, which played such an important role in establishing an efficient manufacturing capability in the United States and which contributed to winning World War II through improvements in the machining of military hardware.

From mining to metallurgy

Zay Jeffries was born April 22, 1888, near Willow Lake in what is now South Dakota, one year before the state was admitted to the union. His unusual name was taken from the middle syllable of an uncle's name, Isaiah. Zay's parents, Johnston and Florence, had migrated from Illinois to the Dakota Territory in the early 1880s, seeking to improve Johnston's health. In 1890, still seeking better health and also prosperity, the growing family moved westward once again, this time settling at Fort Pierre, SD, just across the Missouri river from the town of Pierre. It was in Fort Pierre that Zay grew up and attended elementary school, later attending Pierre High School, a daily ferry ride across the Missouri river. There he studied geology, which was not uncommon at the time for a community so dependent on mineral resources. His exposure to geology was what eventually brought him to metallurgy and then to science more broadly.

Jeffries enrolled in the South Dakota School of Mines in Rapid City, SD, then a small school of only 11 faculty members and 44 students.

Following his graduation from Pierre High School in 1906, Jeffries enrolled in the South Dakota School of Mines in Rapid City, SD, then a small school of only 11 faculty members and 44 students. While he initially intended to major in geology, he was soon attracted to the courses in mining and metallurgical engineering. This change in direction was motivated by what Jeffries perceived to be the better job prospects in mining and the influence of Charles A. Fulton, a distinguished teacher of mining engineering and the president of the School of Mines. His association with Fulton was later to shape the early part of his career as an academic and research scholar.

Jeffries excelled at the School of Mines and took on summer jobs involving manual labor in the mining industry. He graduated at the top of his class in 1910 with a B.S. degree in mining engineering and immediately accepted a job as an assayer for the Ideal Mining Company in Custer, SD. While he was successful in his new job and impressed his superiors, he kept up his studies in the hope of a possible return to the School of Mines. Jeffries' opportunity came in the spring of 1911 when his mentor, Fulton, announced that he had accepted an appointment as professor and head of metallurgy at the Case Institute of Technology in Cleveland. He invited Jeffries to join him there as an instructor of metallurgy. So by the fall of 1911 Jeffries was at Case, starting his seminal work in the field of metallurgy.

Jeffries married Frances Schrader on December 27, 1911. They had met in Rapid City during his days at the School of Mines. The couple had two daughters, Betty (born in 1914) and Marian (1923). Betty married John H. Kerr, a businessman in Cleveland, and had two children. But she died of cancer at the early age of 46. Marian married E. H. Kittredge, Jr., of Greenville, South Carolina, and had four children. Her family still lives in Greenville, South Carolina, not far from the so-called "thermal belt" in Southwestern North Carolina, where Jeffries and his wife spent their winter months after his retirement.

Jeffries served as an instructor at Case for five years before being appointed assistant professor there in 1916. It was during this time that he started his renowned work on the measurement of grain size in polycrystalline metals—the basis for his thesis for the degree of Metallurgical Engineer awarded by the South Dakota School of Mines in 1914. Also during this period he was engaged in consulting for metallurgical companies in the Cleveland area and was involved in patent litigation as well.

Jeffries soon determined that his credibility as a technical consultant would be greatly enhanced if he were to have a doctoral degree. Having already started to build a reputation for his published work, he was able to make an unusual arrangement with Professor Albert Sauveur of Harvard University to work for his doctoral degree at that institution. Jeffries did this partly in absentia to accommodate his consulting and family obligations in the Cleveland area, though he did have a year of residence at Cambridge. He was awarded a Doctor of Science degree from Harvard in 1918, based on a two-part dissertation that involved the study of grain growth in metals and the related effect of temperature on metals' mechanical properties.

Going with the grain

Jeffries was perhaps best known for his work on measuring and controlling grain size in metals. In the fall of 1911, when he started his scientific work as an instructor at the Case Institute of Technology, there was considerable uncertainty about the structure of metals and especially about whether the grains in ordinary polygranular metals were fully crystalline. The great British metallurgist Henry Sorby had shown in the latter part of the 19th century that grains in polygranular metals were largely crystalline, even after severe plastic deformation. But because some polycrystalline metals, notably tungsten, were known to fracture in a completely brittle manner, it was widely believed that an amorphous cement layer (which held the grains together) was responsible.

Because microscopes of the day were powerless to show the existence of such an amorphous layer at grain boundaries, Jeffries and others reasoned that measuring and controlling the grain size in metals—and thus the controlling amount of the glassy grain-boundary phase, if it existed—would be an important way to study metals' structure and properties. Thus in the fall of 1911, with the help of a few of his young students, he began to develop new techniques for measuring and controlling the size and distribution of grains in polycrystalline metals. That early work led to his first published papers on the subject, for which he became famous. Jeffries' 1916 paper with A. H. Kline and E. B. Zimmer, "The determination of grain size in metals," became one of the most influential papers in physical metallurgy in the first half of the 20th century. In this paper he showed that a simple line-intercept method could be used to accurately measure the sizes of grains in polycrystalline metals; this method subsequently replaced the slow and expensive planimeter method that had been used previously. Jeffries' measurement technique became the standard for measuring grain size in polycrystalline solids, and it remains the accepted method to this day. His paper on "Grain growth in metals," published in the *Journal of the Institute of Metals* (London) in 1918, became the first part of his doctoral dissertation at Harvard.

In the early part of the 20th century it was believed that fine-grained metals were usually harder and stronger than coarse-grained metals (in part because of the presumed existence of an amorphous layer at the grain boundary). But Jeffries showed that this generalization about strength is only valid at low temperatures.

Jeffries' work on the effect of grain size on the mechanical properties of metals was closely related to another one of his major contributions to physical metallurgy—the idea of an "equi-cohesive temperature." In the early part of the 20th century it was believed that fine-grained metals were usually harder and stronger than coarse-grained metals (in part because of the presumed existence, noted above, of an amorphous layer at the grain boundary.) But Jeffries showed that this generalization about strength is only valid at low temperatures. In fact, he found that at high temperatures fine-grained metals typically become weaker than coarse-grained metals and that this transition occurs above a critical temperature, which he called the "equicohesive temperature," whether an amorphous layer is present or not. While much more understanding of these effects was to come in the latter part of the 20th century, Jeffries had already shown by about 1915 that grain boundaries are a source of weakness at high temperatures and consequently that coarse-grained metals are preferred for high-temperature applications.

Jeffries' paper on the subject, titled "Effect of temperature, deformation, and grain size on the mechanical properties of metals," was published in 1919 in the *Transactions of the American Institute of Mining and Metallurgical Engineers* and became the second part of his doctoral dissertation at Harvard. Jeffries' work in this area has guided the development of high-temperature alloys to this day. Currently, single-crystal superalloys—without any grain boundaries at all—are commonly being used in critical high-temperature applications such as in the gas-turbine engines that powered your last aircraft flight.

A consultant's major contributions

In 1914 Jeffries began to engage in consulting work with Cleveland-area metallurgical industries, most notably the Aluminum Company of America (later called Alcoa) and the General Electric Company (GE), with which he was to have a long association. This exposure to industrial problems shaped his research and in 1917 led him to leave Case to become a metallurgical consultant full-time.

Through his research work on grain size and the equi-cohesive temperature, Jeffries made seminal contributions that dramatically affected the incandescent-light industry. In 1914, B. L. Benbow, the manager of General Electric's Cleveland Wire Works, asked him to advise on the durability problems of tungsten filaments that were being used in incandescent lamps. These filaments were very fragile wires made from tungsten powders, and economical production had not yet been achieved because of filament brittleness introduced by the wire-drawing process and by breakage of the process's diamond dies. If the manufacturing problems associated with wire drawing had not been solved, General Electric would have been forced to make the wires with tungsten powders and live with the fragility of those filaments. But having studied the source of brittleness in tungsten, Jeffries quickly devised a different heat-treating schedule that led to the successful manufacture of tungsten filaments by a more economical wire-drawing method—a technique still in use today—based on heat treatment involving a furnace atmosphere rich enough in carbon monoxide to prevent surface oxidation but lean enough to prevent carburization.

Later in 1914 Jeffries was consulted again to determine why some tungsten filaments in lamps would sag and short out while others would not. Aided by his metallographic technique and focus on grain size, Jeffries quickly discovered that sag-resistant wires were ones that had been heat treated to have very coarse grains. This led to a now-standard method for heat-treating tungsten wires.

The basic mechanism of plastic deformation of crystals by the movement of dislocations was first postulated independently by G. I. Taylor, E. Orowan, and M. Polanyi in three separate papers published in 1934. While Jeffries did not recognize that crystal dislocations had to be present in deformable crystals and are responsible for plastic deformation by crystal slip, he came very close to making this discovery on his own, long before the seminal 1934 papers were published. By the turn of the 20th century it had been established that plastic deformation of metallic crystals involved slip on certain crystallographic planes, wherein one part of a crystal would be translated relative to another (slip), much like the sliding of a deck of cards. Most research metallurgists of the day thought that the slip process was a rigid one in which the two crystal halves would remain rigid as they slipped relative to each other. But in 1916, in a discussion of a paper by C. H. Mathewson and A. Phillips on "The recrystallization of cold-worked alpha brass on annealing," Jeffries realized that metallic crystals would have to have the ability to fragment, so that one part of a crystal would have a slightly different orientation than another. To Jeffries this meant that the rigid slip theory of plastic deformation could not be correct and that something else was involved.

Following up, Jeffries made a trip to Columbia University to explore possibilities with Professor Henry Marion Howe, then regarded as the "dean of American metallurgists." After discussing the matter with Howe over a long afternoon and evening, Jeffries pointed out, based on work he had done on non-sag tungsten filaments, that their wires—with long crystals occupying a wire's entire cross-section—could be plastically bent so that one end of the wire (and of a crystal) would have a different orientation than the other end. He convinced an initially skeptical Howe that this would be impossible if rigid slip were the mechanism of plastic deformation. In fact we now know that the "something else" that Jeffries postulated involved crystal dislocations. But it was not until the early 1950s that the fragmentation of metallic crystals by plastic deformation was found to be caused by arrays of dislocations forming low-angle grain boundaries.

Another concept that Jeffries developed in the early 1920s brought him very close to postulating crystal dislocations as the mechanism by which slip occurs in metallic crystals. In his 1924 textbook *The Science of Metals* coauthored with R. S. Archer, Jeffries described what he called his "slip-interference theory" of the hardening of metals. He was well aware of Alfred Wilm's discovery of age hardening of aluminum-copper alloys, and he had followed the work of Paul Merica at the U.S. Bureau of Standards showing that the hardening occurred when copper-rich particles precipitated from a supersaturated solid solution after quenching from an elevated temperature. Jeffries reasoned that such particles would lead to hardening because they interfered with the slip process. By noting that "the area of slip on any one plane is reduced" by the presence of precipitates (*The Science of Metals*, p. 401), Jeffries came just short of establishing the existence of crystal dislocations. It was only long after that such interruptions in the slip process on a given crystallographic plane were seen to be crystal dislocations. Further, using his slip-interference theory Jeffries produced a very coherent understanding of why there is an optimal precipitate size for maximum hardening, a concept that was not fully appreciated by the materials-science community until the 1960s.

A bittersweet achievement

One of the great satisfactions of Jeffries' life, but also one of his great disappointments, was his leadership of the cemented-carbide tool industry in the United States—a satisfaction because his executive efforts helped to establish the industry; and a disappointment because he and two other GE executives were later indicted and found guilty for violating antitrust and tariff acts in connection with certain licensing and merchandising practices. As indicated below, they were convicted for following licensing practices that had been implicitly approved by a Supreme Court decision in 1928 but overturned 20 years later when the Supreme Court reversed itself on those same practices.

In 1925 the General Electric Company sent one of its research engineers, Samuel L. Hoyt, to Germany to investigate metallurgical processes of interest to GE. Having been involved in the drawing of tungsten wires for light filaments, Hoyt had worked with tungsten carbide as a possible die material. While in Germany he learned of a process that had been developed at the German company F. Krupp AG for making cementedtungsten carbide, wherein particles of tungsten carbide could be embedded in a tough cobalt matrix that made a superior tool, not only for wire drawing but for machining as well. On his return to Schenectady, Hoyt worked to duplicate the process in an effort to make die materials that could be used for wire drawing in GE's lamp division. This led to the development of a cemented-carbide material, which the company called Carboloy.

GE recognized the broad potential value of this material for machining, but subsequent patent searches determined that the Germans had already been awarded a patent on an alloy identical to Carboloy and further that Krupp had acquired the rights to market that alloy throughout the world. This situation led to negotiations that allowed GE to market Carboloy in the United States. By 1928 GE had formed a separate company, Carboloy Co., with Zay Jeffries as one of the key executives. He became president of Carboloy in 1932 and was named chairman of the board in 1936. The cemented-carbide industry struggled in the years of the depression and continually fought with Krupp over past business agreements; Krupp even stopped marketing the product in the United States. Through a new agreement in 1936, Krupp surrendered its right to export into the United States in return for royalty payments based on its remaining patents. Thus by the late 1930s the cemented-carbide tool industry was entirely in American hands.

In 1940 Carboloy filed a routine suit against a U.S. company that Carboloy considered to be infringing on the patents it had acquired through its agreements with Krupp. Jeffries and others at Carboloy were surprised, if not shocked, that the federal judge presiding in the case handed down a decision that all of the patents that had been granted in the 1920s should not have been granted. This unbelievable ruling almost certainly was motivated by international politics—royalties were owed to Krupp, but the judge concluded that he could not sanction sending money to Hitler's evil government. And the way to stop the flow of money was to strike the patents down, although there was no legitimate legal basis for doing so.

Because the patents were about to expire anyway, and also because the company believed that the unanimous Supreme Court decision from the 1920s was ample protection, Carboloy elected not to challenge the federal judge's ruling. Unfortunately, this action was later interpreted as an admission that Carboloy had been using licensing and merchandising practices that violated the Sherman and Wilson Antitrust Acts. Thus a criminal indictment was brought against Jeffries and others at GE in connection with these antitrust charges.

When the war began, government officials, including the Secretary of War, wrote to the Attorney General essentially begging him not to prosecute because of the need for Jeffries' expertise in the war effort. Thus given the intervention of World War II, the case was not brought to trial until 1947. The defendants were found guilty on all charges more than a year later, in October of 1948. Amazingly, the decision of the court was based on a Supreme Court decision on price-fixing reached earlier in 1948, which completely reversed the decision of the same court 20 years before. The judge in the case was so troubled by the new legal requirement that he saw fit virtually to apologize to Jeffries and the others for having handed down his decision. In a long statement, the judge pointed to the great service that Jeffries had provided to the nation in developing cemented-carbide tools, which played such a key role in winning the war.

Meritorious service

While Jeffries was still in the midst of his productive career as a consultant and executive in the 1920s, he began to take on responsibilities as a leader of professional societies. He served as president in 1929 of the American Society for Steel Treating, later the American Society for Metals (ASM) and yet later ASM International. After he was elected to the National Academy of Sciences in 1939, he served as vice chair of the War Metallurgy Committee and chair of the Advisory Committee on Metals and Minerals. During the World War II years, Jeffries was a so-called “dollar-a-year man,” volunteering his services and leading the effort to determine the allocation of strategic materials. He reported to Vannevar Bush, then head of the Office of Scientific Research and Development, which later became an arm of the Department of Defense. When copper became scarce during the war, Jeffries proposed that pennies be made of steel, and hence the 1943 zinc-coated steel penny. For his work on the War Metallurgy Committee, Jeffries was later honored with the Medal of Merit, the highest award that can be bestowed upon a U.S. citizen. He received this award at the White House while his indictment was dormant but still in place. This circumstance speaks volumes about the government’s high regard for Jeffries’ contributions and its low regard for the antitrust charge.

Jeffries’ other great contributions to the war effort included his three years as chair of the Engineering Section of the National Academy of Sciences during the mid-1940s and his role as a consultant to Arthur H. Compton and the Metallurgical Project as a part of the Manhattan Project to build the atomic bomb. He became a great proponent of atomic energy and even coined the term “nucleonics” to describe nuclear science and technology. His national leadership was recognized in 1948 with his election to the American Philosophical Society.

Jeffries retired from GE in 1949 but continued to work as a consultant and to provide service to his profession. He served as director-general of the first World Metallurgical Congress sponsored by the ASM in the early 1950s and continued his close association with the ASM for the rest of his life. He died near his home in Pittsfield, MA, on May 21, 1965, after losing a battle with prostate cancer.

The mark that Jeffries made on the metallurgical profession and on society was documented in the biography written by W. D. Mogerman a few years after Jeffries’ death.[1] Fittingly, the biography was written at the request of the ASM and was supported financially by some of the very institutions to which Jeffries had devoted his career: the Alcoa Foundation, the Battelle Memorial Institute, the General Electric Company, and the ASM Foundation for Education and Research. To this day, the Cleveland chapter of ASM International annually sponsors an Honorary Zay Jeffries Lecture to commemorate his role as a founding member of that chapter.

NOTES

1. Mogerman, W. D. 1973. *Zay Jeffries*. Metals Park, OH: American Society for Metals.
2. Hoyt, S. L. 1979. *Men of Metals*. Metals Park, OH: American Society for Metals.
3. Jeffries, Z., and R. S. Archer. 1924. *The Science of Metals*. New York, NY: McGraw-Hill Book Co.

SELECTED BIBLIOGRAPHY

1916 Grain growth phenomena in metals. *Transactions of the American Institute of Mining Engineers* 54:571-581.

With A. H. Kline and E. B. Zimmer. The determination of grain size in metals. *Transactions of the American Institute of Mining Engineers* 54:594-607.

Tungsten-molybdenum equilibrium diagram and system of crystallization. *Transactions of the American Institute of Mining Engineers* 56:600-611.

1917 The effect of great hydrostatic pressure on the physical properties of metals. *Journal of the Institute of Metals* 18: 243-252.

Grain-size inheritance in iron and carbon steel. *Transactions of the American Institute of Mining Engineers* 58:669-695.

1918 Grain growth in metals. *Journal of the Institute of Metals (London)* 20:109-140.

1919 The micro-mechanism of the ageing of duralumin. *Journal of the Institute of Metals* 22:329-333.

Effect of temperature, deformation, and grain size on the mechanical properties of metals. *Transactions of the American Institute of Mining and Metallurgical Engineers* 60:474-562.

Metallography of tungsten. *Transactions of the American Institute of Mining and Metallurgical Engineers* 60:588-643.

1920 The measurement of grain size. *Transactions of the Faraday Society* 16:0200-0201.

1921 With W. A. Gibson. Heat treatment of aluminum-alloy castings. *Transactions of the American Institute of Mining and Metallurgical Engineers* 64:270-289.

1922 Physical changes in iron and steel below the thermal critical range. *Transactions of the American Institute of Mining and Metallurgical Engineers* 67:56-67.

1924 With R. S. Archer. *The Science of Metals*. New York, NY: McGraw-Hill Book Co.
The trend in the science of metals. *Transactions of the American Institute of Mining and Metallurgical Engineers* 70:303-327.

1925 With R. S. Archer. New developments in high-strength aluminum alloys. *Transactions of the American Institute of Mining and Metallurgical Engineers* 71:828-845.

1930 The future of the American iron and steel industry. *Transactions of the American Institute of Mining and Metallurgical Engineers* 90:9-22.

1931 The plasticity of metals. *Scientific Monthly* 33:235-243.

1937 Alloys for tools and wear resistance. *Journal of Applied Physics* 8:380-384.

With E. Q. Adams; Physics in the metal industry. *Journal of Applied Physics* 8:48-54.

1945 Metallurgy and the war. *Scientific Monthly* 60:67-70.

1947 The efficient utilization of metals. *Scientific Monthly* 65:325-328.