Metal Moulding

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Numerical control

Numerical control (**NC**) refers to the automation of machine tools that are operated by abstractly programmed commands encoded on a storage medium, as opposed to manually controlled via handwheels or levers, or mechanically automated via cams alone. The first NC machines were built in the 1940s and '50s, based on existing tools that were modified with motors that moved the controls to follow points fed into the system on punched tape. These early servomechanisms were rapidly augmented with analog and digital computers, creating the modern **computer numerical controlled** (**CNC**) machine tools that have revolutionized the manufacturing process.


A CNC Turning Center.

In modern CNC systems, end-to-end component design is highly automated using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs. The programs produce a computer file that is interpreted to extract the commands needed to operate a particular machine via a postprocessor, and then loaded into the CNC machines for production. Since any particular component might require the use of a number of different tools-drills, saws, etc.-modern machines often combine multiple tools into a single "cell". In other cases, a number of different machines are used with an external controller and human or robotic operators that move the component from machine to machine. In either case, the complex series of steps needed to produce any part is highly automated and produces a part that closely matches the original CAD design.


Siemens CNC panel.

History

Earlier forms of automation

Cams

The automation of machine tool control began in the 1800s with cams that "played" a machine tool in the way that cams had long been playing musical boxes or operating elaborate cuckoo clocks. Thomas Blanchard built his gun-stock-copying lathes (1820s-30s), and the work of people such as Christopher Miner Spencer developed the turret lathe into the screw machine (1870s). Cam-based automation had already reached a highly advanced state by World War I (1910s).

However, automation via cams is fundamentally different from numerical control because it cannot be abstractly programmed. Cams can encode information, but getting the information from the abstract level of an engineering drawing into the cam is a manual process that requires sculpting and/or machining and filing.

Various forms of abstractly programmable control had existed during the 1800s: those of the Jacquard loom, player pianos, and mechanical computers pioneered by Charles Babbage and others. These developments had the potential for convergence with the automation of machine tool control starting in that century, but the convergence did not happen until many decades later.

Tracer control

The application of hydraulics to cam-based automation resulted in tracing machines that used a stylus to trace a template, such as the enormous Pratt & Whitney "Keller Machine", which could copy templates several feet across.[1] Another approach was "record and playback", pioneered at General Motors (GM) in the 1950s, which used a storage system to record the movements of a human machinist, and then play them back on demand. Analogous systems are common even today, notably the "teaching lathe" which gives new machinists a hands-on feel for the process. None of these were numerically programmable, however, and required a master machinist at some point in the process, because the "programming" was physical rather than numerical.

Servos and selsyns

One barrier to complete automation was the required tolerances of the machining process, which are routinely on the order of thousandths of an inch. Although connecting some sort of control to a storage device like punched cards was easy, ensuring that the controls were moved to the correct position with the required accuracy was another issue. The movement of the tool resulted in varying forces on the controls that would mean a linear input would not result in linear tool motion. The key development in this area was the introduction of the servomechanism, which produced highly accurate measurement information. Attaching two servos together produced a selsyn, where a remote servo's motions were accurately matched by another. Using a variety of mechanical or electrical systems, the output of the selsyns could be read to ensure proper movement had occurred (in other words, forming a closed-loop control system).

The first serious suggestion that selsyns could be used for machining control was made by Ernst F. W. Alexanderson, a Swedish immigrant to the U.S. working at General Electric (GE). Alexanderson had worked on the problem of torque amplification that allowed the small output of a mechanical computer to drive very large motors, which GE used as part of a larger gun laying system for US Navy ships. Like machining, gun laying requires very high accuracies, much less than a degree, and the forces during the motion of the gun turrets was non-linear. In November 1931 Alexanderson suggested to the Industrial Engineering Department that the same systems could be used to drive the inputs of machine tools, allowing it to follow the outline of a template without the strong physical contact needed by existing tools like the Keller Machine. He stated that it was a "matter of straight engineering development".[2] However, the concept was ahead of its time from a business development perspective, and GE did not take the matter seriously until years later, when others had pioneered the field.

Parsons and the invention of NC

The birth of NC is generally credited to John T. Parsons,[3] a machinist and salesman at his father's machining company, Parsons Corp.

In 1942 he was told that helicopters were going to be the "next big thing" by the former head of Ford Trimotor production, Bill Stout. He called Sikorsky Aircraft to inquire about possible work, and soon got a contract to build the wooden stringers in the rotor blades. After setting up production at a disused furniture factory and ramping up production, one of the blades failed and it was traced to the spar. As at least some of the problem appeared to stem from spot welding a metal collar on the stringer to the metal spar, so Parsons suggested a new method of attaching the stringers to the spar using adhesives, never before tried on an aircraft design.[4]

But that development led Parsons to wonder about the possibility of using stamped metal stringers instead of wood, which would be much easier to make and stronger too. The stringers for the rotors were built to a design provided by Sikorsky, which was sent to them as a series of 17 points defining the outline. Parsons then had to "fill in" the dots with a french curve to generate an outline they could use as a template to build the jigs for the wooden versions. But how to make a tool able to cut metal with that shape was a much harder problem. Parsons went to visit Wright Field to see Frank Stulen, who was the head of the Rotary Ring Branch at the Propeller lab. During their conversation, Stulen concluded that Parsons didn't really know what he was talking about. Parsons realized this, and hired Stulen on the spot. Stulen started work on 1 April 1946 and hired three new engineers to join him.[4]

Stulen's brother worked at Curtis Wright Propeller, and mentioned that they were using punched card calculators for engineering calculations. Stulen decided to adopt the idea to run stress calculations on the rotors, the first detailed automated calculations on helicopter rotors.[4] When Parsons saw what Stulen was doing with the punched card machines, he asked him if they could be used to generate an outline with 200 points instead of the 17 they were given, and offset each point by the radius of the cutting tool on a mill. If you cut at each of those points, it would produce a relatively accurate cutout of the stringer even in hard steel, and it could easily be filed down to a smooth shape. The resulting tool would be useful as a template for stamping metal stringers. Stullen had no problem making such a program, and used it to produce large tables of numbers that would be taken onto the machine floor. Here, one operator read the numbers off the charts to two other operators, one on each of the X- and Y- axes, and they would move the cutting head to that point and make a cut.[4] This was called the "by-the-numbers method".

At that point Parsons conceived of a fully automated tool. With enough points on the outline, no manual working would be needed at all, but with manual operation the time saved by having the part more closely match the outline was offset by the time needed to move the controls. If the machine's inputs were attached directly to the card reader, this delay, and any associated manual errors, would be removed and the number of points could be dramatically increased. Such a machine could repeatedly punch out perfectly accurate templates on command. But at the time he had no funds to develop these ideas.

When one of Parsons's salesmen was on a visit to Wright Field, he was told of the problems the newly-formed US Air Force was having with new jet designs. He asked if Parsons had anything to help them. Parsons showed Lockheed their idea of an automated mill, but they were uninterested. They had already decided to use 5-axis template copiers to produce the stringers, cutting from a metal template, and had ordered the expensive cutting machine already. But as Parsons noted:

> Now just picture the situation for a minute. Lockheed had contracted to design a machine to make these wings. This machine had five axes of cutter movement, and each of these was tracer controlled using a template. Nobody was using my method of making templates, so just imagine what chance they were going to have of making an accurate airfoil shape with inaccurate templates.[4]

Parsons worries soon came true, and Lockheed's protests that they could fix the problem eventually rang hollow. In 1949 the Air Force arranged funding for Parsons to build his machines on his own.[4] Early work with Snyder Machine & Tool Corp proved that the system of directly driving the controls from motors failed to have the accuracy needed to set the machine for a perfectly smooth cut. Since the mechanical controls did not respond in a linear fashion, you couldn't simply drive it with a certain amount of power, because the differing forces would mean the same amount of power would not always produce the same amount of motion in the controls. No matter how many points you included, the outline would still be rough.

Enter MIT

This was not an impossible problem to solve, but would require some sort of feedback system, like a selsyn, to directly measure how far the controls had actually turned. Faced with the daunting task of building such a system, in the spring of 1949 Parsons turned to Gordon S. Brown's Servomechanisms Laboratory at MIT, which was a world leader in mechanical computing and feedback systems.[5] During the war the Lab had built a number of complex motor-driven devices like the motorized gun turret systems for the Boeing B-29 Superfortress and the automatic tracking system for the SCR-584 radar. They were naturally suited to technological transfer into a prototype of Parsons's automated "by-the-numbers" machine.

The MIT team was led by William Pease assisted by James McDonough. They quickly concluded that Parsons's design could be greatly improved; if the machine did not simply cut *at* points A and B, but instead moved smoothly *between* the points, then not only would it make a perfectly smooth cut, but could do so with many fewer points - the mill could cut lines directly instead of having to define a large number of cutting points to "simulate" it. A three-way agreement was arranged between Parsons, MIT, and the Air Force, and the project officially ran from July 1949 to June 1950.[6] The contract called for the construction of two "Card-a-matic Milling Machine"s, a prototype and a production system. Both to be handed to Parsons for attachment to one of their mills in order to develop a deliverable system for cutting stringers.

Instead, in 1950 MIT bought a surplus Cincinnati Milling Machine Company "Hydro-Tel" mill of their own and arranged a new contract directly with the Air Force that froze Parsons out of further development.[4] Parsons would later comment that he "never dreamed that anybody as reputable as MIT would deliberately go ahead and take over my project."[4] In spite of the development being handed to MIT, Parsons filed for a patent on "Motor Controlled Apparatus for Positioning Machine Tool" on 5 May 1952, sparking a filing by MIT for a "Numerical Control Servo-System" on 14 August 1952. Parsons received US Patent 2,820,187 [7] on 14 January 1958, and the company sold an exclusive license to Bendix. IBM, Fujitsu and General Electric all took sub-licenses after having already started development of their own devices.

MIT's machine

MIT fit gears to the various handwheel inputs and drove them with roller chains connected to motors, one for each of the machine's three axes (X, Y, and Z). The associated controller consisted of five refrigerator-sized cabinets that, together, were almost as large as the mill they were connected to. Three of the cabinets contained the motor controllers, one controller for each motor, the other two the digital reading system.[1]

Unlike Parsons's original punched card design, the MIT design used standard 7-track punch tape for input. Three of the tracks were used to control the different axes of the machine, while the other four encoded various control information.[1] The tape was read in a cabinet that also housed six relay-based hardware registers, two for each axis. With every read operation the previously read point was copied into the "starting point" register, and the newly read one into the "ending point".[1] The tape was read continually and the number in the register increased until a "stop" instruction was encountered, four holes in a line.

The final cabinet held a clock that sent pulses through the registers, compared them, and generated output pulses that interpolated between the points. For instance, if the points were far apart the output would have pulses with every clock cycle, whereas closely spaced points would only generate pulses after multiple clock cycles. The pulses are sent into a summing register in the motor controllers, counting up by the number of pulses every time they were received. The summing registers were connected to a digital to analog convertor that output increased power to the motors as the count in the registers increased.[1]

The registers were decremented by encoders attached to the motors and the mill itself, which would reduce the count by one for every one degree of rotation. Once the second point was reached the pulses from the clock would stop, and the motors would eventually drive the mill to the encoded position. Each 1 degree rotation of the controls produced a 0.0005 inch movement of the cutting head. The programmer could control the speed of the cut by selecting points that were closer together for slow movements, or further apart for rapid ones.[1]

The system was publicly demonstrated in September 1952, appearing in that month's *Scientific American*.[1] MIT's system was an outstanding success by any technical measure, quickly making any complex cut with extremely high accuracy that could not easily be duplicated by hand. However, the system was terribly complex, including 250 vacuum tubes, 175 relays and numerous moving parts, reducing its reliability in a production setting. It was also very expensive, the total bill presented to the Air Force was $360,000.14, $2,641,727.63 in 2005 dollars.[8] Between 1952 and 1956 the system was used to mill a number of one-off designs for various aviation firms, in order to study their potential economic impact.[9]

Proliferation of NC

The Air Force funding for the project ran out in 1953, but development was picked up by the Giddings and Lewis Machine Tool Co. In 1955 many of the MIT team left to form Concord Controls, a commercial NC company with Giddings' backing, producing the Numericord controller.[9] Numericord was similar to the MIT design, but replaced the punch tape with a magnetic tape reader that General Electric was working on. The tape contained a number of signals of different phases, which directly encoded the angle of the various controls. The tape was played at a constant speed in the controller, which set its half of the selsyn to the encoded angles while the remote side was attached to the machine controls. Designs were still encoded on paper tape, but the tapes were transferred to a reader/writer that converted them into magnetic form. The magtapes could then be used on any of the machines on the floor, where the controllers were greatly reduced in complexity. Developed to produce highly accurate dies for an aircraft skinning press, the Numericord "NC5" went into operation at G&L's plant at Fond du Lac, WI in 1955.[10]

Monarch Machine Tool also developed an NC-controlled lathe, starting in 1952. They demonstrated their machine at the 1955 Chicago Machine Tool Show, along with a number of other vendors with punched card or paper tape machines that were either fully developed or in prototype form. These included Kearney & Trecker's Milwaukee-Matic II that could change its cutting tool under NC control,[10] a common feature on modern machines.

A Boeing report noted that "numerical control has proved it can reduce costs, reduce lead times, improve quality, reduce tooling and increase productivity."[10] In spite of these developments, and glowing reviews from the few users, uptake of NC was relatively slow. As Parsons later noted:

> The NC concept was so strange to manufacturers, and so slow to catch on, that the US Army itself finally had to build 120 NC machines and lease them to various manufacturers to begin popularizing its use.[4]

In 1958 MIT published its report on the economics of NC. They concluded that the tools were competitive with human operators, but simply moved the time from the machining to the creation of the tapes. In *Forces of Production*, Noble[11] claims that this was the whole point as far as the Air Force was concerned; moving the process off of the highly unionized factory floor and into the un-unionized white collar design office. The cultural context of the early 1950s, a second Red Scare with a widespread fear of a bomber gap and of domestic subversion, sheds light on this interpretation. It was strongly feared that the West would lose the defense production race to the Communists, and that syndicalist power was a path toward losing, either by "getting too soft" (less output, greater unit expense) or even by Communist sympathy and subversion within unions (arising from their common theme of empowering the working class).

CNC arrives

Many of the commands for the experimental parts were programmed "by hand" to produce the punch tapes that were used as input. During the development of Whirlwind, MIT's real-time computer, John Runyon coded a number of subroutines to produce these tapes under computer control. Users could enter a list of points and speeds, and the program would generate the punch tape. In one instance, this process reduced the time required to produce the instruction list and mill the part from 8 hours to 15 minutes. This led to a proposal to the Air Force to produce a generalized "programming" language for numerical control, which was accepted in June 1956.[9]

Starting in September Ross and Pople outlined a language for machine control that was based on points and lines, developing this over several years into the APT programming language. In 1957 the Aircraft Industries Association (AIA) and Air Material Command at the Wright-Patterson Air Force Base joined with MIT to standardize this work and produce a fully computer-controlled NC system. On 25 February 1959 the combined team held a press conference showing the results, including a 3D machined aluminum ash tray that was handed out in the press kit.[9]

Meanwhile, Patrick Hanratty was making similar developments at GE as part of their partnership with G&L on the Numericord. His language, PRONTO, beat APT into commercial use when it was released in 1958.[12] Hanratty then went on to develop MICR magnetic ink characters that were used in cheque processing, before moving to General Motors to work on the groundbreaking DAC-1 CAD system.

APT was soon extended to include "real" curves in 2D-APT-II. With its release, MIT reduced its focus on CNC as it moved into CAD experiments. APT development was picked up with the AIA in San Diego, and in 1962, to Illinois Institute of Technology Research. Work on making APT an international standard started in 1963 under USASI X3.4.7, but many manufacturers of CNC machines had their own one-off additions (like PRONTO), so standardization was not completed until 1968, when there were 25 optional add-ins to the basic system.[9]

Just as APT was being released in the early 1960s, a second generation of lower-cost transistorized computers was hitting the market that were able to process much larger volumes of information in production settings. This so lowered the cost of implementing a NC system that by the mid 1960s, APT runs accounted for a third of all computer time at large aviation firms.

CAD meets CNC

While the Servomechanisms Lab was in the process of developing their first mill, in 1953 MIT's Mechanical Engineering Department dropped the requirement that undergraduates take courses in drawing. The instructors formerly teaching these programs were merged into the Design Division, where an informal discussion of computerized design started. Meanwhile the Electronic Systems Laboratory, the newly rechristened Servomechanisms Laboratory, had been discussing whether or not design would ever start with paper diagrams in the future.[13]

In January 1959, an informal meeting was held involving individuals from both the Electronic Systems Laboratory and the Mechanical Engineering Department's Design Division. Formal meetings followed in April and May, which resulted in the "Computer-Aided Design Project". In December 1959, the Air Force issued a one year contract to ESL for $223,000 to fund the Project, including $20,800 earmarked for 104 hours of computer time at $200 per hour.[14] This proved to be far too little for the ambitious program they had in mind, although their engineering calculation system, AED, was released in March 1965.

In 1959 General Motors started an experimental project to digitize, store and print the many design sketches being generated in the various GM design departments. When the basic concept demonstrated that it could work, they started the DAC-1 project with IBM to develop a production version. One part of the DAC project was the direct conversion of paper diagrams into 3D models, which were then converted into APT commands and cut on milling machines. In November 1963 a trunk lid design moved from 2D paper sketch to 3D clay prototype for the first time.[15] With the exception of the initial sketch, the design-to-production loop had been closed.

Meanwhile MIT's offsite Lincoln Labs was building computers to test new transistorized designs. The ultimate goal was essentially a transistorized Whirlwind known as TX-2, but in order to test various circuit designs a smaller version known as TX-0 was built first. When construction of TX-2 started, time in TX-0 freed up and this led to a number of experiments involving interactive input and use of the machine's CRT display for graphics. Further development of these concepts led to Ivan Sutherland's groundbreaking Sketchpad program on the TX-2.

Sutherland moved to the University of Utah after his Sketchpad work, but it inspired other MIT graduates to attempt the first true CAD system. It was Electronic Drafting Machine (EDM), sold to Control Data and known as "Digigraphics", that Lockheed used to build production parts for the C-5 Galaxy, the first example of an end-to-end CAD/CNC production system.

By 1970 there were a wide variety of CAD firms including Intergraph, Applicon, Computervision, Auto-trol Technology, UGS Corp. and others, as well as large vendors like CDC and IBM.

Proliferation of CNC

The price of computer cycles fell drastically during the 1960s with the widespread introduction of useful minicomputers. Eventually it became less expensive to handle the motor control and feedback with a computer program than it was with dedicated servo systems. Small computers were dedicated to a single mill, placing the entire process in a small box. PDP-8's and Data General Nova computers were common in these roles. The introduction of the microprocessor in the 1970s further reduced the cost of implementation, and today almost all CNC machines use some form of microprocessor to handle all operations.

The introduction of lower-cost CNC machines radically changed the manufacturing industry. Curves are as easy to cut as straight lines, complex 3-D structures are relatively easy to produce, and the number of machining steps that required human action have been dramatically reduced. With the increased automation of manufacturing processes with CNC machining, considerable improvements in consistency and quality have been achieved with no strain on the operator. CNC automation reduced the frequency of errors and provided CNC operators with time to perform additional tasks. CNC automation also allows for more flexibility in the way parts are held in the manufacturing process and the time required to change the machine to produce different components.

During the early 1970s the Western economies were mired in slow economic growth and rising employment costs, and NC machines started to become more attractive. The major U.S. vendors were slow to respond to the demand for machines suitable for lower-cost NC systems, and into this void stepped the Germans. In 1979, sales of German machines surpassed the U.S. designs for the first time. This cycle quickly repeated itself, and by 1980 Japan had taken a leadership position, U.S. sales dropping all the time. Once sitting in the #1 position in terms of sales on a top-ten chart consisting entirely of U.S. companies in 1971, by 1987 Cincinnati Milacron was in 8th place on a chart heavily dominated by Japanese firms.[16]

Many researchers have commented that the U.S. focus on high-end applications left them in an uncompetitive situation when the economic downturn in the early 1970s led to greatly increased demand for low-cost NC systems. Unlike the U.S. companies, who had focused on the highly profitable aerospace market, German and Japanese manufacturers targeted lower-profit segments from the start and were able to enter the low-cost markets much more easily.[16] [17]

As computing and networking evolved, so did direct numerical control (DNC). Its long-term coexistence with less networked variants of NC and CNC is explained by the fact that individual firms tend to stick with whatever is profitable, and their time and money for trying out alternatives is limited. This explains why machine tool models and tape storage media persist in grandfathered fashion even as the state of the art advances.

DIY, Hobby, and Personal CNC

Recent developments in small scale CNC have been enabled, in large part, by the Enhanced Machine Controller project from the National Institute of Standards and Technology (NIST), an agency of the Commerce Department of the United States government. EMC is a public domain program operating under the Linux operating system and working on PC based hardware. After the NIST project ended, development continued, leading to EMC2 [18] which is licensed under the GNU General Public License and Lesser GNU General Public License (GPL and LGPL). Derivations of the original EMC software have also led to several proprietary PC based programs notably TurboCNC, and Mach3, as well as embedded systems based on proprietary hardware. The availability of these PC based control programs has led to the development of DIY CNC, allowing hobbyists to build their own [19] [20] using open source hardware designs. The same basic architecture has allowed manufacturers, such as Sherline and Taig, to produce turnkey lightweight desktop milling machines for hobbyists.

Eventually the homebrew architecture was fully commercialized and used to create larger machinery suitable for commercial and industrial applications. This class of equipment has been referred to as Personal CNC. Parallel to the evolution of personal computers, Personal CNC has its roots in EMC and PC based control, but has evolved to the point where it can replace larger conventional equipment in many instances. As with the Personal Computer, Personal CNC is characterized by equipment whose size, capabilities, and original sales price make it useful for individuals, and which is intended to be operated directly by an end user, often without professional training in CNC technology.

Today

Although modern data storage techniques have moved on from punch tape in almost every other role, tapes are still relatively common in CNC systems. This is because it was often easier to add a punch tape reader to a microprocessor controller than it was to re-write large libraries of tapes into a new format. One change that was implemented fairly widely was the switch from paper to mylar tapes, which are much more mechanically robust. Floppy disks, USB flash drives and local area networking have replaced the tapes to some degree, especially in larger environments that are highly integrated.

The proliferation of CNC led to the need for new CNC standards that were not encumbered by licensing or particular design concepts, like APT. A number of different "standards" proliferated for a time, often based around vector graphics markup languages supported by plotters. One such standard has since become very common, the "G-code" that was originally used on Gerber Scientific plotters and then adapted for CNC use. The file format became so widely used that it has been embodied in an EIA standard. In turn, while G-code is the predominant language used by CNC machines today, there is a push to supplant it with STEP-NC, a system that was deliberately designed for CNC, rather than grown from an existing plotter standard.

While G-code is the most common method of programming, some machine-tool/control manufacturers also have invented their own proprietary "conversational" methods of programming, trying to make it easier to program simple parts and make set-up and modifications at the machine easier (such as Mazak's Mazatrol and Hurco). These have met with varying success.

A more recent advancement in CNC interpreters is support of logical commands, known as parametric programming (also known as macro programming). Parametric programs include both device commands as well as a control language similar to BASIC. The programmer can make if/then/else statements, loops, subprogram calls, perform various arithmetic, and manipulate variables to create a large degree of freedom within one program. An entire product line of different sizes can be programmed using logic and simple math to create and scale an entire range of parts, or create a stock part that can be scaled to any size a customer demands.

Description

Modern CNC mills differ little in concept from the original model built at MIT in 1952. Mills typically consist of a table that moves in the X and Y axes, and a tool spindle that moves in the Z (depth). The position of the tool is driven by motors through a series of step-down gears in order to provide highly accurate movements, or in modern designs, direct-drive stepper motors. Closed-loop control is not mandatory today, as open-loop control works as long as the forces are kept small enough.

As the controller hardware evolved, the mills themselves also evolved. One change has been to enclose the entire mechanism in a large box as a safety measure, often with additional safety interlocks to ensure the operator is far enough from the working piece for safe operation. Most new CNC systems built today are completely electronically controlled.

CNC-like systems are now used for any process that can be described as a series of movements and operations. These include laser cutting, welding, friction stir welding, ultrasonic welding, flame and plasma cutting, bending, spinning, pinning, gluing, fabric cutting, sewing, tape and fiber placement, routing, picking and placing (PnP), and sawing.

Tools with CNC variants

- Drills
- EDMs
- Lathes
- Milling machines
- Wood routers
- Sheet metal works (Turret Punch)
- Wire bending machines
- Hot-wire foam cutters
- Plasma cuttings
- Water jet cutters
- Laser cutting
- Oxy-fuel
- Surface grinders
- Cylindrical grinders
- 3D Printing
- Induction hardening machines

See also

- Computer-aided technologies
  - Computer-aided engineering (CAE)
- Coordinate-measuring machine (CMM)
- Direct Numerical Control (DNC)
- Design for Manufacturability for CNC machining
- Multiaxis machining

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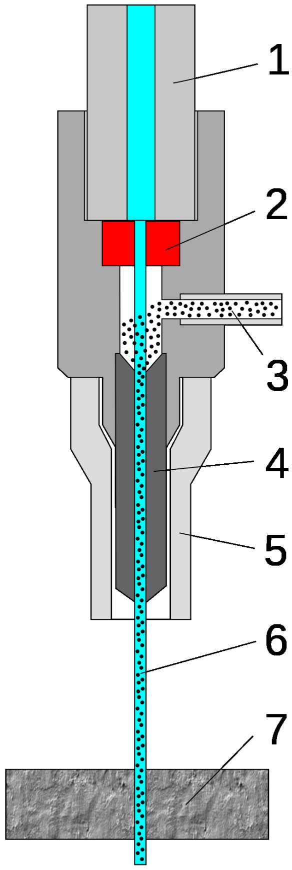
Water jet cutter

A **water jet cutter**, also known as a **waterjet**,[1] is a tool capable of slicing into metal or other materials using a jet of water at high velocity and pressure, or a mixture of water and an abrasive substance. The process is essentially the same as water erosion found in nature but greatly accelerated and concentrated. It is often used during fabrication or manufacture of parts for machinery and other devices. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. It has found applications in a diverse number of industries from mining to aerospace where it is used for operations such as cutting, shaping, carving, and reaming.



A diagram of a water jet cutter:
1 - high-pressure water inlet
2 - jewel (ruby or diamond)
3 - abrasive (garnet)
4 - mixing tube
5 - guard
6 - cutting water jet
7 - cut material

History

In the 1950s, forestry engineer Norman Franz experimented with an early form of water jet cutter to cut lumber. However, the technology did not advance notably until the 1970s when Mohamed Hashish created a technique to add abrasives to the water jet cutter. This and other concepts allowed Yih-Ho Michael Pao to develop commercial "ultrahigh-pressure waterjets and abrasive-waterjets into better tools for industrial cutting, drilling, and milling, especially for the flexible factory automation."[2] Today the water jet is unparalleled in many aspects of cutting and has changed the way many products are manufactured. Many types of water jets exist today, including plain water jets, abrasive water jets, percussive water jets, cavitation jets and hybrid jets.

Operation

The cutter is commonly connected to a high-pressure water pump where the water is then ejected from the nozzle, cutting through the material by spraying it with the jet of high-speed water. Additives in the form of suspended grit or other abrasives, such as garnet and aluminum oxide, can assist in this process.

Benefits

An important benefit of the water jet cutter is the ability to cut material without interfering with the material's inherent structure as there is no "heat-affected zone" or HAZ. Minimizing the effects of heat allows metals to be cut without harming or changing intrinsic properties.[3]

Water jet cutters are also capable of producing rather intricate cuts in material. With specialized software and 3-D machining heads, complex 3-D shapes can be produced.[4]

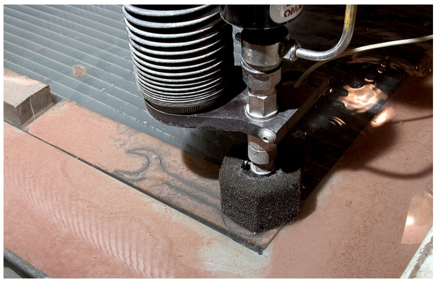
The kerf, or width, of the cut can be changed by changing parts in the nozzle, as well as the type and size of abrasive. Typical abrasive cuts are made with a kerf in the range of 0.04" to 0.05" (1.016 to 1.27 mm), but can be as narrow as 0.02" (0.508 mm). Non-abrasive cuts are normally 0.007" to 0.013" (0.178 to 0.33 mm), but can be as small as 0.003" (0.076 mm), which is approximately the width of a human hair. These small jets can make very small detail possible in a wide range of applications.

Waterjets are capable of attaining accuracy of 0.005" (0.13 mm), and repeatability of 0.001" (0.03 mm).[4]

Water jet is considered a "green" technology. Water jets produce no hazardous waste, reducing waste disposal costs. They can cut off large pieces of reusable scrap material that might have been lost using traditional cutting methods. Parts can be closely nested to maximize material use, and the water jet saves material by creating very little kerf. Water jets use very little water (a half gallon to approximately one gallon per minute depending on cutting head orifice size), and the water that is used can be recycled using a closed-looped system. Waste water usually is clean enough to filter and dispose of down a drain. The garnet abrasive is a non-toxic natural substance that can be recycled for repeated use. Garnet usually can be disposed of in a landfill. Water jets also eliminate airborne dust particles, smoke, fumes, and contaminants[4] from cutting materials such as asbestos and fiberglass. This greatly improves the work environment and reduces problems arising from operator exposure.[5]

Versatility

Because the nature of the cutting stream can be easily modified the water jet can be used in nearly every industry; there are many different materials that the water jet can cut. Some of them have unique characteristics that require special attention when cutting.[6]



A water jet cutter creating a specialist tool

Materials commonly cut with a water jet include rubber, foam, plastics, composites, stone, tile, metals, food, paper and much more. Materials that cannot be cut with a water jet are tempered glass, diamonds and certain ceramics.[5]

Water jet cuts are not typically limited by the thickness of the material, and are capable of cutting materials over eighteen inches (45 cm) thick. The penetrating power of these tools has led to the exploration of their use as anti-tank weapons but, due to their short range and the advent of composite armour, research was discontinued.

Availability

Commercial water jet cutting systems are available from manufacturers all over the world, in a range of sizes, and with water pumps capable of a range of pressures. Typical water jet cutting machines have a working envelope as small as a few square feet, or up to hundreds of square feet. Ultra-high pressure water pumps are available from as low as 40,000 psi (276 MPa) up to 100,000 psi (689 MPa).[4] [7]

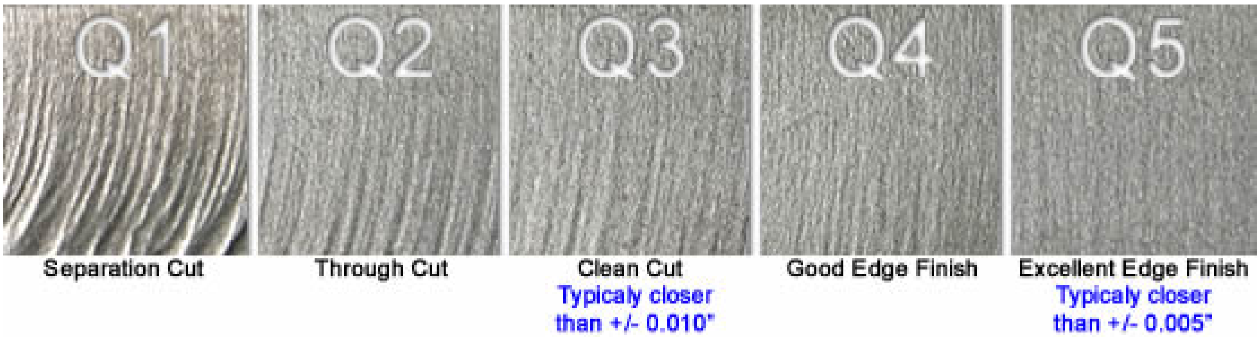
Process

There are six main process characteristics to water jet cutting:

1. Uses a high velocity stream of abrasive particles suspended in a stream of Ultra High Pressure Water (30,000 - 90,000 psi) which is produced by a water jet intensifier pump.[8]
2. Is used for machining a large array of materials, including heat-sensitive, delicate or very hard materials.
3. Produces no heat damage to workpiece surface or edges.
4. Nozzles are typically made of sintered boride.
5. Produces a taper of less than 1 degree on most cuts, which can be reduced or eliminated entirely by slowing down the cut process.
6. Distance of nozzle from workpiece affects the size of the kerf and the removal rate of material. Typical distance is .125".

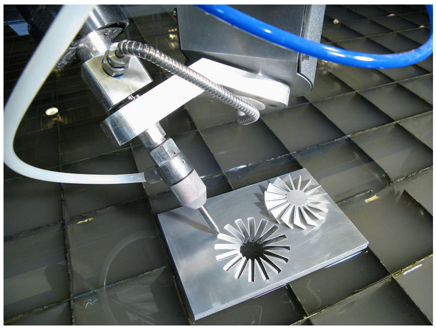
Temperature is not as much of a factor.

Edge quality

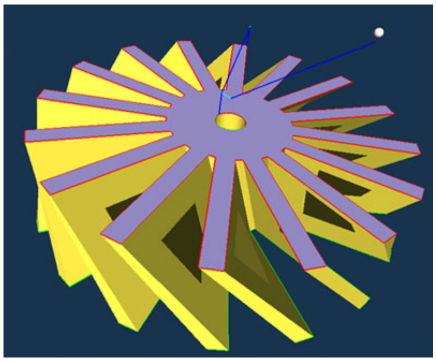


Edge quality for water jet cut parts is defined with the numbers 1 through 5. Lower numbers indicate rougher edge finish; higher numbers are smoother. For thin materials, the difference in cutting speed for Quality 1 could be as much as 3 times faster than the speed for Quality 5. For thicker materials, Quality 1 could be 6 times faster than Quality 5. For example, 4" thick Aluminum Q5 would be 0.72 ipm (18 mm/min) and Q1 would be 4.2 ipm (107 mm/min), 5.8 times faster.[9]

Multi-axis cutting



A 5-Axis Waterjet Cutting Head



A 5-Axis Waterjet Part

With recent advances in control and motion technology, 5-axis water jet cutting (abrasive and pure) has become a reality. Where the normal axes on a water jet are named X (back/forth), Y(left/right) and Z (up/down), a 5-axis system will typically add an A axis (angle from perpendicular) and C axes (rotation around the Z-axis). Depending on the cutting head, the maximum cutting angle for the A axis can be anywhere from 55, 60, or in some cases even 90 degrees from vertical. As such, 5-axis cutting opens up a wide range of applications that can be machined on a water jet cutting machine.[10]

A 5-axis cutting head can be used to cut 4-axis parts, where the bottom surface geometries are shifted a certain amount to produce the appropriate angle and the Z-axis remains at one height. This can be useful for applications like weld preparation where a bevel angle needs to be cut on all sides of a part that will later be welded, or for taper compensation purposes where the kerf angle is transferred to the waste material - thus eliminating the taper commonly found on water jet-cut parts. A 5-axis head can cut parts where the Z-axis is also moving along with all the other axis. This full 5-axis cutting could be used for cutting contours on various surfaces of formed parts.[10]

Because of the angles that can be cut, part programs may need to have additional cuts to free the part from the sheet. Attempting to slide a complex part at a severe angle from a plate can be difficult without appropriate relief cuts.[10]

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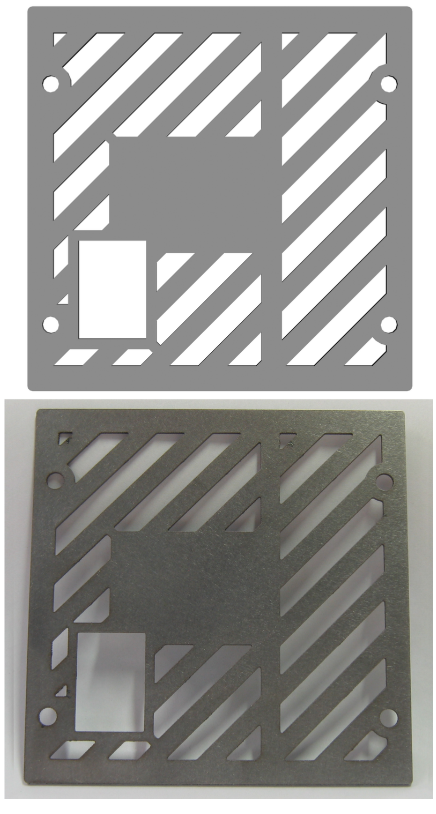
External links

- Waterjets.org (http://www.waterjets.org)
- How Water Jets Work (http://science.howstuffworks.com/question553.htm), HowStuffWorks.com video

Laser cutting

Laser cutting is a technology that uses a laser to cut materials, and is typically used for industrial manufacturing applications, but is also starting to appear in schools. Laser cutting works by directing the output of a high-power laser, by computer, at the material to be cut. The material then either melts, burns, vaporizes away, or is blown away by a jet of gas,[1] leaving an edge with a high-quality surface finish. Industrial laser cutters are used to cut flat-sheet material as well as structural and piping materials.



CAD (top) and stainless steel laser-cut part (bottom)

Types


A diffusion cooled resonator

There are three main types of lasers used in laser cutting. The CO_2 laser is suited for cutting, boring, and engraving. The neodymium (Nd) and neodymium yttrium-aluminum-garnet (Nd-YAG) lasers are identical in style and differ only in application. Nd is used for boring and where high energy but low repetition are required. The Nd-YAG laser is used where very high power is needed and for boring and engraving. Both CO_2 and Nd/ Nd-YAG lasers can be used for welding.[2]

Common variants of CO_2 lasers include fast axial flow, slow axial flow, transverse flow, and slab.

CO_2 lasers are commonly "pumped" by passing a current through the gas mix (DC-excited) or using radio frequency energy (RF-excited). The RF method is newer and has become more popular. Since DC designs require electrodes inside the cavity, they can encounter electrode erosion and plating of electrode material on glassware and optics. Since RF resonators have external electrodes they are not prone to those problems.

CO_2 lasers are used for industrial cutting of many materials including mild steel, aluminum, stainless steel, titanium, paper, wax, plastics, wood, and fabrics. YAG lasers are primarily used for cutting and scribing metals and ceramics.

In addition to the power source, the type of gas flow can affect performance as well. In a fast axial flow resonator, the mixture of carbon dioxide, helium and nitrogen is circulated at high velocity by a turbine or blower. Transverse flow lasers circulate the gas mix at a lower velocity, requiring a simpler blower. Slab or diffusion cooled resonators have a static gas field that requires no pressurization or glassware, leading to savings on replacement turbines and glassware.

The laser generator and external optics (including the focus lens) require cooling. Depending on system size and configuration, waste heat may be transferred by a coolant or directly to air. Water is a commonly used coolant, usually circulated through a chiller or heat transfer system.

Lasing Materials	Applications
CO_2	Boring Cutting/Scribing Engraving
Nd	High-energy pulses Low repetition speed (1 kHz) Boring
Nd-YAG	Very high energy pulses Boring Engraving Trimming

Laser microjet

A **laser microjet** is a water-jet guided laser in which a pulsed laser beam is coupled into a low-pressure water jet. This is used to perform laser cutting functions while using the water jet to guide the laser beam, much like an optical fiber, through total internal reflection. The advantages of this are that the water also removes debris and cools the material. Additional advantages over traditional "dry" laser cutting are high dicing speeds, parallel kerf and omnidirectional cutting.[3]

Process

Generation of the laser beam involves stimulating a lasing material by electrical discharges or lamps within a closed container. As the lasing material is stimulated, the beam is reflected internally by means of a partial mirror, until it achieves sufficient energy to escape as a stream of monochromatic coherent light. Mirrors or fiber optics are typically used to direct the coherent light to a lens, which focuses the light at the work zone. The narrowest part of the focused beam is generally less than 0.0125 in (0.3175 mm). in diameter. Depending upon material thickness, kerf widths as small as 0.004 in (0.1016 mm) are possible.[4] In order to be able to start cutting from somewhere else than the edge, a pierce is done before every cut. Piercing usually involves a high-power pulsed laser beam which slowly (taking around 5–15 seconds for $\frac{1}{2}$-inch-thick (13 mm) stainless steel, for example) makes a hole in the material.

There are many different methods in cutting using lasers, with different types used to cut different material. Some of the methods are vaporization, melt and blow, melt blow and burn, thermal stress cracking, scribing, cold cutting and burning stabilized laser cutting.

Beam geometry

The parallel rays of coherent light from the laser source may be 1/16 inch to 1/2 inch (1.5875 mm to 12.7 mm) in diameter. This beam is normally focused and intensified by a lens or a mirror to a very small spot of about 0.001 inch (0.0254 mm) to create a very intense laser beam. Recent investigations reveal that the laser beam has a distinctive polarization. In order to achieve the smoothest possible finish during contour cutting, the direction of polarization must be rotated as it goes around the periphery of a contoured workpiece. For sheet metal cutting, the focal length is usually between 1.5 inches and 3 inches (38.1 mm and 76.2 mm)[5]

Industrial Laser Cutting of Steel with Cutting Instructions Programmed Through the CNC Interface

Vaporization cutting

In vaporization cutting the focused beam heats the surface of the material to boiling point and generates a keyhole. The keyhole leads to a sudden increase in absorptivity quickly deepening the hole. As the hole deepens and the material boils, vapor generated erodes the molten walls blowing eject out and further enlarging the hole. Non melting material such as wood, carbon and thermoset plastics are usually cut by this method.

Melt and blow

Melt and blow or fusion cutting uses high-pressure gas to blow molten material from the cutting area, greatly decreasing the power requirement. First the material is heated to melting point then a gas jet blows the molten material out of the kerf avoiding the need to raise the temperature of the material any further. Materials cut with this process are usually metals.

Thermal stress cracking

Brittle materials are particularly sensitive to thermal fracture, a feature exploited in thermal stress cracking. A beam is focused on the surface causing localized heating and thermal expansion. This results in a crack that can then be guided by moving the beam. The crack can be moved in order of m/s. It is usually used in cutting of glass.

Reactive cutting

Also called "burning stabilized laser gas cutting", "flame cutting".

Reactive cutting is like oxygen torch cutting but with a laser beam as the ignition source. Mostly used for cutting carbon steel in thicknesses over 1 mm. This process can be used to cut very thick steel plates with relatively little laser power.

Tolerances and surface finish

New laser cutters have positioning accuracy of 10 micrometers and repeatability of 5 micrometers.

Standard roughness Rz increases with the sheet thickness, but decreases with laser power and cutting speed. When cutting low carbon steel with laser power of 800 W, standard roughness Rz is 10 μm for sheet thickness of 1 mm, 20 μm for 3 mm, and 25 μm for 6 mm. Rz = 12.528*(S^0.542)/((P^0.528)*(V^0.322)) where: S = steel sheet thickness in mm; P = laser power in kW (Some new laser cutters have laser power of 4 kW.); V = cutting speed in meters per minute[6]

This process is capable of holding quite close tolerances, often to within 0.001 inch (0.025 mm) Part geometry and the mechanical soundness of the machine have much to do with tolerance capabilities. The typical surface finish resulting from laser beam cutting may range from 125 to 250 micro-inches (0.003 mm to 0.006 mm).[2]

Machine configurations

There are generally three different configurations of industrial laser cutting machines: Moving material, Hybrid, and Flying Optics systems. These refer to the way that the laser beam is moved over the material to be cut or processed. For all of these, the axes of motion are typically designated X and Y axis. If the cutting head may be controlled, it is designated as the Z-axis.

Dual Pallet Flying Optics Laser

Moving material lasers have a stationary cutting head and move the material under it. This method provides a constant distance from the laser generator to the workpiece and a single point from which to remove cutting effluent. It requires fewer optics, but requires moving the workpiece. This style machine tends to have the fewest beam delivery optics, but also tends to be the slowest.

Flying Optics Laserhead

Hybrid lasers provide a table which moves in one axis (usually the X-axis) and move the head along the shorter (Y) axis. This results in a more constant beam delivery path length than a flying optic machine and may permit a simpler beam delivery system. This can result in reduced power loss in the delivery system and more capacity per watt than flying optics machines.

Flying optics lasers feature a stationary table and a cutting head (with laser beam) that moves over the workpiece in both of the horizontal dimensions. Flying optics cutters keep the workpiece stationary during processing and often do not require material clamping. The moving mass is constant, so dynamics are not affected by varying size of the workpiece. Flying optics machines are the fastest type, which is advantageous when cutting thinner workpieces.[7]

Flying optic machines must use some method to take into account the changing beam length from near field (close to resonator) cutting to far field (far away from resonator) cutting. Common methods for controlling this include collimation, adaptive optics or the use of a constant beam length axis.

The above is written about X-Y systems for cutting flat materials. The same discussion applies to five and six-axis machines, which permit cutting formed workpieces. In addition, there are various methods of orienting the laser beam to a shaped workpiece, maintaining a proper focus distance and nozzle standoff, etc.

Pulsing

Pulsed lasers which provide a high-power burst of energy for a short period are very effective in some laser cutting processes, particularly for piercing, or when very small holes or very low cutting speeds are required, since if a constant laser beam were used, the heat could reach the point of melting the whole piece being cut.

Most industrial lasers have the ability to pulse or cut CW (Continuous Wave) under NC (numerical control) program control.

Double pulse lasers use a series of pulse pairs to improve material removal rate and hole quality. Essentially, the first pulse removes material from the surface and the second prevents the ejecta from adhering to the side of the hole or cut.[8]

Advantages and disadvantages

Advantages of laser cutting over mechanical cutting include easier workholding and reduced contamination of workpiece (since there is no cutting edge which can become contaminated by the material or contaminate the material). Precision may be better, since the laser beam does not wear during the process. There is also a reduced chance of warping the material that is being cut, as laser systems have a small heat-affected zone. Some materials are also very difficult or impossible to cut by more traditional means.

Laser cutting for metals has the advantages over plasma cutting of being more precise and using less energy when cutting sheet metal, however, most industrial lasers cannot cut through the greater metal thickness that plasma can. Newer lasers machines operating at higher power (6000 watts, as contrasted with early laser cutting machines' 1500 watt ratings) are approaching plasma machines in their ability to cut through thick materials, but the capital cost of such machines is much higher than that of plasma cutting machines capable of cutting thick materials like steel plate.

The main disadvantage of laser cutting is the high power consumption. Industrial laser efficiency may range from 5% to 15%. The power consumption and efficiency of any particular laser will vary depending on output power and operating parameters. This will depend on type of laser and how well the laser is matched to the work at hand. The amount of laser cutting power required, known as *heat input*, for a particular job depends on the material type, thickness, process (reactive/inert) used, and desired cutting rate.

Amount of heat input required for various material at various thicknesses using a CO_2 laser (watts)[9]

Material	Material thickness (in)				
	0.02	**0.04**	**0.08**	**0.125**	**0.25**
Stainless steel	1000	1000	1000	500	250
Aluminum	1000	1000	1000	3800	10000
Mild steel	-	400	-	500	-
Titanium	250	210	210	-	-
Plywood	-	-	-	-	650
Boron/epoxy	-	-	-	3000	-

Production and cutting rates

The production rate is limited by a number of factors. Maximum cutting rate is limited by a number of factors, including laser power, material thickness, process type (reactive or inert,) and material properties.

Common industrial systems (1 kW+) will cut carbon steel metal from 0.020 inch to 0.5 inch (0.508 mm and 12.7 mm) in thickness. For all intents and purposes, a laser can be up to thirty times faster than standard sawing.

Cutting rates for various materials and thicknesses using a CO_2 laser [ipm]

Workpiece material	Material thickness						
	0.02	0.04	0.08	0.125	0.25	0.5	in.
	0.508	1.016	2.032	3.175	6.35	12.7	mm
Stainless steel	1000	550	325	185	80	18	
Aluminum	800	350	150	100	40	30	
Mild steel	-	210	185	150	100	50	
Titanium	300	300	100	80	60	40	
Plywood	-	-	-	-	180	45	
Boron/epoxy	-	-	-	60	60	25	

History

In 1965, the first production laser cutting machine was used to drill holes in diamond dies. This machine was made by the Western Electric Engineering Research Center.[10] In 1967, the British pioneered laser-assisted oxygen jet cutting for metals. In the early 1970s, this technology was put into production to cut titanium for aerospace applications. At the same time CO_2 lasers were adapted to cut non-metals, such as textiles, because they were absorbed by metals.[11]

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External links

- Laser cutting steel parts (http://www.saunalahti.fi/~animato/3003/3003by.html) for a miniature Live steam locomotive
- Laser Glass Cutting (http://www.gsiglasers.com/LaserProcesses.aspx?page=78) Good Further Information Resource with White Paper
- Laser Cutting and Laser Drilling (http://www.trumpf-laser.com/en/solutions/applications/laser-cutting.html) TRUMPF's page with good information.
- Laser Cutting Articles (http://www.thefabricator.com/LaserCutting/LaserCutting_ArticleList.cfm) The Fabricator's list of laser cutting articles.
- Laser Microjet, a large amount of documentation from the industry (http://www.synova.ch/english/laser-cutting-machine/solutions_result.php?id=34)

Punching

Titanium nitride (TiN) coated industrial punches using Cathodic arc deposition technique

Punching in metalworking is the process of using a punch press to push a punch through the material and into a die to create a hole in the workpiece. A scrap slug from the hole is deposited into the die in the process. Depending on the material being punched this slug may be recycled and reused or discarded. The hole walls will show burnished area, rollover, and die break and must often be further processed. Punching is often the cheapest method for creating holes in sheet metal in medium to high production.

Process

A punch is often made of hardened steel or carbides. The punch press forces the punch into a workpiece piercing a hole that has a diameter equivalent to the punch. A die is located on the opposite side of the workpiece and supports the edge of the hole created to keep it from deforming during the punch. There is a small amount of clearance between the punch's diameter and the die's. This clearance depends on the workpiece material and various tolerances. The slug from the hole falls through the die into some sort of container to either dispose of the slug or recycle it.

Punching Characteristics

- Punching is the most cost effective process of making holes in strip or sheet metal for average to high fabrication
- It is able to create multiple shaped holes
- Punches and dies are usually fabricated from conventional tool steel or carbides
- Creates a burnished region roll-over, and die break on sidewall of the resulting hole[1]

Geometry

The workpiece is often in the form of a sheet or roll. Materials for the workpiece can vary, commonly being metals and plastics. The punch and die themselves can have a variety of shapes to create an array of different shaped holes in the workpiece. Multiple punches may be used together to create a part in one step.

Equipment

Most punch presses are mechanically operated, but simple punches are often hand-powered. Major components of this mechanical press are the frame, motor, ram, die posts, bolster, and bed. The punch is mounted into the ram, and the die is mounted to the bolster plate. The scrap material drops through as the workpiece is advanced for the next hole. A large computer controlled punch press is called a computer numerical controlled turret. It houses punches and their corresponding dies in a revolving indexed turret. These machines use hydraulic, pneumatic, or electrical power to press the shape with enough force to shear the metal.

Forces

The punch force required to punch a piece of sheet metal can be estimated from the following equation:[2]

$$F = 0.7tL(UTS)$$

Where *t* is the sheet metal thickness, *L* is the total length sheared (perimeter of the shape), and *UTS* is the ultimate tensile strength of the material.

Die and punch shapes affect the force during the punching process. The punch force increases during the process as the entire thickness of the material is sheared at once. A beveled punch helps in the shearing of thicker materials by reducing the force at the beginning of the stroke. However, beveling a punch will disort the shape because of lateral forces that develop. Compound dies allow multiple shaping to occur. Using compound dies will generally slow down the process and are typically more expensive than other dies. Progressive dies may be used in high production operations. Different punching operations and dies may be used at different stages of the operation on the same machine.

Related processes

Other processes such as stamping, blanking, perforating, parting, drawing, notching, lancing and bending operations are all related to punching.

Plastics

Punching in plastics fabrication usually refers to the removal of scrap plastic from the desired article. For example, in extrusion blow molding it is common to use punching dies to remove tails, molding flash (scrap plastic) and handle slugs from bottles or other molded containers.

In shuttle machinery, the containers are usually trimmed in the machines, and finished containers leave the blow molding machine. Other blow molding equipment, such as rotary wheel machinery, requires the use of downstream trimming. Types of downstream trimming equipment include detabbers for tail removal, rotary or reciprocating punch trimmers, and spin trimmers.

References

[1] Todd, Robert H., Dell K. Allen, and Leo Alting. *Manufacturing Processes Reference Guide*. New York: Industrial Press Inc.1994.Pg 107.
[2] Kalpakjian, Serope; Schmid, Steven R. (2006). Manufacturing Engineering and Technology (5th edition ed.) p. 428.

External links

- http://www.emachineshop.com/machine-shop/CNC-Turret-Punching/page90.html

Press brake

A **press brake**, also known as a **brake press** or just **brake**, is a machine tool for bending sheet and plate material, most commonly sheet metal.[1]


A press brake bending a sheet of steel.

Typically, two C-frames form the sides of the press brake, connected to a table at the bottom and on a moveable beam at the top. The bottom tool is mounted on the table with the top tool mounted on the upper beam.[2]

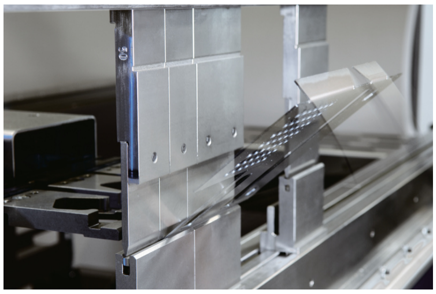
Types


Hydraulic press brake

A brake can be described by basic parameters, such as the force or tonnage and the working length.[1] Additional parameters include the amplitude or stroke, the distance between the frame uprights or side housings, distance to the backgauge, and work height. The upper beam usually operates at a speed ranging from 1 to 15 mm/sec.[2]

There are several types of brakes as described by the means of applying force: mechanical, pneumatic, hydraulic, and servo-electric.

In a mechanical press, energy is added to a flywheel with an electric motor. A clutch engages the flywheel to power a crank mechanism that moves the ram vertically. Accuracy and speed are two advantages of the mechanical press.[3]


Bending process

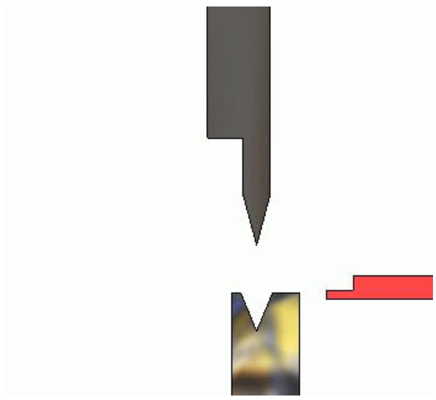
Hydraulic presses operate by means of two synchronized hydraulic cylinders on the C-frames moving the upper beam.[2] [3] Servo-electric brakes use a servo-motor to drive a ballscrew or belt drive to exert tonnage on the ram.

Pneumatic presses utilize air pressure to develop tonnage on the ram.

Until the 1950s, mechanical brakes dominated the world market. The advent of better hydraulics and computer controls have led to hydraulic machines being the most popular.

Pneumatic and servo-electric machines are typically used in lower tonnage applications. Hydraulic brakes produce accurate high quality products are reliable, use little energy and are safer.

Recent improvements are mainly in the control and a device called a backgauge. A back gauge is a device that can be used to accurately position a piece of metal so that the brake puts the bend in the correct place. Furthermore the backgauge can be programmed to move between bends to repeatedly make complex parts. Early brakes relied on the tooling to determine the bend angle of the bend. The animation to the right shows the operation of the backgauge, setting the distance from the edge of the material or previous bend to the center of the die.



Press brakes often include multi-axis computer-controlled backgauges. Optical sensors allow operators to make adjustments during the bending process. These sensors send real-time data about the bending angle in the bend cycle to machine controls that adjust process parameters.[2]

Dies

Press brakes can be used for many different forming jobs with the right die design. Types of dies include:[3]

- V-dies—the most common type of die. The bottom dies can be purchased with different-sized die openings to handle a variety of materials and bend angles.
- Rotary bending dies—a cylindrical shape with an 88-degree V-notch cut along its axis is seated in the "saddle" of the punch.The die is an anvil over which the rocker bends the sheet.
- 90 degree dies—largely used for bottoming operations. The die opening dimension depends on material thickness.
- Acute angle (air-bending) dies—used in air bending, these can actually be used to produce acute, 90 degree, and obtuse angles by varying how deeply the punch enters the die by adjusting the ram.
- Gooseneck (return-flanging) dies—The punch is designed to allow for clearance of already formed flanges
- Offset dies—a combination punch and die set that bends two angles in one stroke to produce a Z shape.
- Hemming dies—two-stage dies combining an acute angle die with a flattening tool.
- Seaming dies—There are a number of ways to build dies to produce seams in sheets and tubes.
- Radius dies—A radiused bend can be produced by a rounded punch. The bottom die may be a V-die or may include a spring pad or rubber pad to form the bottom of the die.
- Beading dies—A bead or a "stopped rib" may be a feature that stiffens the resulting part. The punch has a rounded head with flat shoulders on each side of the bead. The bottom die is the inverse of the punch.
- Curling dies—The die forms a curled or coiled edge on the sheet.
- Tube- and pipe-forming dies—a first operation bends the edges of the sheet to make the piece roll up. Then a die similar to a curling die causes the tube to be formed. Larger tubes are formed over a mandrel.
- Four-way die blocks—A single die block may have a V machined into each of four sides for ease of changeover of small jobs.
- Channel-forming dies—A punch can be pressed into a die to form two angles at the bottom of the sheet, forming an angular channel.
- U-bend dies—Similar to channel forming, but with a rounded bottom. Springback may be a problem and a means may need to be provided for countering it.
- Box-forming dies—While a box may be formed by simple angle bends on each side, the different side lengths of a rectangular box must be accommodated by building the punch in sections. The punch also needs to be high enough to accommodate the height of the resulting box's sides.
- Corrugating dies—Such dies have a wavy surface and may involve spring-loaded punch elements.
- Multiple-bend dies—A die set may be built in the shape of the desired profile and form several bends on a single stroke of the press.
- Rocker-type dies—A rocker insert in the punch may allow for some side-to-side motion, in addition to the up-and-down motion of the press.

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[2] "Press Brake Bending: Methods and Challenges," *Metalforming* magazine, Precision Metalforming Association, August, 2008.

[3] *Tool and Manufacturing Engineers Handbook* (TMEH), Volume 2, *Forming*. Society of Manufacturing Engineers, 1984.

Further reading

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- Cincinnati Incorporated "Press Brake Capacity Guide" http://www.e-ci.com/pdf/Press-Brake-Capacities_PT50691.pdf
- Press Brake Load Calculator - http://www.e-ci.com/loadcalc.php

Gas tungsten arc welding

Gas tungsten arc welding (**GTAW**), also known as **tungsten inert gas** (**TIG**) **welding**, is an arc welding process that uses a nonconsumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by a shielding gas (usually an inert gas such as argon), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces energy which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma.

TIG welding of a bronze sculpture

GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing procedures such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques. A related process, plasma arc welding, uses a slightly different welding torch to create a more focused welding arc and as a result is often automated.[1]

Development

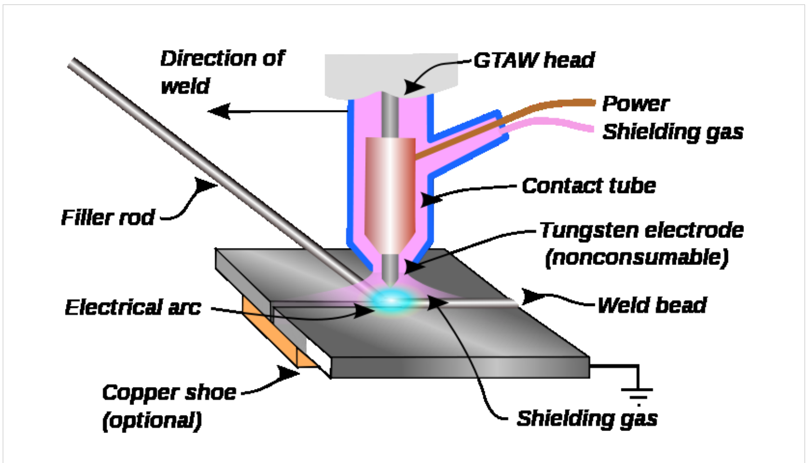
After the discovery of the electric arc in 1800 by Humphry Davy, arc welding developed slowly. C. L. Coffin had the idea of welding in an inert gas atmosphere in 1890, but even in the early 1900s, welding non-ferrous materials like aluminum and magnesium remained difficult, because these metals reacted rapidly with the air, resulting in porous and dross-filled welds.[2] Processes using flux-covered electrodes did not satisfactorily protect the weld area from contamination. To solve the problem, bottled inert gases were used in the beginning of the 1930s. A few years later, a direct current, gas-shielded welding process emerged in the aircraft industry for welding magnesium.

This process was perfected in 1941, and became known as heliarc or tungsten inert gas welding, because it utilized a tungsten electrode and helium as a shielding gas. Initially, the electrode overheated quickly, and in spite of tungsten's high melting temperature, particles of tungsten were transferred to the weld. To address this problem, the polarity of the electrode was changed from positive to negative, but this made it unsuitable for welding many non-ferrous materials. Finally, the development of alternating current units made it possible to stabilize the arc and produce high quality aluminum and magnesium welds.[3]

Developments continued during the following decades. Linde Air Products developed water-cooled torches that helped to prevent overheating when welding with high currents.[4] Additionally, during the 1950s, as the process continued to gain popularity, some users turned to carbon dioxide as an alternative to the more expensive welding atmospheres consisting of argon and helium. However, this proved unacceptable for welding aluminum and magnesium because it reduced weld quality, and as a result, it is rarely used with GTAW today.

In 1953, a new process based on GTAW was developed, called plasma arc welding. It affords greater control and improves weld quality by using a nozzle to focus the electric arc, but is largely limited to automated systems, whereas GTAW remains primarily a manual, hand-held method.[5] Development within the GTAW process has continued as well, and today a number of variations exist. Among the most popular are the pulsed-current, manual programmed, hot-wire, dabber, and increased penetration GTAW methods.[6]

Operation



GTAW weld area

Manual gas tungsten arc welding is often considered the most difficult of all the welding processes commonly used in industry. Because the welder must maintain a short arc length, great care and skill are required to prevent contact between the electrode and the workpiece. Similar to torch welding, GTAW normally requires two hands, since most applications require that the welder manually feed a filler metal into the weld area with one hand while manipulating the welding torch in the other. However, some welds combining thin materials (known as autogenous or fusion welds) can be accomplished without filler metal; most notably edge, corner, and butt joints.

To strike the welding arc, a high frequency generator (similar to a Tesla coil) provides a spark; this spark is a conductive path for the welding current through the shielding gas and allows the arc to be initiated while the electrode and the workpiece are separated, typically about 1.5–3 mm (0.06–0.12 in) apart. This high voltage, high frequency burst can be damaging to some vehicle electrical systems and electronics, because induced voltages on vehicle wiring can also cause small conductive sparks in the vehicle wiring or within semiconductor packaging. Vehicle 12V power may conduct across these ionized paths, driven by the high-current 12V vehicle battery. These currents can be sufficiently destructive as to disable the vehicle; thus the warning to disconnect the vehicle battery power from both +12 and ground before using welding equipment on vehicles.

An alternate way to initiate the arc is the "scratch start". Scratching the electrode against the work with the power on also serve to strike an arc, in the same way as SMAW ("stick") arc welding. However, scratch starting can cause contamination of the weld and electrode. Some GTAW equipment is capable of a mode called "touch start" or "lift arc"; here the equipment reduces the voltage on the electrode to only a few volts, with a current limit of one or two amps (well below the limit that causes metal to transfer and contamination of the weld or electrode). When the

GTAW equipment detects that the electrode has left the surface and a spark is present, it immediately (within microseconds) increases power, converting the spark to a full arc.

Once the arc is struck, the welder moves the torch in a small circle to create a welding pool, the size of which depends on the size of the electrode and the amount of current. While maintaining a constant separation between the electrode and the workpiece, the operator then moves the torch back slightly and tilts it backward about 10–15 degrees from vertical. Filler metal is added manually to the front end of the weld pool as it is needed.[7]

Welders often develop a technique of rapidly alternating between moving the torch forward (to advance the weld pool) and adding filler metal. The filler rod is withdrawn from the weld pool each time the electrode advances, but it is never removed from the gas shield to prevent oxidation of its surface and contamination of the weld. Filler rods composed of metals with low melting temperature, such as aluminum, require that the operator maintain some distance from the arc while staying inside the gas shield. If held too close to the arc, the filler rod can melt before it makes contact with the weld puddle. As the weld nears completion, the arc current is often gradually reduced to allow the weld crater to solidify and prevent the formation of crater cracks at the end of the weld.[8] [9]

Operation modes

GTAW can use a positive direct current, negative direct current or an alternating current, depending on the power supply set up. A negative direct current from the electrode causes a stream of electrons to collide with the surface, generating large amounts of heat at the weld region. This creates a deep, narrow weld. In the opposite process where the electrode is connected to the positive power supply terminal, positively charged ions flow from the part being welded to the tip of the electrode instead, so the heating action of the electrons is mostly on the electrode. This mode also helps to remove oxide layers from the surface of the region to be welded, which is good for metals such as aluminum or magnesium. A shallow, wide weld is produced from this mode, with minimum heat input. Alternating current gives a combination of negative and positive modes, giving a cleaning effect and imparts a lot of heat as well.

Safety

Like other arc welding processes, GTAW can be dangerous if proper precautions are not taken. The process produces intense ultraviolet radiation, which can cause a form of sunburn and, in a few cases, trigger the development of skin cancer. Flying sparks and droplets of molten metal can cause severe burns and start a fire if flammable material is nearby, though GTAW generally produces very few sparks or metal droplets when performed properly.

It is essential that the welder wear suitable protective clothing, including leather gloves, a closed shirt collar to protect the neck (especially the throat), a protective long sleeve jacket and a suitable welding helmet to prevent retinal damage or ultraviolet burns to the cornea, often called arc eye. The shade of welding lens will depend upon the amperage of the welding current. Due to the absence of smoke in GTAW, the arc appears brighter than shielded metal arc welding and more ultraviolet radiation is produced. Exposure of bare skin near a GTAW arc for even a few seconds may cause a painful sunburn. Additionally, the tungsten electrode is heated to a white hot state like the filament of a lightbulb, adding greatly to the total radiated light and heat energy. Transparent welding curtains, made of a polyvinyl chloride plastic film, dyed in order to block UV radiation, are often used to shield nearby personnel from exposure.

Welders are also often exposed to dangerous gases and particulate matter. Shielding gases can displace oxygen and lead to asphyxiation, and while smoke is not produced, the arc in GTAW produces very short wavelength ultraviolet light, which causes surrounding air to break down and form ozone. Metals will volatilize and heavy metals can be taken into the lungs. Similarly, the heat can cause poisonous fumes to form from cleaning and degreasing materials. For example chlorinated products will break down producing poisonous phosgene. Cleaning operations using these agents should not be performed near the site of welding, and proper ventilation is necessary to protect the welder.[10]

Applications

While the aerospace industry is one of the primary users of gas tungsten arc welding, the process is used in a number of other areas. Many industries use GTAW for welding thin workpieces, especially nonferrous metals. It is used extensively in the manufacture of space vehicles, and is also frequently employed to weld small-diameter, thin-wall tubing such as those used in the bicycle industry. In addition, GTAW is often used to make root or first pass welds for piping of various sizes. In maintenance and repair work, the process is commonly used to repair tools and dies, especially components made of aluminum and magnesium.[11] Because the weld metal is not transferred directly across the electric arc like most open arc welding processes, a vast assortment of welding filler metal is available to the welding engineer. In fact, no other welding process permits the welding of so many alloys in so many product configurations. Filler metal alloys, such as elemental aluminum and chromium, can be lost through the electric arc from volatilization. This loss does not occur with the GTAW process. Because the resulting welds have the same chemical integrity as the original base metal or match the base metals more closely, GTAW welds are highly resistant to corrosion and cracking over long time periods, GTAW is the welding procedure of choice for critical welding operations like sealing spent nuclear fuel canisters before burial.[12]

Quality

Engineers prefer GTAW welds because of its low-hydrogen properties and the match of mechanical and chemical properties with the base material. Maximum weld quality is assured by maintaining the cleanliness of the operation—all equipment and materials used must be free from oil, moisture, dirt and other impurities, as these cause weld porosity and consequently a decrease in weld strength and quality. To remove oil and grease, alcohol or similar commercial solvents may be used, while a stainless steel wire brush or chemical process can remove oxides from the surfaces of metals like aluminum. Rust on steels can be removed by first grit blasting the surface and then using a wire brush to remove any embedded grit. These steps are especially important when negative polarity direct current is used, because such a power supply provides no cleaning during the welding process, unlike positive polarity direct current or alternating current.[13] To maintain a clean weld pool during welding, the shielding gas flow should be sufficient and consistent so that the gas covers the weld and blocks impurities in the atmosphere. GTA welding in windy or drafty environments increases the amount of shielding gas necessary to protect the weld, increasing the cost and making the process unpopular outdoors.

GTAW fillet weld

Because of GTAW's relative difficulty and the importance of proper technique, skilled operators are employed for important applications. Welders in the U.S. should be qualified following the requirements of the American Welding Society or American Society of Mechanical Engineers. Low heat input, caused by low welding current or high welding speed, can limit penetration and cause the weld bead to lift away from the surface being welded. If there is too much heat input, however, the weld bead grows in width while the likelihood of excessive penetration and spatter increase. Additionally, if the welder holds the welding torch too far from the workpiece, shielding gas is wasted and the appearance of the weld worsens.

If the amount of current used exceeds the capability of the electrode, tungsten inclusions in the weld may result. Known as tungsten spitting, it can be identified with radiography and prevented by changing the type of electrode or increasing the electrode diameter. In addition, if the electrode is not well protected by the gas shield or the operator accidentally allows it to contact the molten metal, it can become dirty or contaminated. This often causes the welding arc to become unstable, requiring that electrode be ground with a diamond abrasive to remove the impurity.[14]

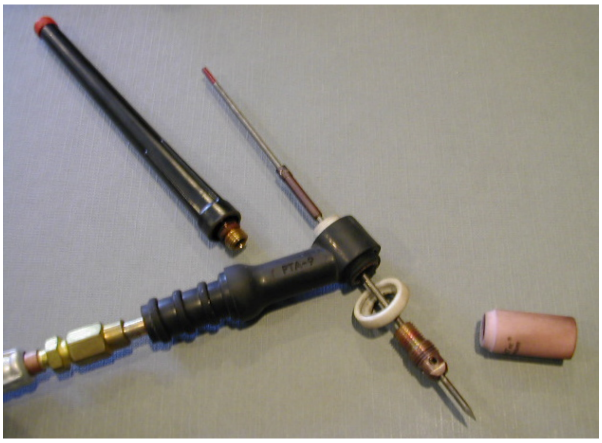
Equipment

The equipment required for the gas tungsten arc welding operation includes a welding torch utilizing a nonconsumable tungsten electrode, a constant-current welding power supply, and a shielding gas source.

GTAW torch with various electrodes, cups, collets and gas diffusers

Welding torch

GTAW welding torches are designed for either automatic or manual operation and are equipped with cooling systems using air or water. The automatic and manual torches are similar in construction, but the manual torch has a handle while the automatic torch normally comes with a mounting rack. The angle between the centerline of the handle and the centerline of the tungsten electrode, known as the head angle, can be varied on some manual torches according to the preference of the operator. Air cooling systems are most often used for low-current operations (up to about 200 A), while water cooling is required for high-current welding (up to about 600 A). The torches are connected with cables to the power supply and with hoses to the shielding gas source and where used, the water supply.



GTAW torch, disassembled

The internal metal parts of a torch are made of hard alloys of copper or brass in order to transmit current and heat effectively. The tungsten electrode must be held firmly in the center of the torch with an appropriately sized collet, and ports around the electrode provide a constant flow of shielding gas. Collets are sized according to the diameter of the tungsten electrode they hold. The body of the torch is made of heat-resistant, insulating plastics covering the metal components, providing insulation from heat and electricity to protect the welder.

The size of the welding torch nozzle depends on the amount of shielded area desired. The size of the gas nozzle will depend upon the diameter of the electrode, the joint configuration, and the availability of access to the joint by the welder. The inside diameter of the nozzle is preferably at least three times the diameter of the electrode, but there are no hard rules. The welder will judge the effectiveness of the shielding and increase the nozzle size to increase the area protected by the external gas shield as needed. The nozzle must be heat resistant and thus is normally made of alumina or a ceramic material, but fused quartz, a glass-like substance, offers greater visibility. Devices can be inserted into the nozzle for special applications, such as gas lenses or valves to improve the control shielding gas flow to reduce turbulence and introduction of contaminated atmosphere into the shielded area. Hand switches to control welding current can be added to the manual GTAW torches.[15]

Power supply

Gas tungsten arc welding uses a constant current power source, meaning that the current (and thus the heat) remains relatively constant, even if the arc distance and voltage change. This is important because most applications of GTAW are manual or semiautomatic, requiring that an operator hold the torch. Maintaining a suitably steady arc distance is difficult if a constant voltage power source is used instead, since it can cause dramatic heat variations and make welding more difficult.[16]

GTAW power supply

The preferred polarity of the GTAW system depends largely on the type of metal being welded. Direct current with a negatively charged electrode (DCEN) is often employed when welding steels, nickel, titanium, and other metals. It can also be used in automatic GTA welding of aluminum or magnesium when helium is used as a shielding gas. The negatively charged electrode generates heat by emitting electrons which travel across the arc, causing thermal ionization of the shielding gas and increasing the temperature of the base material. The ionized shielding gas flows toward the electrode, not the base material. Direct current with a positively charged electrode (DCEP) is less common, and is used primarily for shallow welds since less heat is generated in the base material. Instead of flowing from the electrode to the base material, as in DCEN, electrons go the other direction, causing the electrode to reach very high temperatures. To help it maintain its shape and prevent softening, a larger electrode is often used. As the electrons flow toward the electrode, ionized shielding gas flows back toward the base material, cleaning the weld by removing oxides and other impurities and thereby improving its quality and appearance.

Alternating current, commonly used when welding aluminum and magnesium manually or semi-automatically, combines the two direct currents by making the electrode and base material alternate between positive and negative charge. This causes the electron flow to switch directions constantly, preventing the tungsten electrode from overheating while maintaining the heat in the base material. Surface oxides are still removed during the electrode-positive portion of the cycle and the base metal is heated more deeply during the electrode-negative portion of the cycle. Some power supplies enable operators to use an unbalanced alternating current wave by modifying the exact percentage of time that the current spends in each state of polarity, giving them more control over the amount of heat and cleaning action supplied by the power source. In addition, operators must be wary of rectification, in which the arc fails to reignite as it passes from straight polarity (negative electrode) to reverse polarity (positive electrode). To remedy the problem, a square wave power supply can be used, as can high-frequency voltage to encourage ignition.[17]

Electrode

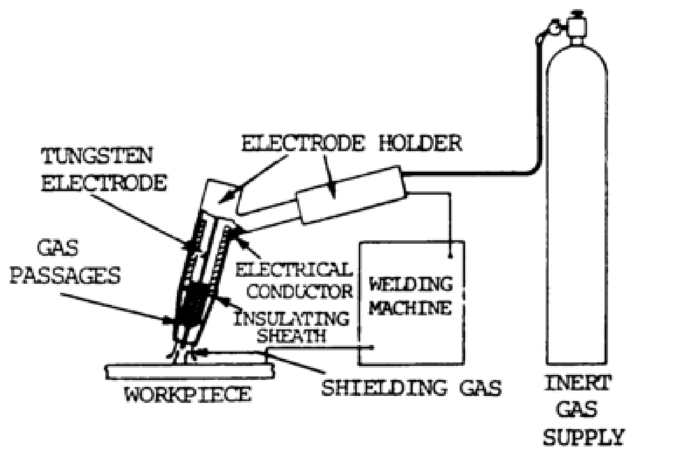
ISO Class	ISO Color	AWS Class	AWS Color	Alloy[18]
WP	Green	EWP	Green	None
WC20	Gray	EWCe-2	Orange	~2% CeO_2
WL10	Black	EWLa-1	Black	~1% La_2O_3
WL15	Gold	EWLa-1.5	Gold	~1.5% La_2O_3
WL20	Sky-blue	EWLa-2	Blue	~2% La_2O_3
WT10	Yellow	EWTh-1	Yellow	~1% ThO_2
WT20	Red	EWTh-2	Red	~2% ThO_2
WT30	Violet			~3% ThO_2
WT40	Orange			~4% ThO_2
WY20	Blue			~2% Y_2O_3
WZ3	Brown	EWZr-1	Brown	~0.3% ZrO_2
WZ8	White			~0.8% ZrO_2

The electrode used in GTAW is made of tungsten or a tungsten alloy, because tungsten has the highest melting temperature among pure metals, at 3422 °C (6192 °F). As a result, the electrode is not consumed during welding, though some erosion (called burn-off) can occur. Electrodes can have either a clean finish or a ground finish—clean finish electrodes have been chemically cleaned, while ground finish electrodes have been ground to a uniform size and have a polished surface, making them optimal for heat conduction. The diameter of the electrode can vary between 0.5 and 6.4 millimetres (0.02 and 0.25 in), and their length can range from 75 to 610 millimetres (3.0 to 24 in).

A number of tungsten alloys have been standardized by the International Organization for Standardization and the American Welding Society in ISO 6848 and AWS A5.12, respectively, for use in GTAW electrodes, and are summarized in the adjacent table. Pure tungsten electrodes (classified as WP or EWP) are general purpose and low cost electrodes. Cerium oxide (or ceria) as an alloying element improves arc stability and ease of starting while decreasing burn-off. Using an alloy of lanthanum oxide (or lanthana) has a similar effect. Thorium oxide (or thoria) alloy electrodes were designed for DC applications and can withstand somewhat higher temperatures while providing many of the benefits of other alloys. However, it is somewhat radioactive. Inhalation of the thorium grinding dust during preparation of the electrode is hazardous to one's health. As a replacement to thoriated electrodes, electrodes with larger concentrations of lanthanum oxide can be used. Electrodes containing zirconium oxide (or zirconia) increase the current capacity while improving arc stability and starting and increasing electrode life. In addition, electrode manufacturers may create alternative tungsten alloys with specified metal additions, and these are designated with the classification EWG under the AWS system.

Filler metals are also used in nearly all applications of GTAW, the major exception being the welding of thin materials. Filler metals are available with different diameters and are made of a variety of materials. In most cases, the filler metal in the form of a rod is added to the weld pool manually, but some applications call for an automatically fed filler metal, which often is stored on spools or coils.[19]

Shielding gas



GTAW system setup

As with other welding processes such as gas metal arc welding, shielding gases are necessary in GTAW to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. The gas also transfers heat from the tungsten electrode to the metal, and it helps start and maintain a stable arc.

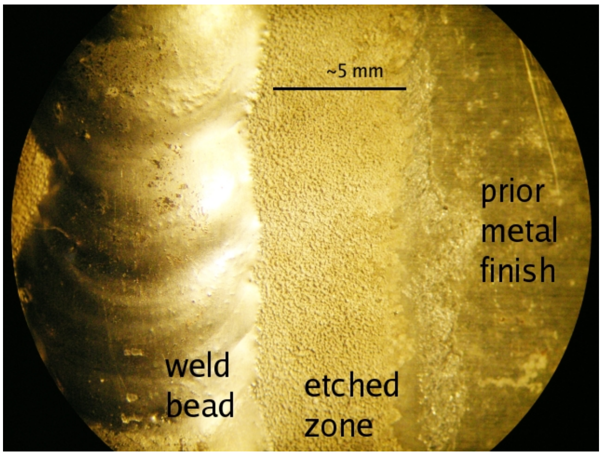
The selection of a shielding gas depends on several factors, including the type of material being welded, joint design, and desired final weld appearance. Argon is the most commonly used shielding gas for GTAW, since it helps prevent defects due to a varying arc length. When used with alternating current, the use of argon results in high weld quality and good appearance. Another common shielding gas, helium, is most often used to increase the weld penetration in a joint, to increase the welding speed, and to weld metals with high heat conductivity, such as copper and aluminum. A significant disadvantage is the difficulty of striking an arc with helium gas, and the decreased weld quality associated with a varying arc length.

Argon-helium mixtures are also frequently utilized in GTAW, since they can increase control of the heat input while maintaining the benefits of using argon. Normally, the mixtures are made with primarily helium (often about 75% or higher) and a balance of argon. These mixtures increase the speed and quality of the AC welding of aluminum, and also make it easier to strike an arc. Another shielding gas mixture, argon-hydrogen, is used in the mechanized welding of light gauge stainless steel, but because hydrogen can cause porosity, its uses are limited.[20] Similarly, nitrogen can sometimes be added to argon to help stabilize the austenite in austentitic stainless steels and increase penetration when welding copper. Due to porosity problems in ferritic steels and limited benefits, however, it is not a popular shielding gas additive.[21]

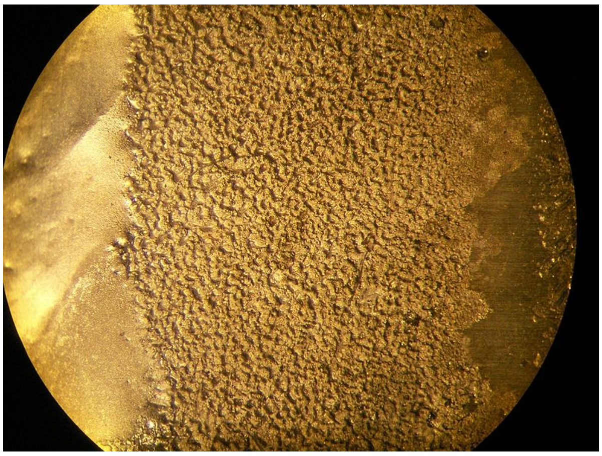
Materials

Gas tungsten arc welding is most commonly used to weld stainless steel and nonferrous materials, such as aluminum and magnesium, but it can be applied to nearly all metals, with notable exceptions being lead and zinc. Its applications involving carbon steels are limited not because of process restrictions, but because of the existence of more economical steel welding techniques, such as gas metal arc welding and shielded metal arc welding. Furthermore, GTAW can be performed in a variety of other-than-flat positions, depending on the skill of the welder and the materials being welded.[22]

Aluminum and magnesium



A TIG weld showing an accentuated AC etched zone


Closeup view of an aluminium TIG weld AC etch zone

Aluminum and magnesium are most often welded using alternating current, but the use of direct current is also possible, depending on the properties desired. Before welding, the work area should be cleaned and may be preheated to 175 to 200 °C (347 to 392 °F) for aluminum or to a maximum of 150 °C (302 °F) for thick magnesium workpieces to improve penetration and increase travel speed. AC current can provide a self-cleaning effect, removing the thin, refractory aluminium oxide (sapphire) layer that forms on aluminium metal within minutes of exposure to air. This oxide layer must be removed for welding to occur. When alternating current is used, pure tungsten electrodes or zirconiated tungsten electrodes are preferred over thoriated electrodes, as the latter are more likely to "spit" electrode particles across the welding arc into the weld. Blunt electrode tips are preferred, and pure argon shielding gas should be employed for thin workpieces. Introducing helium allows for greater penetration in thicker workpieces, but can make arc starting difficult.

Direct current of either polarity, positive or negative, can be used to weld aluminum and magnesium as well. Direct current with a negatively charged electrode (DCEN) allows for high penetration. Argon is commonly used as a shielding gas for DCEN welding of aluminum. Shielding gases with high helium contents are often used for higher penetration in thicker materials. Thoriated electrodes are suitable for use in DCEN welding of aluminum. Direct current with a positively charged electrode (DCEP) is used primarily for shallow welds, especially those with a joint thickness of less than 1.6 mm (0.063 in). A thoriated tungsten electrode is commonly used, along with a pure argon shielding gas.[23]

Steels

For GTA welding of carbon and stainless steels, the selection of a filler material is important to prevent excessive porosity. Oxides on the filler material and workpieces must be removed before welding to prevent contamination, and immediately prior to welding, alcohol or acetone should be used to clean the surface. Preheating is generally not necessary for mild steels less than one inch thick, but low alloy steels may require preheating to slow the cooling process and prevent the formation of martensite in the heat-affected zone. Tool steels should also be preheated to prevent cracking in the heat-affected zone. Austenitic stainless steels do not require preheating, but martensitic and ferritic chromium stainless steels do. A DCEN power source is normally used, and thoriated electrodes, tapered to a sharp point, are recommended. Pure argon is used for thin workpieces, but helium can be introduced as thickness increases.[24]

Copper alloys

TIG welding of copper and some of its alloys is possible, but in order to get a seam free of oxidation and porosities, shielding gas needs to be provided on the root side of the weld. Alternatively, a special "backing tape", consisting of a fiberglass weave on heat-resistant aluminum tape can be used, to prevent air reaching the molten metal.

Dissimilar metals

Welding dissimilar metals often introduces new difficulties to GTAW welding, because most materials do not easily fuse to form a strong bond. However, welds of dissimilar materials have numerous applications in manufacturing, repair work, and the prevention of corrosion and oxidation. In some joints, a compatible filler metal is chosen to help form the bond, and this filler metal can be the same as one of the base materials (for example, using a stainless steel filler metal with stainless steel and carbon steel as base materials), or a different metal (such as the use of a nickel filler metal for joining steel and cast iron). Very different materials may be coated or "buttered" with a material compatible with a particular filler metal, and then welded. In addition, GTAW can be used in cladding or overlaying dissimilar materials.

When welding dissimilar metals, the joint must have an accurate fit, with proper gap dimensions and bevel angles. Care should be taken to avoid melting excessive base material. Pulsed current is particularly useful for these applications, as it helps limit the heat input. The filler metal should be added quickly, and a large weld pool should be avoided to prevent dilution of the base materials.[25]

Process variations

Pulsed-current

In the pulsed-current mode, the welding current rapidly alternates between two levels. The higher current state is known as the pulse current, while the lower current level is called the background current. During the period of pulse current, the weld area is heated and fusion occurs. Upon dropping to the background current, the weld area is allowed to cool and solidify. Pulsed-current GTAW has a number of advantages, including lower heat input and consequently a reduction in distortion and warpage in thin workpieces. In addition, it allows for greater control of the weld pool, and can increase weld penetration, welding speed, and quality. A similar method, manual programmed GTAW, allows the operator to program a specific rate and magnitude of current variations, making it useful for specialized applications.[26]

Dabber

The dabber variation is used to precisely place weld metal on thin edges. The automatic process replicates the motions of manual welding by feeding a cold filler wire into the weld area and dabbing (or oscillating) it into the welding arc. It can be used in conjunction with pulsed current, and is used to weld a variety of alloys, including titanium, nickel, and tool steels. Common applications include rebuilding seals in jet engines and building up saw blades, milling cutters, drill bits, and mower blades.[27]

Hot wire

Welding filler metal can be resistance heated to a temperature near its melting point before being introduced into the weld pool. This increases the deposition rate of machine and automatic GTAW welding processes. More pounds per hour of filler metal is introduced into the weld joint than when filler metal is added cold and the heat of the electric arc introduces all of the heat. This process is used extensively in base material build up before machining, clad metal overlays, and hardfacing operations.

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Notes

[1] Weman, 31, 37–38
[2] Cary and Helzer, 5–8
[3] Lincoln Electric, 1.1-7–1.1-8
[4] Cary and Helzer, 8
[5] Lincoln Electric, 1.1-8
[6] Cary and Helzer, 75
[7] Lincoln Electric, 5.4-7–5.4-8
[8] Jeffus, 378
[9] Lincoln Electric, 9.4–7.
[10] Cary and Helzer, 42, 75
[11] Cary and Helzer, 77
[12] Watkins and Mizia, 424–426
[13] Minnick, 120–21
[14] Cary and Helzer, 74–75
[15] Cary and Helzer, 71–72
[16] Cary and Helzer, 71
[17] Minnick, 14–16
[18] MarkeTech International
[19] Cary and Helzer, 72–73
[20] Minnick, 71–73
[21] Jeffus, 361
[22] Weman, 31
[23] Minnick, 135–49
[24] Minnick, 156–69
[25] Minnick, 197–206
[26] Cary and Helzer, 75–76
[27] Cary and Helzer, 76–77

External links

- GTAW handbook (http://www.millerwelds.com/education/TIGhandbook/)
- Selection and Preparation Guide for Tungsten Electrodes (http://www.millerwelds.com/education/articles/articles83.html)
- MMA Basics (http://www.weldingshop.co.uk/arc-mma-welding-basics/info_23.html)
- Tig welding basics (http://www.weldingshop.co.uk/tig-welding-basics/info_21.html)

Gas metal arc welding

Gas metal arc welding

Gas metal arc welding (GMAW), sometimes referred to by its subtypes **metal inert gas (MIG) welding** or **metal active gas (MAG) welding**, is a semi-automatic or automatic arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray, and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations.

Originally developed for welding aluminum and other non-ferrous materials in the 1940s, GMAW was soon applied to steels because it allowed for lower welding time compared to other welding processes. The cost of inert gas limited its use in steels until several years later, when the use of semi-inert gases such as carbon dioxide became common. Further developments during the 1950s and 1960s gave the process more versatility and as a result, it became a highly used industrial process. Today, GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation. The automobile industry in particular uses GMAW welding almost exclusively. Unlike welding processes that do not employ a shielding gas, such as shielded metal arc welding, it is rarely used outdoors or in other areas of air volatility. A related process, flux cored arc welding, often does not utilize a shielding gas, instead employing a hollow electrode wire that is filled with flux on the inside.

Development

The principles of gas metal arc welding began to be understood in the early 19th century, after Humphry Davy discovered the short pulsed electric arcs in 1800[1] and then Vasily Petrov independently produced the continuous electric arc in 1802[2] (soon followed by Davy). In his work published in 1803 Petrov proposed the usage of electric arc in welding, having managed to perform a simple experimental welding.[2] But it was not until the 1880s that the technology became developed with the aim of industrial usage. At first, the practical method of carbon arc welding invented by Nikolay Benardos was used,[3] utilising carbon electrodes known from the time of Davy and Petrov. By the late 1880s, metal electrodes had been invented by Nikolay Slavyanov (1888)[4] and C. L. Coffin (1890). In 1920, an early predecessor of GMAW was invented by P. O. Nobel of General Electric. It used a bare electrode wire and direct current, and used arc voltage to regulate the feed rate. It did not use a shielding gas to protect the weld, as developments in welding atmospheres did not take place until later that decade. In 1926 another forerunner of GMAW was released, but it was not suitable for practical use.[5]

It was not until 1948 that GMAW was finally developed by the Battelle Memorial Institute. It used a smaller diameter electrode and a constant voltage power source, which had been developed by H. E. Kennedy. It offered a high deposition rate, but the high cost of inert gases limited its use to non-ferrous materials and cost savings were not obtained. In 1953, the use of carbon dioxide as a welding atmosphere was developed, and it quickly gained popularity in GMAW, since it made welding steel more economical. In 1958 and 1959, the short-arc variation of GMAW was released, which increased welding versatility and made the welding of thin materials possible while relying on smaller electrode wires and more advanced power supplies. It quickly became the most popular GMAW variation. The spray-arc transfer variation was developed in the early 1960s, when experimenters added small amounts of oxygen to inert gases. More recently, pulsed current has been applied, giving rise to a new method called the pulsed spray-arc variation.[6]

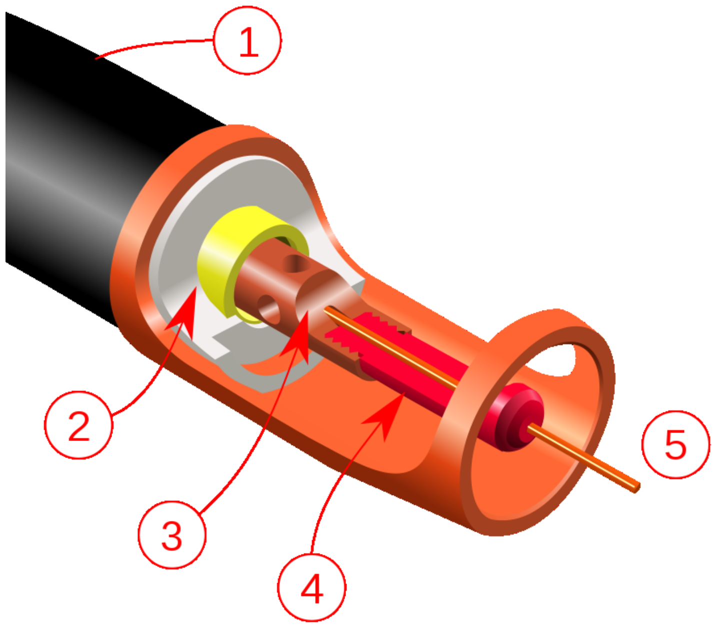
As noted, GMAW is currently one of the most popular welding methods, especially in industrial environments. It is used extensively by the sheet metal industry and, by extension, the automobile industry. There, the method is often used for arc spot welding, thereby replacing riveting or resistance spot welding. It is also popular for automated welding, in which robots handle the workpieces and the welding gun to quicken the manufacturing process.[7] Generally, it is unsuitable for welding outdoors, because the movement of the surrounding air can dissipate the shielding gas and thus make welding more difficult, while also decreasing the quality of the weld. The problem can be alleviated to some extent by increasing the shielding gas output, but this can be expensive and may also affect the quality of the weld. In general, processes such as shielded metal arc welding and flux cored arc welding are preferred for welding outdoors, making the use of GMAW in the construction industry rather limited. Furthermore, the use of a shielding gas makes GMAW an unpopular underwater welding process, but can be used in space since there is no oxygen to oxidize the weld.

Equipment

To perform gas metal arc welding, the basic necessary equipment is a welding gun, a wire feed unit, a welding power supply, an electrode wire, and a shielding gas supply.

Welding gun and wire feed unit

The typical GMAW welding gun has a number of key parts—a control switch, a contact tip, a power cable, a gas nozzle, an electrode conduit and liner, and a gas hose. The control switch, or trigger, when pressed by the operator, initiates the wire feed, electric power, and the shielding gas flow, causing an electric arc to be struck. The contact tip, normally made of copper and sometimes chemically treated to reduce spatter, is connected to the welding power source through the power cable and transmits the electrical energy to the electrode while directing it to the weld area. It must be firmly secured and properly sized, since it must allow the passage of the electrode while maintaining an electrical contact. Before arriving at the contact tip, the wire is protected and guided by the electrode conduit and liner, which help prevent buckling and maintain an uninterrupted wire feed. The gas nozzle is used to evenly direct the shielding gas into the welding zone—if the flow is inconsistent, it may not provide adequate protection of the weld area. Larger nozzles provide greater shielding gas flow, which is useful for high current welding operations, in which the size of the molten weld pool is increased. The gas is supplied to the nozzle through a gas hose, which is connected to the tanks of shielding gas. Sometimes, a water hose is also built into the welding gun, cooling the gun in high heat operations.[8]



GMAW torch nozzle cutaway image. **(1)** Torch handle, **(2)** Molded phenolic dielectric (shown in white) and threaded metal nut insert (yellow), **(3)** Shielding gas diffuser, **(4)** Contact tip, **(5)** Nozzle output face

A GMAW wire feed unit

The wire feed unit supplies the electrode to the work, driving it through the conduit and on to the contact tip. Most models provide the wire at a constant feed rate, but more advanced machines can vary the feed rate in response to the arc length and voltage. Some wire feeders can reach feed rates as high as 30.5 m/min (1200 in/min),[9] but feed rates for semiautomatic GMAW typically range from 2 to 10 m/min (75–400 in/min).[10]

Tool style

The top electrode holder is a semiautomatic air-cooled holder; compressed air is circulated through it to maintain moderate temperatures. It is used with lower current levels for welding lap- or butt joints. The second most common type of electrode holder is a semiautomatic water-cooled; the only difference being that water takes the place of air. It uses higher current levels for welding T- or corner joints. The third typical holder type is an automatic electrode holder that is water cooled; this holder is used typically with automated equipment.[11]

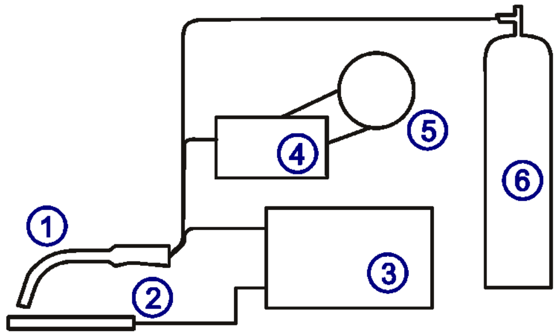
Power supply

Most applications of gas metal arc welding use a constant voltage power supply. As a result, any change in arc length (which is directly related to voltage) results in a large change in heat input and current. A shorter arc length will cause a much greater heat input, which will make the wire electrode melt more quickly and thereby restore the original arc length. This helps operators keep the arc length consistent even when manually welding with hand-held welding guns. To achieve a similar effect, sometimes a constant current power source is used in combination with an arc voltage-controlled wire feed unit. In this case, a change in arc length makes the wire feed rate adjust in order to maintain a relatively constant arc length. In rare circumstances, a constant current power source and a constant wire feed rate unit might be coupled, especially for the welding of metals with high thermal conductivities, such as aluminum. This grants the operator additional control over the heat input into the weld, but requires significant skill to perform successfully.[12]

Alternating current is rarely used with GMAW; instead, direct current is employed and the electrode is generally positively charged. Since the anode tends to have a greater heat concentration, this results in faster melting of the feed wire, which increases weld penetration and welding speed. The polarity can be reversed only when special emissive-coated electrode wires are used, but since these are not popular, a negatively charged electrode is rarely employed.[13]

Electrode

Electrode selection is based primarily on the composition of the metal being welded, the process variation being used, joint design and the material surface conditions. Electrode selection greatly influences the mechanical properties of the weld and is a key factor of weld quality. In general the finished weld metal should have mechanical properties similar to those of the base material with no defects such as discontinuities, entrained contaminants or porosity within the weld. To achieve these goals a wide variety of electrodes exist. All commercially available electrodes contain deoxidizing metals such as silicon, manganese, titanium and aluminum in small percentages to help prevent oxygen porosity. Some contain denitriding metals such as titanium and zirconium to avoid nitrogen porosity.[14] Depending on the process variation and base material being welded the diameters of the electrodes used in GMAW typically range from 0.7 to 2.4 mm (0.028–0.095 in) but can be as large as 4 mm (0.16 in). The smallest electrodes, generally up to 1.14 mm (0.045 in)[15] are associated with the short-circuiting metal transfer process, while the most common spray-transfer process mode electrodes are usually at least 0.9 mm (0.035 in).[16] [10]



GMAW Circuit diagram. **(1)** Welding torch, **(2)** Workpiece, **(3)** Power source, **(4)** Wire feed unit, **(5)** Electrode source, **(6)** Shielding gas supply.

Shielding gas

Shielding gases are necessary for gas metal arc welding to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. This problem is common to all arc welding processes; for example, in the older Shielded-Metal Arc Welding process (SMAW), the electrode is coated with a solid flux which evolves a protective cloud of carbon dioxide when melted by the arc. In GMAW, however, the electrode wire does not have a flux coating, and a separate shielding gas is employed to protect the weld. This eliminates slag, the hard residue from the flux that builds up after welding and must be chipped off to reveal the completed weld.

The choice of a shielding gas depends on several factors, most importantly the type of material being welded and the process variation being used. Pure inert gases such as argon and helium are only used for nonferrous welding; with steel they do not provide adequate weld penetration (argon) or cause an erratic arc and encourage spatter (with helium). Pure carbon dioxide, on the other hand, allows for deep penetration welds but encourages oxide formation, which adversely affect the mechanical properties of the weld. Its low cost makes it an attractive choice, but because of the reactivity of the arc plasma, spatter is unavoidable and welding thin materials is difficult. As a result, argon and carbon dioxide are frequently mixed in a 75%/25% to 90%/10% mixture. Generally, in short circuit GMAW, higher carbon dioxide content increases the weld heat and energy when all other weld parameters (volts, current, electrode type and diameter) are held the same. As the carbon dioxide content increases over 20%, spray transfer GMAW becomes increasingly problematic, especially with smaller electrode diameters.[17]

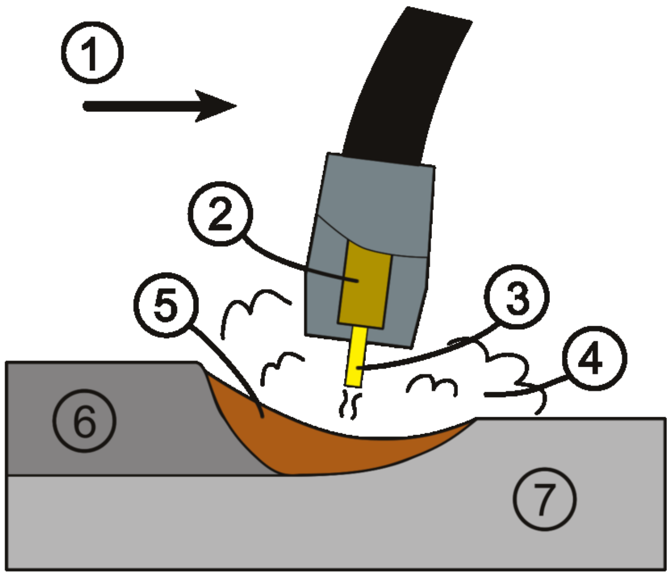
Argon is also commonly mixed with other gases, oxygen, helium, hydrogen, and nitrogen. The addition of up to 5% oxygen (like the higher concentrations of carbon dioxide mentioned above) can be helpful in welding stainless steel, however, in most applications carbon dioxide is preferred.[18] Increased oxygen makes the shielding gas oxidize the electrode, which can lead to porosity in the deposit if the electrode does not contain sufficient deoxidizers. Excessive oxygen, especially when used in application for which it is not prescribed, can lead to brittleness in the heat affected zone. Argon-helium mixtures are extremely inert, and can be used on nonferrous materials. A helium concentration of 50%–75% raises the required voltage and increases the heat in the arc, due to helium's higher ionization temperature. Hydrogen is sometimes added to argon in small concentrations (up to about 5%) for welding nickel and thick stainless steel workpieces. In higher concentrations (up to 25% hydrogen), it may be used for welding conductive materials such as copper. However, it should not be used on steel, aluminum or magnesium because it can cause porosity and hydrogen embrittlement. Additionally, nitrogen is sometimes added to argon to a concentration of 25%–50% for welding copper, but the use of nitrogen, especially in North America, is limited.

Shielding gas mixtures of three or more gases are also available. Mixtures of argon, carbon dioxide and oxygen are marketed for welding steels. Other mixtures add a small amount of helium to argon-oxygen combinations, these mixtures are claimed to allow higher arc voltages and welding speed. Helium is also sometimes used as the base gas, with small amounts of argon and carbon dioxide added. However, because it is less dense than air, helium is less effective in shielding the weld than argon– which is denser than air. It also can lead to arc stability and penetration issues, and increased spatter, due to its much more energetic arc plasma. Helium is also substantially more expensive than other shielding gases. Other specialized and often proprietary gas mixtures claim even greater benefits for specific applications.[19]

The desirable rate of shielding-gas flow depends primarily on weld geometry, speed, current, the type of gas, and the metal transfer mode being utilized. Welding flat surfaces requires higher flow than welding grooved materials, since the gas is dispersed more quickly. Faster welding speeds, in general, mean that more gas needs to be supplied to provide adequate coverage. Additionally, higher current requires greater flow, and generally, more helium is required to provide adequate coverage than if argon is used. Perhaps most importantly, the four primary variations of GMAW have differing shielding gas flow requirements—for the small weld pools of the short circuiting and pulsed spray modes, about 10 L/min (20 ft^3/h) is generally suitable, whereas for globular transfer, around 15 L/min (30 ft^3/h) is preferred. The spray transfer variation normally requires more shielding-gas flow because of its higher heat input and thus larger weld pool. Typical gas-flow amounts are approximately 20–25 L/min (40–50 ft^3/h).[10]

Operation

For most of its applications gas metal arc welding is a fairly simple welding process to learn requiring no more than a week or two to master basic welding technique. Even when welding is performed by well-trained operators weld quality can fluctuate since it depends on a number of external factors. All GMAW is dangerous, though perhaps less so than some other welding methods, such as shielded metal arc welding.[20]



GMAW weld area. **(1)** Direction of travel, **(2)** Contact tube, **(3)** Electrode, **(4)** Shielding gas, **(5)** Molten weld metal, **(6)** Solidified weld metal, **(7)** Workpiece.

Technique

The basic technique for GMAW is quite simple, since the electrode is fed automatically through the torch. By contrast, in gas tungsten arc welding, the welder must handle a welding torch in one hand and a separate filler wire in the other, and in shielded metal arc welding, the operator must frequently chip off slag and change welding electrodes. GMAW requires only that the operator guide the welding gun with proper position and orientation along the area being welded. Keeping a consistent contact tip-to-work distance (the *stick out* distance) is important, because a long stickout distance can cause the electrode to overheat and will also waste shielding gas. Stickout distance varies for different GMAW weld processes and applications.[21] [22] [23] [24] For short-circuit transfer, the stickout is generally 1/4 inch to 1/2 inch, for spray transfer the stickout is generally 1/2 inch. The position of the end of the contact tip to the gas nozzle are related to the stickout distance and also varies with transfer type and application. The orientation of the gun is also important—it should be held so as to bisect the angle between the workpieces; that is, at 45 degrees for a fillet weld and 90 degrees for welding a flat surface. The travel angle, or lead angle, is the angle of the torch with respect to the direction of travel, and it should generally remain approximately vertical. However, the desirable angle changes somewhat depending on the type of shielding gas used—with pure inert gases, the bottom of the torch is often slightly in front of the upper section, while the opposite is true when the welding atmosphere is carbon dioxide.[25]

Quality

Two of the most prevalent quality problems in GMAW are dross and porosity. If not controlled, they can lead to weaker, less ductile welds. Dross is an especially common problem in aluminum GMAW welds, normally coming from particles of aluminum oxide or aluminum nitride present in the electrode or base materials. Electrodes and workpieces must be brushed with a wire brush or chemically treated to remove oxides on the surface. Any oxygen in contact with the weld pool, whether from the atmosphere or the shielding gas, causes dross as well. As a result, sufficient flow of inert shielding gases is necessary, and welding in volatile air should be avoided.[26]

In GMAW the primary cause of porosity is gas entrapment in the weld pool, which occurs when the metal solidifies before the gas escapes. The gas can come from impurities in the shielding gas or on the workpiece, as well as from an excessively long or violent arc. Generally, the amount of gas entrapped is directly related to the cooling rate of the weld pool. Because of its higher thermal conductivity, aluminum welds are especially susceptible to greater cooling rates and thus additional porosity. To reduce it, the workpiece and electrode should be clean, the welding speed diminished and the current set high enough to provide sufficient heat input and stable metal transfer but low enough that the arc remains steady. Preheating can also help reduce the cooling rate in some cases by reducing the temperature gradient between the weld area and the base material.[27]

Safety

Gas metal arc welding can be dangerous if proper precautions are not taken. Since GMAW employs an electric arc, welders wear protective clothing, including heavy leather gloves and protective long sleeve jackets, to avoid exposure to extreme heat and flames. In addition, the brightness of the electric arc is a source of the condition known as arc eye, an inflammation of the cornea caused by ultraviolet light and, in prolonged exposure, possible burning of the retina in the eye. Conventional welding helmets contain dark face plates to prevent this exposure. Newer helmet designs feature a liquid crystal-type face plate that self-darken upon exposure to high amounts of UV light. Transparent welding curtains, made of a polyvinyl chloride plastic film, are often used to shield nearby workers and bystanders from exposure to the UV light from the electric arc.[28]

Welders are also often exposed to dangerous gases and particulate matter. GMAW produces smoke containing particles of various types of oxides, and the size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. Additionally, carbon dioxide and ozone gases can prove dangerous if ventilation is inadequate. Furthermore, because the use of compressed gases in GMAW pose an explosion and fire risk, some common precautions include limiting the amount of oxygen in the air and keeping combustible materials away from the workplace.[29] While porosity usually results from atmospheric contamination, too much shielding gas has a similar effect; if the flow rate is too high it may create a vortex that draws in the surrounding air, thereby contaminating the weld pool as it cools. The gas output should be felt (as a cool breeze) on a dry hand but not enough to create any noticeable pressure, this equates to between 20–25 psi (mild and stainless steel). Above 26 volts the gas debit should be augmented slightly since the weld pool takes longer to cool. As a factor that is often ignored, many flow meters are never adjusted and typically run between 35–45 psi. A healthy reduction of gas will not affect the quality of the weld, will save money on shielding gas and reduce the rate at which the tank must be replaced.

Metal transfer modes

The three transfer modes in GMAW are globular, short-circuiting, and spray. There are a few recognized variations of these three transfer modes including modified short-circuiting and pulsed-spray.[30]

Globular

GMAW with globular metal transfer is often considered the most undesirable of the three major GMAW variations, because of its tendency to produce high heat, a poor weld surface, and spatter. The method was originally developed as a cost efficient way to weld steel using GMAW, because this variation uses carbon dioxide, a less expensive shielding gas than argon. Adding to its economic advantage was its high deposition rate, allowing welding speeds of up to 110 mm/s (250 in/min).[10] As the weld is made, a ball of molten metal from the electrode tends to build up on the end of the electrode, often in irregular shapes with a larger diameter than the electrode itself. When the droplet finally detaches either by gravity or short circuiting, it falls to the workpiece, leaving an uneven surface and often causing spatter.[31] As a result of the large molten droplet, the process is generally limited to flat and horizontal welding positions. The high amount of heat generated also is a downside, because it forces the welder to use a larger electrode wire, increases the size of the weld pool, and causes greater residual stresses and distortion in the weld area.

Short-circuiting

Further developments in welding steel with GMAW led to a variation known as short-circuiting or short-arc GMAW, in which the current is lower than for the globular method. As a result of the lower current, the heat input for the short-arc variation is considerably reduced, making it possible to weld thinner materials while decreasing the amount of distortion and residual stress in the weld area. As in globular welding, molten droplets form on the tip of the electrode, but instead of dropping to the weld pool, they bridge the gap between the electrode and the weld pool as a result of the lower wire feed rate. This causes a short circuit and extinguishes the arc, but it is quickly reignited after the surface tension of the weld pool pulls the molten metal bead off the electrode tip. This process is repeated about 100 times per second, making the arc appear constant to the human eye. This type of metal transfer provides better weld quality and less spatter than the globular variation, and allows for welding in all positions, albeit with slower deposition of weld material. Setting the weld process parameters (volts, amps and wire feed rate) within a relatively narrow band is critical to maintaining a stable arc: generally between 100 to 200 amps at 17 to 22 volts for most applications. Also, using short-arc transfer can result in lack of fusion and insufficient penetration when welding thicker materials, due to the lower arc energy and rapidly freezing weld pool.[32] Like the globular variation, it can only be used on ferrous metals.[10] [33] [34]

Modified short-circuiting

There are proprietary derivatives of the short-circuiting transfer mode which use a modified waveform to reduce some of the problems found with short-circuiting, mainly spatter and a turbulent weld pool. Typically these systems sense the progression of the short circuit as it happens and modulate the current to limit the amount of force behind spatter and turbulence-producing events. Several manufacturers now sell welding power supplies which employ technology to this end: Miller Electric has a process called Regulated Metal Deposition (RMD), while Lincoln Electric sells their process called Surface Tension Transfer (STT). Other companies take a different approach to making short circuit transfer usable: Fronius has a technique called Cold Metal Transfer (CMT) which physically withdraws the electrode from the welding puddle at a certain rate and pattern.

RMD and STT achieve the modified short circuiting via software that controls the current. The RMD process breaks the process into seven steps:

1. **Wet**: Let the ball on the end of the wire wet-out to the puddle.
2. **Pinch**: Increase the current to a level high enough to initiate a pinch effect.

3. **Clear**: Maintain and slightly increase the pinch current to clear the short circuit while simultaneously watching for pinch detection.
4. **Blink**: Upon pinch detection, rapidly decrease the current. Pinch detection occurs before the short clears. The inverter “shuts off” and current decays to a low level before the short circuit breaks.
5. **Ball**: Increase current to form a ball for the next short circuit.
6. **Background**: Drop the current to a low enough level to allow a short circuit to occur.
7. **Pre-short**: If the background current exists for a relatively long time, the pre-short period drops current to an even lower level to make sure arc force does not produce excessive puddle agitation.

Spray

Spray transfer GMAW was the first metal transfer method used in GMAW, and well-suited to welding aluminum and stainless steel while employing an inert shielding gas. In this GMAW process, the weld electrode metal is rapidly passed along the stable electric arc from the electrode to the workpiece, essentially eliminating spatter and resulting in a high-quality weld finish. As the current and voltage increases beyond the range of short circuit transfer the weld electrode metal transfer transitions from larger globules through small droplets to a vaporized stream at the highest energies.[35] Since this vaporized spray transfer variation of the GMAW weld process requires higher voltage and current than short circuit transfer, and as a result of the higher heat input and larger weld pool area (for a given weld electrode diameter), it is generally used only on workpieces of thicknesses above about 6.4 mm (0.25 in).[36] Also, because of the large weld pool, it is often limited to flat and horizontal welding positions and sometimes also used for vertical-down welds. It is generally not practical for root pass welds.[37] When a smaller electrode is used in conjunction with lower heat input, its versatility increases. The maximum deposition rate for spray arc GMAW is relatively high; about 60 mm/s (150 in/min).[10] [10] [38]

Pulsed-spray

A variation of the spray transfer mode, pulse-spray is based on the principles of spray transfer but uses a pulsing current to melt the filler wire and allow one small molten droplet to fall with each pulse. The pulses allow the average current to be lower, decreasing the overall heat input and thereby decreasing the size of the weld pool and heat-affected zone while making it possible to weld thin workpieces. The pulse provides a stable arc and no spatter, since no short-circuiting takes place. This also makes the process suitable for nearly all metals, and thicker electrode wire can be used as well. The smaller weld pool gives the variation greater versatility, making it possible to weld in all positions. In comparison with short arc GMAW, this method has a somewhat slower maximum speed (85 mm/s or 200 in/min) and the process also requires that the shielding gas be primarily argon with a low carbon dioxide concentration. Additionally, it requires a special power source capable of providing current pulses with a frequency between 30 and 400 pulses per second. However, the method has gained popularity, since it requires lower heat input and can be used to weld thin workpieces, as well as nonferrous materials.[10] [39] [40] [41]

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[32] Craig 1991, p. 11
[33] Cary & Helzer 2005, p. 98
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[35] Craig 1991, p. 82
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External links

- ESAB Process Handbook (http://www.esabna.com/EUWeb/MIG_handbook/592mig1_1.htm)
- OSHA Safety and Health Topics- Welding, Cutting, and Brazing (http://www.osha.gov/SLTC/weldingcuttingbrazing/)
- Fume formation rates in gas metal arc welding (http://files.aws.org/wj/supplement/Quimby/ARTICLE5.pdf) - research article from the 1999 Welding Journal
- Edison Welding Institute (http://www.ewi.org)
- GMAW from The Welding Institute (http://www.twi.co.uk/content/jk4.html)

Powder coating

Powder coating is a type of coating that is applied as a free-flowing, dry powder. The main difference between a conventional liquid paint and a powder coating is that the powder coating does not require a solvent to keep the binder and filler parts in a liquid suspension form. The coating is typically applied electrostatically and is then cured under heat to allow it to flow and form a "skin". The powder may be a thermoplastic or a thermoset polymer. It is usually used to create a hard finish that is tougher than conventional paint. Powder coating is mainly used for coating of metals, such as "whiteware", aluminium extrusions, and automobile and bicycle parts. Newer technologies allow other materials, such as MDF (medium-density fibreboard), to be powder coated using different methods.

Aluminium extrusions being powder coated

Advantages and disadvantages

There are several advantages of powder coating over conventional liquid coatings:

1. Powder coatings emit zero or near zero volatile organic compounds (VOC).
2. Powder coatings can produce much thicker coatings than conventional liquid coatings without running or sagging.
3. Powder coating overspray can be recycled and thus it is possible to achieve nearly 100% use of the coating.
4. Powder coating production lines produce less hazardous waste than conventional liquid coatings.
5. Capital equipment and operating costs for a powder line are generally less than for conventional liquid lines.
6. Powder coated items generally have fewer appearance differences between horizontally coated surfaces and vertically coated surfaces than liquid coated items.
7. A wide range of specialty effects is easily accomplished which would be impossible to achieve with other coating processes.

While powder coatings have many advantages over other coating processes, there are some disadvantages to the technology. While it is relatively easy to apply thick coatings which have smooth, texture-free surfaces, it is not as easy to apply smooth thin films. As the film thickness is reduced, the film becomes more and more orange peeled in texture due to the particle size and glass transition temperature (TG) of the powder. Also powder coatings will break down when exposed to UV rays between 5 to 10 years. On smaller jobs, the cost of powder coating will be higher than spray painting.

For optimum material handling and ease of application, most powder coatings have a particle size in the range of 30 to 50 μm and a TG above 40°C. For such powder coatings, film build-ups of greater than 50 μm may be required to obtain an acceptably smooth film. The surface texture which is considered desirable or acceptable depends on the end product. Many manufacturers actually prefer to have a certain degree of orange peel since it helps to hide metal defects that have occurred during manufacture, and the resulting coating is less prone to showing fingerprints.

There are very specialized operations where powder coatings of less than 30 micrometres or with a TG below 40°C are used in order to produce smooth thin films. One variation of the dry powder coating process, the "Powder Slurry" process, combines the advantages of powder coatings and liquid coatings by dispersing very fine powders of 1–5 micrometre particle size into water, which then allows very smooth, low film thickness coatings to be produced.

Powder coatings have a major advantage in that the overspray can be recycled. However, if multiple colors are being sprayed in a single spray booth, this may limit the ability to recycle the overspray.

Types of powder coatings

There are two main categories of powder coatings: thermosets and thermoplastics. The thermosetting variety incorporates a cross-linker into the formulation. When the powder is baked, it reacts with other chemical groups in the powder polymer and increases the molecular weight and improves the performance properties. The thermoplastic variety does not undergo any additional reactions during the baking process, but rather only flows out into the final coating.

The most common polymers used are polyester, polyurethane, polyester-epoxy (known as hybrid), straight epoxy (fusion bonded epoxy) and acrylics.

Production:

1. The polymer granules are mixed with hardener, pigments and other powder ingredients in a mixer
2. The mixture is heated in an extruder
3. The extruded mixture is rolled flat, cooled and broken into small chips
4. The chips are milled to make a fine powder

The powder coating process

The powder coating process involves three basic steps:

1. Part preparation or the pre-treatment
2. The powder application
3. Curing

Part preparation processes and equipment

Removal of oil, soil, lubrication greases, metal oxides, welding scales etc. is essential prior to the powder coating process. It can be done by a variety of chemical and mechanical methods. The selection of the method depends on the size and the material of the part to be powder coated, the type of soil to be removed and the performance requirement of the finished product.

Chemical pre-treatments involve the use of phosphates or chromates in submersion or spray application. These often occur in multiple stages and consist of degreasing, etching, de-smutting, various rinses and the final phosphating or chromating of the substrate. The pre-treatment process both cleans and improves bonding of the powder to the metal. Recent additional processes have been developed that avoid the use of chromates, as these can be toxic to the environment. Titanium zirconium and silanes offer similar performance against corrosion and adhesion of the powder.

Another method of preparing the surface prior to coating is known as abrasive blasting or sandblasting and shot blasting. Blast media and blasting abrasives are used to provide surface texturing and preparation, etching, finishing, and degreasing for products made of wood, plastic, or glass. The most important properties to consider are chemical composition and density; particle shape and size; and impact resistance.

Silicon carbide grit blast media is brittle, sharp, and suitable for grinding metals and low-tensile strength, non-metallic materials. Plastic media blast equipment uses plastic abrasives that are sensitive to substrates such as aluminum, but still suitable for de-coating and surface finishing. Sand blast media uses high-purity crystals that have low-metal content. Glass bead blast media contains glass beads of various sizes.

Cast steel shot or steel grit is used to clean and prepare the surface before coating. Shot blasting recycles the media and is environmentally friendly. This method of preparation is highly efficient on steel parts such as I-beams, angles, pipes, tubes and large fabricated pieces.

Different powder coating applications can require alternative methods of preparation such as abrasive blasting prior to coating. The online consumer market typically offers media blasting services coupled with their coating services at additional costs.

Powder application processes

The most common way of applying the powder coating to metal objects is to spray the powder using an electrostatic gun, or *corona* gun. The gun imparts a positive electric charge on the powder, which is then sprayed towards the grounded object by mechanical or compressed air spraying and then accelerated toward the workpiece by the powerful electrostatic charge. There are a wide variety of spray nozzles available for use in electrostatic coating. The type of nozzle used will depend on the shape of the workpiece to be painted and the consistency of the paint. The object is then heated, and the powder melts into a uniform film, and is then cooled to form a hard coating. It is also common to heat the metal first and spray the powder onto the hot substrate. Preheating can help to achieve a more uniform finish but can also create other problems, such as runs caused by excess powder. See the article "Fusion Bonded Epoxy Coatings"

Another type of gun is called a *tribo* gun, which charges the powder by (triboelectric) friction. In this case, the powder picks up a positive charge while rubbing along the wall of a Teflon tube inside the barrel of the gun. These charged powder particles then adhere to the grounded substrate. Using a tribo gun requires a different formulation of powder than the more common corona guns. Tribo guns are not subject to some of the problems associated with corona guns, however, such as back ionization and the Faraday cage effect.

Example of powder coating spray guns

Powder can also be applied using specifically adapted electrostatic discs.

Another method of applying powder coating, called the fluidized bed method, is by heating the substrate and then dipping it into an aerated, powder-filled bed. The powder sticks and melts to the hot object. Further heating is usually required to finish curing the coating. This method is generally used when the desired thickness of coating is to exceed 300 micrometres. This is how most dishwasher racks are coated.

Electrostatic fluidized bed coating: Electrostatic fluidized bed application uses the same fluidizing technique and the conventional fluidized bed dip process but with much less powder depth in the bed. An electrostatic charging media is placed inside the bed so that the powder material becomes charged as the fluidizing air lifts it up. Charged particles of powder move upward and form a cloud of charged powder above the fluid bed. When a grounded part is passed through the charged cloud the particles will be attracted to its surface. The parts are not preheated as they are for the conventional fluidized bed dip process.

Electrostatic magnetic brush (EMB) coating: an innovative coating method for flat materials that applies powder coating with roller technique, enabling relative high speeds and a very accurate layer thickness between 5 and 100 micrometre. The base for this process is conventional copier technology . Currently in use in some high- tech coating applications and very promising for commercial powder coating on flat substrates (steel, aluminium, MDF, paper, board) as well in sheet to sheet and/or roll to roll processes. This process can potentially be integrated in any existing coating line.

Curing

When a thermoset powder is exposed to elevated temperature, it begins to melt, flows out, and then chemically reacts to form a higher molecular weight polymer in a network-like structure. This cure process, called crosslinking, requires a certain temperature for a certain length of time in order to reach full cure and establish the full film properties for which the material was designed. Normally the powders cure at 200°C (390°F) for 10 minutes. The curing schedule could vary according to the manufacturer's specifications.

The application of energy to the product to be cured can be accomplished by convection cure ovens or infrared cure ovens.

Removing powder coating

Methylene chloride is generally effective at removing powder coating, however most other organic solvents (acetone, thinners, etc.) are completely ineffective. Most recently the suspected human carcinogen methylene chloride is being replaced by benzyl alcohol with great success. Powder coating can also be removed with abrasive blasting. 98% sulfuric acid commercial grade also removes powder coating film. Certain low grade powder coats can be removed with steel wool, though this might be a more labor-intensive process than desired.

See also

- Laser printer
- Fusion bonded epoxy coating
- Sandblasting

External links

- Powder Coating Process Description [1]
- Characteristics of the different types of powder coatings: Polyesters, Enhanced Polyesters, Epoxy, Hybrids, Polyurethane, and Acrylics] [2]

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Anodizing

These inexpensive decorative carabiners have an anodized aluminium surface that has been dyed and are made in many colors.

Anodizing, or **anodising** in British English, is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of metal parts. The process is called "anodizing" because the part to be treated forms the anode electrode of an electrical circuit. Anodizing increases corrosion resistance and wear resistance, and provides better adhesion for paint primers and glues than bare metal. Anodic films can also be used for a number of cosmetic effects, either with thick porous coatings that can absorb dyes or with thin transparent coatings that add interference effects to reflected light. Anodizing is also used to prevent galling of threaded components and to make dielectric films for electrolytic capacitors. Anodic films are most commonly applied to protect aluminium alloys, although processes also exist for titanium, zinc, magnesium, niobium, and tantalum. This process is not a useful treatment for iron or carbon steel because these metals exfoliate when oxidized; i.e. the iron oxide (also known as rust) flakes off, constantly exposing the underlying metal to corrosion.

Anodization changes the microscopic texture of the surface and changes the crystal structure of the metal near the surface. Thick coatings are normally porous, so a sealing process is often needed to achieve corrosion resistance. Anodized aluminium surfaces, for example, are harder than aluminium but have low to moderate wear resistance that can be improved with increasing thickness or by applying suitable sealing substances. Anodic films are generally much stronger and more adherent than most types of paint and metal plating, but also more brittle. This makes them less likely to crack and peel from aging and wear, but more susceptible to cracking from thermal stress.

History

Anodizing was first used on an industrial scale in 1923 to protect Duralumin seaplane parts from corrosion. This early chromic acid process was called the Bengough-Stuart process and was documented in British defence specification DEF STAN 03-24/3. It is still used today despite its legacy requirements for a complicated voltage cycle now known to be unnecessary. Variations of this process soon evolved, and the first sulfuric acid anodizing process was patented by Gower and O'Brien in 1927. Sulfuric acid soon became and remains the most common anodizing electrolyte.[1]

Oxalic acid anodizing was first patented in Japan in 1923 and later widely used in Germany, particularly for architectural applications. Anodized aluminium extrusion was a popular architectural material in the 1960s and 1970s, but has since been displaced by cheaper plastics and powdercoating.[2] The phosphoric acid processes are the most recent major development, so far only used as pretreatments for adhesives or organic paints.[1] A wide variety of proprietary and increasingly complex variations of all these anodizing processes continue to be developed by industry, so the growing trend in military and industrial standards is to classify by coating properties rather than by process chemistry.

Anodized aluminium

Aluminium alloys are anodized to increase corrosion resistance, to increase surface hardness, and to allow dyeing (coloring), improved lubrication, or improved adhesion. The anodic layer is non-conductive.[3]

When exposed to air at room temperature, or any other gas containing oxygen, pure aluminium self-passivates by forming a surface layer of amorphous aluminium oxide 2 to 3 nm thick,[4] which provides very effective protection against corrosion. Aluminium alloys typically form a thicker oxide layer, 5-15 nm thick, but tend to be more susceptible to corrosion. Aluminium alloy parts are anodized to greatly increase the thickness of this layer for corrosion resistance. The corrosion resistance of aluminium alloys is significantly decreased by certain alloying elements or impurities: copper, iron, and silicon,[5] so 2000, 4000, and 6000-series alloys tend to be most susceptible. Some aluminium aircraft parts, architectural materials, and consumer products are anodized. Anodized aluminium can be found on mp3 players, flashlights, cookware, cameras, sporting goods, window frames, roofs, in electrolytic capacitors, and on many other products both for corrosion resistance and the ability to retain dye. Although anodizing only has moderate wear resistance, the deeper pores can better retain a lubricating film than a smooth surface would.

Anodized coatings have a much lower thermal conductivity and coefficient of linear expansion than aluminium. As a result, the coating will crack from thermal stress if exposed to temperatures above 80 °C. The coating can crack, but it will not peel.[6] The melting point of aluminium oxide is 2050 °C, much higher than pure aluminium's 658 °C.[6] (This can make welding more difficult.) In typical commercial aluminium anodization processes, the aluminium oxide is grown down into the surface and out from the surface by equal amounts. So anodizing will increase the part dimensions on each surface by half of the oxide thickness. For example a coating that is (2 μm) thick, will increase the part dimensions by (1 μm) per surface. If the part is anodized on all sides, then all linear dimensions will increase by the oxide thickness. Anodized aluminium surfaces are harder than aluminium but have low to moderate wear resistance, although this can be improved with thickness and sealing.

Process

Preceding the anodization process, wrought alloys are cleaned in either a hot soak cleaner or in a solvent bath and may be etched in sodium hydroxide (normally with added sodium gluconate), ammonium bifluoride or brightened in a mix of acids. Cast alloys are normally best just cleaned due to the presence of intermetallic substances unless they are a high purity alloy such as LM0.

The anodized aluminium layer is grown by passing a direct current through an electrolytic solution, with the aluminium object serving as the anode (the positive electrode). The current releases hydrogen at the cathode (the negative electrode) and oxygen at the surface of the aluminium anode, creating a build-up of aluminium oxide. Alternating current and pulsed current is also possible but rarely used. The voltage required by various solutions may range from 1 to 300 V DC, although most fall in the range of 15 to 21 V. Higher voltages are typically required for thicker coatings formed in sulfuric and organic acid. The anodizing current varies with the area of aluminium being anodized, and typically ranges from 0.3 to 3 amperes of current per square decimeter (20 to 200 mA/in^2).

Aluminium anodizing is usually performed in an acid solution which slowly dissolves the aluminium oxide. The acid action is balanced with the oxidation rate to form a coating with nanopores, 10-150 nm in diameter.[6] These pores are what allows the electrolyte solution and current to reach the aluminium substrate and continue growing the coating to greater thickness beyond what is produced by autopassivation.[7] However, these same pores will later permit air or water to reach the substrate and initiate corrosion if not sealed. They are often filled with colored dyes and/or corrosion inhibitors before sealing. Because the dye is only superficial, the underlying oxide may continue to provide corrosion protection even if minor wear and scratches may break through the dyed layer.

Conditions such as electrolyte concentration, acidity, solution temperature, and current must be controlled to allow the formation of a consistent oxide layer. Harder, thicker films tend to be produced by more dilute solutions at lower temperatures with higher voltages and currents. The film thickness can range from under 0.5 micrometers for bright decorative work up to 150 micrometers for architectural applications.

The most widely used anodizing specification, MIL-A-8625, defines three types of aluminium anodization. Type I is Chromic Acid Anodization, Type II is Sulfuric Acid Anodization and Type III is sulfuric acid hardcoat anodization. Other anodizing specifications include MIL-A-63576, AMS 2469, AMS 2470, AMS 2471, AMS 2472, AMS 2482, ASTM B580, ASTM D3933, ISO 10074 and BS 5599. AMS 2468 is obsolete. None of these specifications define a detailed process or chemistry, but rather a set of tests and quality assurance measures which the anodized product must meet. BS 1615 provides guidance in the selection of alloys for anodizing. For British defence work, a detailed chromic and sulfuric anodizing processes are described by DEF STAN 03-24/3 and DEF STAN 03-25/3 respectively.

Chromic acid anodizing (Type I)

The oldest anodizing process uses chromic acid. It is widely known as the Bengough-Stuart process. In North America it is known as Type I because it is so designated by the MIL-A-8625 standard, but it is also covered by AMS 2470 and MIL-A-8625 Type IB. In the UK it is normally specified as Def Stan 03/24 and used in areas that are prone to come into contact with propellants etc. There are also Boeing and Airbus standards. Chromic acid produces thinner, 0.5 μm to 18 μm (0.00002" to 0.0007")[8] more opaque films that are softer, ductile, and to a degree self-healing. They are harder to dye and may be applied as a pretreatment before painting. The method of film formation is different from using sulfuric acid in that the voltage is ramped up through the process cycle.

Sulfuric acid anodizing (Type II & III)

Sulfuric acid is the most widely used solution to produce anodized coating. Coatings of moderate thickness 1.8 μm to 25 μm (0.00007" to 0.001")[8] are known as Type II in North America, as named by MIL-A-8625, while coatings thicker than 25 μm (0.001") are known as Type III, hardcoat, hard anodizing, or engineered anodizing. Very thin coatings similar to those produced by chromic anodizing are known as Type IIB. Thick coatings require more process control,[6] and are produced in a refrigerated tank near the freezing point of water with higher voltages than the thinner coatings. Hard anodizing can be made between 13 and 150 μm (0.0005" to 0.006") thick. Anodizing thickness increases wear resistance, corrosion resistance, ability to retain lubricants and PTFE coatings, and electrical and thermal insulation. Standards for thin (Soft/Standard) sulfuric anodizing are given by MIL-A-8625 Types II and IIB, AMS 2471 (undyed), and AMS 2472 (dyed), BS EN ISO 12373/1 (decorative), BS EN 3987 (Architectural) . Standards for thick sulfuric anodizing are given by MIL-A-8625 Type III, AMS 2469, BS 5599, BS EN 2536 and the obsolete AMS 2468 and DEF STAN 03-26/1.

Organic acid anodizing

Anodizing can produce yellowish integral colors without dyes if it is carried out in weak acids with high voltages, high current densities, and strong refrigeration.[6] Shades of color are restricted to a range which includes pale yellow, gold, deep bronze, brown, grey, and black. Some advanced variations can produce a white coating with 80% reflectivity. The shade of color produced is sensitive to variations in the metallurgy of the underlying alloy and cannot be reproduced consistently.[2]

Anodization in some organic acids, for example Malic Acid, can enter a 'runaway' situation, in which the current drives the acid to attack the aluminum far more aggressively than normal, resulting in huge pits and scarring. Also, if the current or voltage are driven too high, 'burning' can set in; in this case the supplies act as if nearly shorted and large, uneven and amorphous black regions develop.

Integral color anodizing is generally done with organic acids, but the same effect has been produced in laboratory with very dilute sulfuric acid. Integral color anodizing was originally performed with oxalic acid, but sulfonated aromatic compounds containing oxygen, particularly sulfosalicylic acid, have been more common since the 1960s.[2] Thicknesses up to 50μm can be achieved. Organic acid anodizing is called Type IC by MIL-A-8625.

Phosphoric acid anodizing

Anodizing can be carried out in phosphoric acid, usually as a surface preparation for adhesives. This is described in standard ASTM D3933.

Borate and tartrate baths

Anodizing can also be performed in borate or tartrate baths in which aluminium oxide is insoluble. In these processes, the coating growth stops when the part is fully covered, and the thickness is linearly related to the voltage applied.[6] These coatings are free of pores, relative to the sulfuric and chromic acid processes.[6] This type of coating is widely used to make electrolytic capacitors, because the thin aluminium films (typically less than 0.5 μm) would risk being pierced by acidic processes.[1]

Plasma electrolytic oxidation

Plasma electrolytic oxidation is a similar process, but where higher voltages are applied. This causes sparks to occur, and results in more crystalline/ceramic type coatings.

Other metals

Anodized titanium

selected colors achievable through anodization of titanium.

Anodized titanium is used in a recent generation of dental implants. An anodized oxide layer has a thickness in the range of 500 to 1000 angstroms (50 to 100 nm), much thicker than that for a naturally formed oxide layer, which has a range of 50 to 250 angstroms.

Titanium anodic films cannot be made thicker than about 300 nm, and are therefore susceptible to mechanical damage.[9] Standards for titanium anodizing are given by AMS 2487 and AMS 2488.

Anodizing titanium generates an array of different colors without dyes, for which it is sometimes used in art, costume jewelry, body piercing jewelry and wedding rings. The color formed is dependent on the thickness of the oxide (which is determined by the anodizing voltage); it is caused by the interference of light reflecting off the oxide surface with light traveling through it and reflecting off the underlying metal surface. Titanium nitride coatings can also be formed, which have a brown or golden color and have the same wear and corrosion benefits as anodization.

Anodized magnesium

Magnesium is anodized primarily as a primer for paint. A thin (5μm) film is sufficient for this.[9] Thicker coatings of 25μm and up can provide mild corrosion resistance when sealed with oil, wax, or sodium silicate.[9] Standards for magnesium anodizing are given in AMS 2466, AMS 2478, AMS 2479, and ASTM B893.

Anodized zinc

Zinc is rarely anodized, but a process was developed by the International Lead Zinc Research Organization and covered by MIL-A-81801.[9] A solution of ammonium phosphate, chromate and fluoride with voltages of up to 200V can produce olive green coatings up to 80μm thick.[9] The coatings are hard and corrosion resistant.

Anodized niobium

Niobium anodizes in a similar fashion to titanium with a range of attractive colors being formed by interference at different film thicknesses. Again the film thickness is dependent on the anodising voltage.[10] [11] Uses include jewelry and commemorative coins.

Anodized tantalum

Tantalum anodizes in a similar fashion to titanium and niobium with a range of attractive colors being formed by interference at different film thicknesses. Again the film thickness is dependent on the anodizing voltage and typically ranges from 18-23 Angstroms per volt depending on electrolyte and temperature. Uses include Tantalum capacitors

Dyeing

The most common anodizing processes, for example sulfuric acid on aluminium, produce a porous surface which can accept dyes easily. The number of dye colors is almost endless; however, the colors produced tend to vary according to the base alloy. Though some may prefer lighter colors, in practice they may be difficult to produce on certain alloys such as high-silicon casting grades and 2000-series aluminium-copper alloys. Another concern is the "lightfastness" of organic dyestuffs—some colors (reds and blues) are particularly prone to fading. Black dyes and gold produced by inorganic means (ferric ammonium oxalate) are more lightfast. Dyed anodizing is usually sealed to reduce or eliminate dye bleed out.

Colored iPod Mini cases are dyed following anodization and before thermal sealing

Alternatively, metal (usually tin) can be electrolytically deposited in the pores of the anodic coating to provide colors that are more lightfast. Metal dye colors range from pale champagne to black. Bronze shades are commonly used for architectural use.

Alternatively the color may be produced integral to the film. This is done during the anodizing process using organic acids mixed with the sulfuric electrolyte and a pulsed current.

Splash effects are created by dying the unsealed porous surface in lighter colors and then splashing darker color dyes onto the surface. Aqueous and solvent based dye mixtures may also be alternately applied since the colored dyes will resist each other and leave spotted effects.

Printing

Photo quality images and graphics in vivid color may be printed into the unsealed porous oxide layer using color dyes via silkscreen, sublimation transfer or digital printer. Line art quality graphics can be achieved by use of a printer. Color graphics may also be directly applied by hand using an airbrush, sponge or paintbrush. Printed anodizing is sealed to prevent or reduce dye bleed out. Uses include baseball bats, signs, furniture, surgical trays, motorcycle components, and architectural moulding.

Sealing

Acidic anodizing solutions produce pores in the anodized coating. These pores can absorb dyes and retain lubricants, but are also an avenue for corrosion. When lubrication properties are not critical, they are usually sealed after dyeing to increase corrosion resistance and dye retention. Long immersion in boiling-hot deionized water or steam is the simplest sealing process, although it is not completely effective and reduces abrasion resistance by 20%.[6] The oxide is converted into its hydrated form, and the resulting swelling reduces the porosity of the surface. Cold sealing, where the pores are closed by impregnation of a sealant in a room-temperature bath, is more popular due to energy savings. Coatings sealed in this method are not suitable for adhesive bonding. Teflon, nickel acetate, cobalt acetate, and hot sodium or potassium dichromate seals are commonly used. MIL-A-8625 requires sealing for thin coatings (Types I and II) and allows it as an option for thick ones (Type III).

Cleaning

Anodized aluminium used in areas that are exposed to the elements should be cleaned or restored every two years. Anodized aluminium surfaces are susceptible to Panel Edge Staining, a unique type of surface staining that can affect the structural integrity of the metal.

Environmental impact

Anodizing is one of the more environmentally-friendly metal finishing processes. With the exception of organic (aka integral color) anodizing, the by-products do not contain heavy metals, halogens or volatiles. The most common anodizing effluents, aluminium hydroxide and aluminium sulfate, are recycled for the manufacturing of alum, baking powder, cosmetics, newsprint and fertilizer or used by industrial wastewater treatment systems.[12]

Mechanical considerations

Anodizing will raise the surface, since the oxide created occupies more space than the base metal converted. This will generally not be of consequence except in the case of small holes threaded to accept screws. Anodizing may cause the screws to bind, thus the threaded holes may need to be chased with a tap to restore the original dimensions. Alternately, special oversize taps may be used to precompensate for this growth. In the case of unthreaded holes that accept fixed diameter pins or rods a slightly oversized hole to allow for the dimension change may be appropriate.

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External links

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Screen-printing

Part of the series on the **History of printing**	
Woodblock printing	200
Movable type	1040
Printing press	1454
Lithography	1796
Laser printing	1969
Thermal printing	circa 1972

Screen printing is a printing technique that uses a woven mesh to support an ink-blocking stencil. The attached stencil forms open areas of mesh that transfer ink or other printable materials which can be pressed through the mesh as a sharp-edged image onto a substrate. A roller or squeegee is moved across the screen stencil, forcing or pumping ink past the threads of the woven mesh in the open areas.

A silk screen design.

Screen printing is also a stencil method of print making in which a design is imposed on a screen of silk or other fine mesh, with blank areas coated with an impermeable substance, and ink is forced through the mesh onto the printing surface. It is also known as **silkscreen**, **seriography**, and **serigraph**.

Etymology

This information may not be as accurate as it seems. There is considerable and semantic discussion about the process, and the various terms for what is essentially the same technique. Much of the current confusion is based on the popular traditional reference to the process of *screen printing* as *silkscreen printing*. Traditionally silk was used for screen-printing, hence the name silk screening. Currently, synthetic threads are commonly used in the screen printing process. The most popular mesh in general use is made of polyester. There are special-use mesh materials of nylon and stainless steel available to the screen printer.

Encyclopedia references, encyclopedias and trade publications also use an array of spellings for this process with the two most often encountered English spellings as, *screenprinting* spelled as a single undivided word, and the more popular two word title of *screen printing* without hyphenation.

History

Screen printing first appeared in a recognizable form in China during the Song Dynasty (960–1279 AD).[1] [2] Japan and other Asian countries adopted this method of printing and advanced the craft using it in conjunction with block printing and hand applied paints.

Screen printing was largely introduced to Western Europe from Asia sometime in the late 18th century, but did not gain large acceptance or use in Europe until silk mesh was more available for trade from the east and a profitable outlet for the medium discovered.

Screen printing was first patented in England by Samuel Simon in 1907.[2] [3] It was originally used as a popular method to print expensive wall paper, printed on linen, silk, and other fine fabrics. Western screen printers developed reclusive, defensive and exclusionary business policies intended to keep secret their workshops' knowledge and techniques.[4]

Early in the 1910s, several printers experimenting with photo-reactive chemicals used the well-known actinic light activated cross linking or hardening traits of potassium, sodium or ammonium Chromate and dichromate chemicals with glues and gelatin compounds. Roy Beck, Charles Peter and Edward Owens studied and experimented with chromic acid salt sensitized emulsions for photo-reactive stencils. This trio of developers would prove to revolutionize the commercial screen printing industry by introducing photo-imaged stencils to the industry, though the acceptance of this method would take many years. Commercial screen printing now uses sensitizers far safer and less toxic than bichromates. Currently there are large selections of pre-sensitized and "user mixed" sensitized emulsion chemicals for creating photo-reactive stencils.[4]

Joseph Ulano founded the industry chemical supplier Ulano and in 1928 created a method of applying a lacquer soluble stencil material to a removable base. This stencil material was cut into shapes, the print areas removed and the remaining material adhered to mesh to create a sharp edged screen stencil.[5]

Originally a profitable industrial technology, screen printing was eventually adopted by artists as an expressive and conveniently repeatable medium for duplication well before the 20th century. It is currently popular both in fine arts and in commercial printing, where it is commonly used to print images on Posters, T-shirts, hats, CDs, DVDs, ceramics, glass, polyethylene, polypropylene, paper, metals, and wood.

A group of artists who later formed the National Serigraphic Society coined the word Serigraphy in the 1930s to differentiate the artistic application of screen printing from the industrial use of the process.[6] "Serigraphy" is a combination word from the Latin word "Seri" (silk) and the Greek word "graphein" (to write or draw).[7]

The Printer's National Environmental Assistance Center says "Screenprinting is arguably the most versatile of all printing processes."[8] Since rudimentary screenprinting materials are so affordable and readily available, it has been used frequently in underground settings and subcultures, and the non-professional look of such DIY culture screenprints have become a significant cultural aesthetic seen on movie posters, record album covers, flyers, shirts, commercial fonts in advertising, in artwork and elsewhere.

History 1960s to present

Credit is generally given to the artist Andy Warhol for popularizing screen printing identified as serigraphy, in the United States. Warhol is particularly identified with his 1962 depiction of actress Marilyn Monroe screen printed in garish colours.[9] [10]

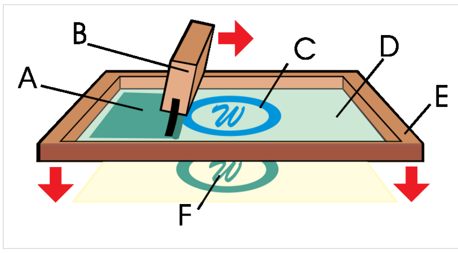
American entrepreneur, artist and inventor Michael Vasilantone would start to use, develop, and sell a rotary multicolour garment screen printing machine in 1960. Vasilantone would later file for patent[11] on his invention in 1967 granted number 3,427,964 on February 18, 1969.[11] The original rotary machine was manufactured to print logos and team information on bowling garments but soon directed to the new fad of printing on t-shirts. The Vasilantone patent was licensed by multiple manufacturers, the resulting production and boom in printed t-shirts made the rotary *garment* screen printing machine the most popular device for screen printing in the industry. Screen printing on garments currently accounts for over half of the screen printing activity in the United States.[12]

In June 1986, Marc Tartaglia, Marc Tartaglia Jr. and Michael Tartaglia created a silk screening device which is defined in its US Patent Document as, "Multi-colored designs are applied on a plurality of textile fabric or sheet materials with a silk screen printer having seven platens arranged in two horizontal rows below a longitudinal heater which is movable across either row." This invention received the patent number 4,671,174 on June 9, 1987, however the patent no longer exists.

Graphic screenprinting is widely used today to create many mass or large batch produced graphics, such as posters or display stands. Full colour prints can be created by printing in CMYK (cyan, magenta, yellow and black ('key')). Screenprinting is often preferred over other processes such as dye sublimation or inkjet printing because of its low cost and ability to print on many types of media.

Screen printing lends itself well to printing on canvas. Andy Warhol, Rob Ryan, Blexbolex, Arthur Okamura, Robert Rauschenberg, Harry Gottlieb, and many other artists have used screen printing as an expression of creativity and artistic vision.

Printing technique



A screen is made of a piece of porous, finely woven fabric called mesh stretched over a frame of aluminium or wood. Originally human hair then silk was woven into screen mesh; currently most mesh is made of man-made materials such as steel, nylon, and polyester. Areas of the screen are blocked off with a non-permeable material to form a stencil, which is a negative of the image to be printed; that is, the open spaces are where the ink will appear.

The screen is placed atop a substrate such as paper or fabric. Ink is placed on top of the screen, and a fill bar (also known as a floodbar) is used to fill the mesh openings with ink. The operator begins with the fill bar at the rear of the screen and behind a reservoir of ink. The operator lifts the screen to prevent contact with the substrate and then using a slight amount of downward force pulls the fill bar to the front of the screen. This effectively fills the mesh openings with ink and moves the ink reservoir to the front of the screen. The operator then uses a squeegee (rubber blade) to move the mesh down to the substrate and pushes the squeegee to the rear of the screen. The ink that is in the mesh opening is pumped or squeezed by capillary action to the substrate in a controlled and prescribed amount, i.e. the wet ink deposit is proportional to the thickness of the mesh and or stencil. As the squeegee moves toward the rear of the screen the tension of the mesh pulls the mesh up away from the substrate (called snap-off) leaving the ink upon the substrate surface.

There are three common types of screenprinting presses. The 'flat-bed', 'cylinder', and the most widely used type, the 'rotary'.[8]

Textile items printed with multi-colour designs often use a wet on wet technique, or colors dried while on the press, while graphic items are allowed to dry between colours that are then printed with another screen and often in a different color after the product is re-aligned on the press.

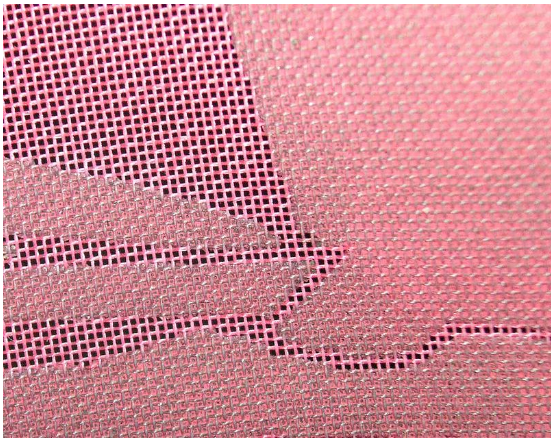
The screen can be re-used after cleaning. However if the design is no longer needed, then the screen can be "reclaimed"; that is, cleared of all emulsion and used again. The reclaiming process involves removing the ink from the screen then spraying on a stencil remover. Stencil removers come in the form of liquids, gels, or powders. The powdered types have to be mixed with water before use, and so can be considered to belong to the liquid category. After applying the stencil remover, the emulsion must be washed out using a pressure washer.

Most screens are ready for recoating at this stage, but sometimes screens will have to undergo a further step in the reclaiming process called dehazing. This additional step removes haze or "ghost images" left behind in the screen once the emulsion has been removed. Ghost images tend to faintly outline the open areas of previous stencils, hence the name. They are the result of ink residue trapped in the mesh, often in the knuckles of the mesh (the points where threads cross).[13]

While the public thinks of garments in conjunction with screenprinting, the technique is used on tens of thousands of items, including decals, clock and watch faces, balloons, and many other products. The technique has even been adapted for more advanced uses, such as laying down conductors and resistors in multi-layer circuits using thin ceramic layers as the substrate.

Stenciling techniques

There are several ways to create a stencil for screenprinting. An early method was to create it by hand in the desired shape, either by cutting the design from a non-porous material and attaching it to the bottom of the screen, or by painting a negative image directly on the screen with a filler material which became impermeable when it dried. For a more painterly technique, the artist would choose to paint the image with drawing fluid, wait for the image to dry, and then coat the entire screen with screen filler. After the filler had dried, water was used to spray out the screen, and only the areas that were painted by the drawing fluid would wash away, leaving a stencil around it. This process enabled the artist to incorporate their hand into the process, to stay true to their drawing.



A macro photo of a screenprint with a photographically produced stencil. The ink will be printed where the stencil does not cover the substrate.

A method that has increased in popularity over the past 70 years is the photo emulsion technique:

1. The original image is created on a transparent overlay such as acetate or tracing paper. The image may be drawn or painted directly on the overlay, photocopied, or printed with an inkjet or laser printer, as long as the areas to be inked are opaque. A black-and-white positive may also be used (projected on to the screen). However, unlike traditional platemaking, these screens are normally exposed by using film positives.
2. A screen must then be selected. There are several different mesh counts that can be used depending on the detail of the design being printed. Once a screen is selected, the screen must be coated with emulsion and let to dry in the dark. Once dry, the screen is ready to be burned/exposed.
3. The overlay is placed over the emulsion-coated screen, and then exposed with a light source containing ultraviolet light in the 350-420 nanometer spectrum. The UV light passes through the clear areas and create a polymerization (hardening) of the emulsion.
4. The screen is washed off thoroughly. The areas of emulsion that were not exposed to light dissolve and wash away, leaving a negative stencil of the image on the mesh.

Photographic screens can reproduce images with a high level of detail, and can be reused for tens of thousands of copies. The ease of producing transparent overlays from any black-and-white image makes this the most convenient method for artists who are not familiar with other printmaking techniques. Artists can obtain screens, frames, emulsion, and lights separately; there are also preassembled kits, which are especially popular for printing small items such as greeting cards.

Another advantage of screenprinting is that large quantities can be produced rapidly with new automatic presses, up to 1800 shirts in 1 hour.[14] The current speed loading record is 1805 shirts printed in one hour, documented on 18 February 2005. Maddie Sikorski of the New Buffalo Shirt Factory in Clarence, New York (USA) set this record at the Image Wear Expo in Orlando, Florida, USA, using a 12-colour M&R Formula Press and an M&R Passport Automatic Textile Unloader.with The world speed record represents a speed that is over four times the typical average speed for manual loading of shirts for automated screen printing.[12]

Screenprinting materials

Caviar beads

again a glue is printed in the shape of the design, to which small plastic beads are then applied – works well with solid block areas creating an interesting tactile surface.

Discharge inks

used to print lighter colours onto dark background fabrics, they work by removing the dye in the garment – this means they leave a much softer texture. They are less graphic in nature than plastisol inks, and exact colours are difficult to control, but especially good for distressed prints and underbasing on dark garments that are to be printed with additional layers of plastisol.

Expanding ink (puff)

an additive to plastisol inks which raises the print off the garment, creating a 3D feel.

Flocking

consists of a glue printed onto the fabric and then foil or flock (or other special effect) material is applied for a mirror finish or a velvet touch.

Four colour process or the CMYK color model

artwork is created and then separated into four colours (CMYK) which combine to create the full spectrum of colours needed for photographic prints. This means a large number of colours can be simulated using only 4 screens, reducing costs, time, and set-up. The inks are required to blend and are more translucent, meaning a compromise with vibrancy of colour.

Glitter/Shimmer

metallic flakes are suspended in the ink base to create this sparkle effect. Usually available in gold or silver but can be mixed to make most colours.

Gloss

a clear base laid over previously printed inks to create a shiny finish.

Metallic

similar to glitter, but smaller particles suspended in the ink. A glue is printed onto the fabric, then nanoscale fibers applied on it.

Mirrored silver

Another solvent based ink, but you can almost see your face in it.

Nylobond

a special ink additive for printing onto technical or waterproof fabrics.

Plastisol

the most common ink used in commercial garment decoration. Good colour opacity onto dark garments and clear graphic detail with, as the name suggests, a more plasticized texture. This print can be made softer with special additives or heavier by adding extra layers of ink. Plastisol inks require heat (approx. 150°C (300°F) for many inks) to cure the print.

PVC and Phthalate Free

relatively new breed of ink and printing with the benefits of plastisol but without the two main toxic components - soft feeling print.

Suede Ink

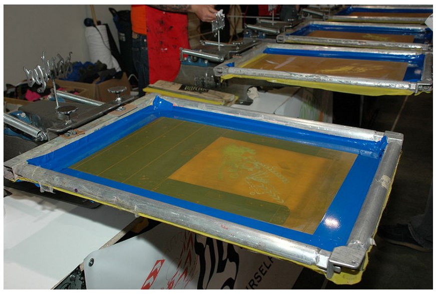
Suede is a milky coloured additive that is added to plastisol. With suede additive you can make any colour of plastisol have a suede feel. It is actually a puff blowing agent that does not bubble as much as regular puff ink.

The directions vary from manufacturer to manufacturer, but generally you can add up to 50% suede additive to your normal plastisol.

Water-Based inks

these penetrate the fabric more than the plastisol inks and create a much softer feel. Ideal for printing darker inks onto lighter coloured garments. Also useful for larger area prints where texture is important. Some inks require heat or an added catalyst to make the print permanent.

Versatility



Screenprinting is more versatile than traditional printing techniques. The surface does not have to be printed under pressure, unlike etching or lithography, and it does not have to be planar. Screenprinting inks can be used to work with a variety of materials, such as textiles, ceramics, wood, paper, glass, metal, and plastic. As a result, screenprinting is used in many different industries, including:

- Balloons
- Clothing
- Medical devices
- Printed electronics, including circuit board printing
- Product labels
- Signs and displays
- Snowboard graphics
- Textile fabric
- Thick film technology

Semiconducting material

In screen printing on wafer-based solar PV cells, the mesh and buses of silver are printed on the front; furthermore, the buses of silver are printed on the back. Subsequently, aluminum paste is dispensed over the whole surface of the back for passivation and surface reflection.[15] One of the parameters that can vary and can be controlled in screen printing is the thickness of the print. This makes it useful for some of the techniques of printing solar cells, electronics etc.

One of the most critical processes to maintain high yield. Solar wafers are becoming thinner and larger, so careful printing is required to maintain a lower breakage rate. On the other hand, high throughput at the printing stage improves the throughput of the whole cell production line.[15]

Garment decoration, modern application notes

Traditionally production garment decoration has relied on screen printing for printing designs on garments including t-shirts; recently, new methods and technologies have become available. Digital printing directly onto garments using modified consumer-quality, and task-specific designed inkjet printers. Screen printing, however, has remained an attractive, cost effective and high production-rate method of printing designs onto garments. Digital printing directly onto garments is referred to as DTG or DTS representing Direct To Garment or Direct To Shirt. DTG or DTS direct printing has advantages and disadvantages compared to screen printing. One noted advantage of DTG/DTS is number of visually perceived colors and the obvious photo-reproduction and photo-like print. DTG/DTS is often WYSIWYG an acronym for What You See Is What You Get, whereas screen printing often requires skilled artistic modification and then must be photo reproduced onto screens and printed. DTG/DTS has the advantage of quick one-off designs and small quantity orders where the screen printing process involves several independent time consuming steps. Screen printing is a production method and quickly overtakes DTG/DTS in cost per print as the higher the volume the lower cost per print becomes, screen printing also has the advantage of a large selection of different types of inks that are all considerably less expensive per garment than DTG/DTS inks.

Screen printing press

To efficiently print multiple copies of the screen design on garments, amateur and professional printers usually use a screen printing press. Many companies offer simple to sophisticated printing presses. Most of these presses are manual. A few that are industrial-grade-automatic printers require minimal manual labor and increase production significantly.

See also

- Dye
- Glass
- Ink jet
- Multi-layer
- Metal
- Plastic
- Printed electronics
- Printed T-shirt
- Roll-to-roll printing.
- Seriolithograph
- Textile printing

Notes

[1] http://www.jstor.org/pss/4629553
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[14] http://www.mrprint.com/EN/News.aspx?id=1129
[15] http://www.omron-semi-pv.eu/en/wafer-based-pv/front-end/screen-printing.html

External links

- http://www.fespa.com/- The Federation of European Screen Printers Associations
- http://www.sgia.org/- SGIA - Specialty Graphic Imaging Association

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