ADVANCED MANUFACTURING TECHNOLOGIES: POLYMER MECHANICS, FDM AND EDM PROCESSES

Editor

HAKAN ADATEPE

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DIE-SINKING EDM PROCESS: SYSTEM COMPONENTS, PARAMETERS, AND THERMOMECHANICAL SURFACE EFFECTS

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1. INTRODUCTION

The production of components with complex geometries, high hardness, and difficult-to-machine characteristics presents several limitations when conventional manufacturing methods are employed. Moreover, the increasing demand for hard-to-machine materials such as tool steels, carbides, superalloys, and titanium alloys in the automotive, aerospace, electronics, optics, medical device, and communication industries has made the evolution and advancement of manufacturing processes a necessity [1–3]. Electrical Discharge Machining (EDM) is a non-traditional manufacturing process that has gained widespread application in contemporary production technologies [4,5]. Developed in the early

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1940s, this manufacturing method is based on melting and shaping the workpiece material through a series of repetitive electrical discharges between the electrode and the workpiece within a dielectric fluid. EDM, in general, operates as a thermal-erosion manufacturing process in which material is removed from the workpiece surface under the influence and controlled direction of electrical energy [6,7].

Although the concept of melting material through electrical sparks was first considered around 1770 by the English scientist Joseph Priestley, the first EDM device was developed during the Second World War in 1943 by the Russian researchers B.R. and N.I. Lazarenko at Moscow University [5]. By the 1980s, significant advancements in machining efficiency were achieved with the emergence of Computer Numerical Control (CNC) systems and their integration into EDM machines. These substantial advantages of the EDM process were highly demanded by the manufacturing industry, which at that time was seeking economical solutions and effective methods for producing parts with complex geometries, and this demand continues today. In addition, the capability to increase the number of electrodes and to manage task changes during the same machining operation through computer-controlled systems was achieved. The development and continuous innovation of control systems have expanded the industrial applicability of EDM, transforming it into a precise and reliable material-removal technique. Since there is no physical contact between the electrode and the workpiece during the EDM process, and no cutting forces are applied, the deformation issues commonly encountered in conventional machining methods—such as mechanical stresses, vibrations, and loss of dimensional accuracy do not occur on the processed material [8]. Material can be machined regardless of its hardness, provided that it is electrically conductive. In this respect, the method is effectively utilized for machining difficult-to-process materials such as ceramics and titanium alloys [9]. Moreover, EDM is an effective method for machining materials that require high dimensional accuracy. It enables the drilling of precise holes on inclined and curved surfaces. In addition to offering significant advantages in the production of complex three-dimensional machine components, the EDM process has sometimes been regarded as the sole feasible option for manufacturing such geometries. Overall, the EDM manufacturing method provides notable advantages in terms of technique, time, and cost for producing components that cannot be achieved through conventional machining processes [10,11].

In parallel with the development of EDM technology, a wide range of sub-methods that adhere to its fundamental principles have emerged, resulting in substantial diversification of the process. Based on the electrical-discharge (spark) principle, which enables the controlled erosion of electrically conductive materials, this method has been expanded through various similar or variant processes such as die-sinking EDM, wire electrical discharge machining (WEDM), electrical discharge drilling (EDD), electrical discharge turning (EDT), wire electrical discharge turning (WEDT), and their micro-scale derivatives, including μ-EDM, μ-WEDM, and μ-EDD.

2. WORKING PRINCIPLE OF DIE-SINKING EDM

2.1. Electrical Discharge Formation

Die-sinking, or sinker EDM, is commonly defined in the literature as the conventional EDM process. In the EDM material-removal mechanism, the erosion of electrically conductive materials is based on the controlled utilization of thermoelectric energy. This method is widely preferred, particularly for the manufacturing of machine components with complex geometries. To transfer the desired shape onto the workpiece, the electrode must be prepared to carry the negative form of the target geometry [12,13]. The fundamental components of the die-sinking EDM machine are shown in Figure 1.

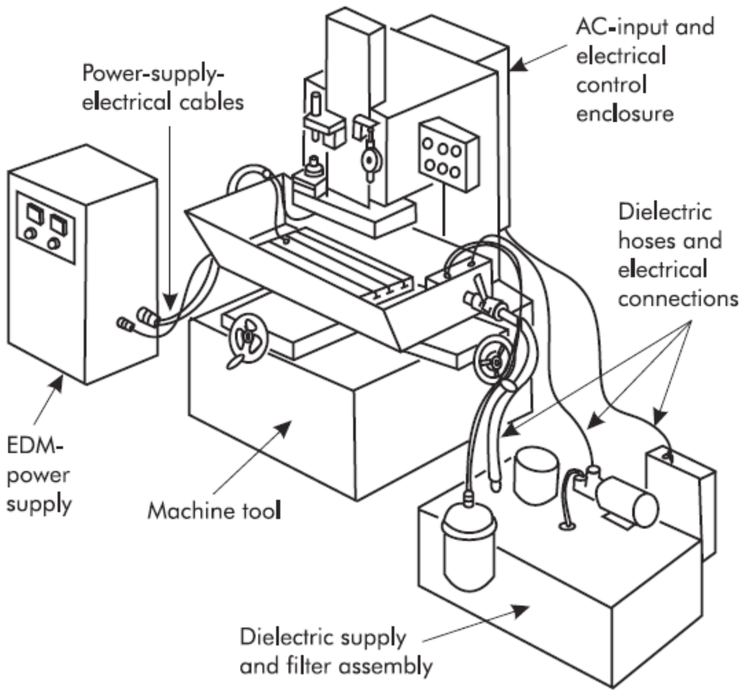

Figure 1. Die-sinking EDM machine [14]

During the process, a high electrical voltage is applied between the electrode and the workpiece, which is immersed in a dielectric insulating fluid. The successive electrical discharges at this voltage result in localized material removal (MR) on the workpiece surface. The electric field concentrates at the smallest gap between the electrode and the workpiece, causing the voltage to rise; however, at this stage, no current is yet formed. Over time, ionization increases, and the dielectric fluid's insulating capability weakens within a channel that narrows toward the center of the field. When the voltage reaches its peak, the current remains zero; after a short delay, the voltage begins to decrease while the current rapidly increases, during which localized melting occurs on the workpiece surface. The discharge current is converted into a high amount of thermal energy within the dielectric fluid. This energy forms a plasma channel between the electrode and the workpiece, with temperatures reaching 8000–12,000 °C. The plasma channel rapidly heats the material and removes a certain amount of molten metal from the surface, thereby performing the material-removal process. The direct current (DC) power supply generates pulse currents at approximately 20,000–30,000 Hz. When the current pulse terminates, the plasma channel rapidly collapses, the temperature decreases, and the dielectric fluid refills the gap; during this stage, the molten metal particles are flushed from the machining zone by the fluid [4,14,15].

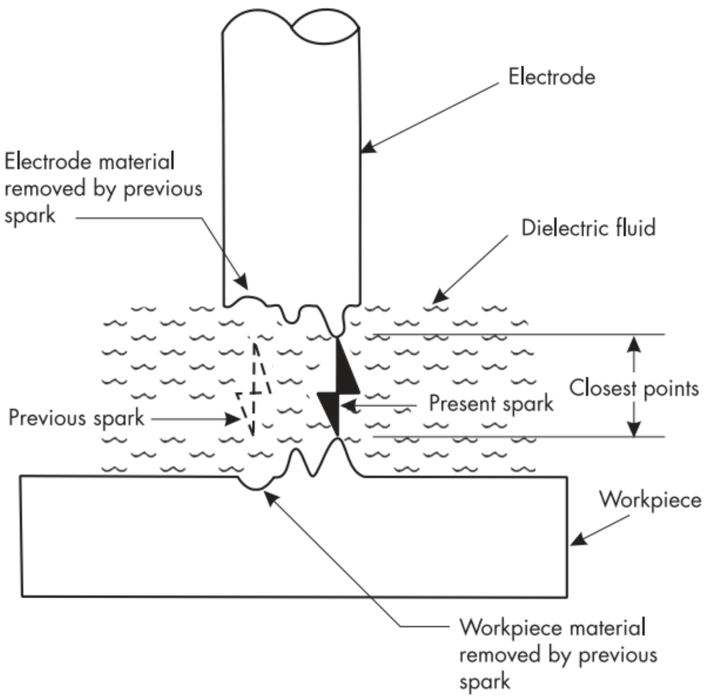

Figure 2. The continuous generation of successive sparks between the electrode and the workpiece [14]

For a spark to occur between the electrode and the workpiece, a gap must be present; this gap is called the spark gap. Repetitive high-frequency electrical pulses are transmitted through the plasma channel formed between the electrode and the workpiece, thereby generating an ionized zone within the dielectric fluid. When the current is interrupted, the molten metal particles are removed from the machining zone by the dielectric fluid. Subsequently, resolidification occurs on the melted metal surface, and this resolidified region is defined in the literature as the white layer. This discharge and material-removal mechanism operates as a cyclic process, repeating every millisecond [5,16,17].

2.2. System Components

2.2.1. Power Supply

The spark energy is generated by the DC power supply integrated into the EDM machine. The machine's control system regulates the electrical energy required for each discharge through a switching (on–off) mechanism, thereby producing current pulses with appropriate magnitude and duration [18]. The formation of sparks between the electrode and the workpiece depends on the dielectric fluid's electrical resistance. Before machining, the electrode is advanced toward the workpiece, and when the gap between them reaches approximately 0.025 mm, the dielectric fluid still maintains its insulating characteristic. At this stage, the gap is filled with the dielectric. As the electrode advances, an open-circuit voltage of approximately 170 V is applied across the electrode–workpiece gap. At this stage, no current flows through the circuit, and the system remains in the open-circuit voltage state. When the gap distance becomes sufficiently small, the electric field intensity increases, causing the dielectric fluid to ionize and transition from an insulating to a conductive state. Following this transformation, a plasma channel is formed, and the current pulse is transmitted between the electrode and the workpiece. When the current pulse terminates, the dielectric rapidly deionizes and returns to its initial insulating state. The ionization–deionization cycle of the dielectric is a periodic process that occurs thousands of times per second during machining. These power supply pulses are continuously monitored in the machine via voltage feedback. The measured voltage serves as a fundamental reference for evaluating machining conditions. If the electrode is not sufficiently close for spark initiation, the system displays the open-circuit voltage on the voltmeter. When a spark occurs, the observed voltage is called the discharge voltage. While the open-circuit voltage typically ranges from 100 to 300 V, the discharge voltage generally ranges from 20 to 50 V. Due to the high magnitudes of open-circuit voltages, proper insulation, equipment protection, and manufacturer-specified safety measures must be strictly implemented. In the EDM process, the electrode and the workpiece are polarized by connecting them to the positive or negative terminal of the power supply. When the electrode is connected to the negative terminal, positive ions migrate toward the electrode, while electrons are attracted to the workpiece. The selection of polarity significantly affects wear rate, surface integrity, and overall machining efficiency [19].

2.2.2. Dielectric Fluid

In the EDM process, the dielectric fluid serves as an insulating medium that resists the flow of electrical current, and the gap between the electrode and the workpiece is filled with it. Since the choice of dielectric fluid directly affects process stability and discharge characteristics, it is critical to EDM operations. When the electric field intensity reaches a certain level during current application, the fluid becomes ionized and transitions from an insulating to a conductive state; this threshold is called the ionization point. The quality and continuity of the discharge, as well as the material removal rate (MRR), largely depend on the physical and chemical properties of the dielectric fluid. Numerous dielectric fluids exist with different viscosities, cooling capacities, and compositional characteristics. In industry, the most commonly used dielectric media are kerosene and other hydrocarbon-based oils [20]. The EDM dielectric fluid performs several fundamental functions during the electro-erosion process: it acts as an electrical barrier between the electrode and the workpiece, cools the machining zone, facilitates the resolidification of vaporized material, and removes molten metal particles from the discharge gap [21].

2.2.3. Servo and Gap Control Mechanisms

In the die-sinking EDM process, the servo and gap control mechanisms are fundamental determinants of machining stability and surface integrity. Maintaining the spark gap between the electrode and the workpiece at a constant value on the order of micrometers is critical for controlled plasma channel formation and consistent material removal. For this purpose, the servo control system employs a closed-loop configuration that continuously monitors the voltage and current signals within the gap [22]. A decrease in the gap voltage indicates that the gap is narrowing and that the risk of short-circuiting or arcing is increasing; in this case, the servo mechanism retracts the electrode to restore the gap to a safe level. Conversely, an increase in the gap voltage signifies that the gap has widened excessively and that the ionization level required for spark initiation is insufficient; under these conditions, the servo system advances the electrode to re-establish the optimum gap distance [23]. In modern EDM systems, adaptive control algorithms are used alongside the servo mechanism to adjust the feed rate, discharge parameters, and dielectric flushing conditions in real time during machining. In this way, the machining speed is increased, electrode wear is reduced, and geometric accuracy and surface quality are significantly improved. This advanced control approach substantially enhances process stability and repeatability, particularly in the machining of molds and precision engineering components with complex geometries [24].

2.3. EDM Process Parameters

2.3.1. Discharge Voltage

The voltage at which machining begins, with the initiation of spark formation, is referred to as the discharge voltage [25]. In EDM, the discharge voltage is determined by the spark gap and the dielectric fluid's electrical resistance. Before current flows, the open-circuit voltage rises until an ionization path is formed through the dielectric fluid. Once a current path is established between the electrode and the workpiece, the voltage decreases and stabilizes at the operating level. The set voltage determines the distance between the electrode and the workpiece. As electrical current increases, the material-melting rate and surface quality improve, while tool life decreases. In summary, due to the influence of electrical energy on the spark, machining characteristics such as material melting rate, surface quality, and electrode tool life are directly affected [26,27].

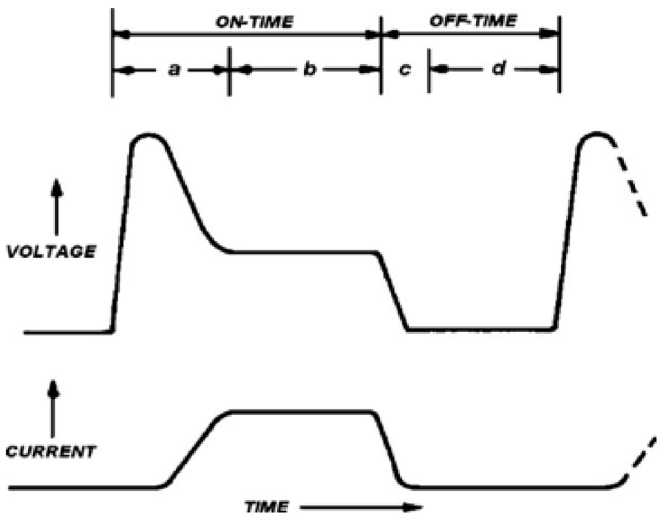

Figure 3. Profile of EDM pulse [28]

2.3.2. Peak Current

It is the amount of power measured during electrical discharges during material removal from the workpiece and depends on the current used. It is measured in amperes. It is one of the most critical process parameters in EDM. For each current pulse, the current operates at a predetermined level referred to as the peak current. In many EDM applications, the required current is determined by the surface area over which material removal occurs. An increase in current raises MRR and improves surface quality, but reduces tool life. High amperage is used in rough machining operations and in processes involving large surface areas. In addition to these factors, one of the most critical issues in EDM is electrode wear caused by electrical loading. Since the electrode surface serves as a template, rapid electrode wear prevents its reuse in subsequent productions, leading to an inefficient, more costly manufacturing process [5,27].

2.3.3. Pulse

During the material removal process, each current cycle occurs within microseconds. Since material melting takes place during the on-time of the current, the pulse duration and the number of cycles per second are critical parameters. The material removal rate is directly related to the amount of energy supplied to the system during the current on-time [17]. This amount of energy is controlled by the peak current (maximum current) and the pulse duration. The period during which the current remains on in the system is generally referred to as the pulse duration. The time interval between switching the current on and off is called the pulse interval. A longer pulse duration means more material is melted. As a result, the crater formed will be broader and deeper than one produced with a shorter pulse duration. Larger craters generate a rougher surface. Extended pulse durations cause more heat to diffuse and penetrate the material, leading to a broader area of the recast layer on the material surface. However, excessively long pulse durations can also be detrimental. When the optimal pulse duration for a given electrode–workpiece combination is exceeded, the material removal rate begins to decrease. The pulse interval affects the cutting speed and regularity. In theory, a short pulse cycle is more effective for material removal; however, if the cycle becomes too short, the dielectric fluid cannot ionize, leading to instability in the subsequent spark.

2.3.4. Pulse waveform

In the EDM process, the pulse shape is generally rectangular; however, advanced generator designs capable of producing various pulse forms have also been developed to improve machining performance. In the literature, the pulse shape has been shown to influence electrode wear rate and tool life significantly. Furthermore, specialized generator systems that facilitate the initial stage of spark initiation and enhance discharge stability have been developed, thereby improving the initial process stability and substantially increasing the overall machining efficiency [29–31].

2.3.5. Anode and Cathode

The electrode polarity may be either positive or negative. Since the current passing through the gap generates high temperatures, it causes material evaporation at both electrode interfaces. The plasma channel consists of ion and electron flows. Because electron-related processes occur more rapidly, the anode material predominantly undergoes erosion. This effect results in minimal wear on tool electrodes and becomes important for rapid material melting. However, during long discharge durations, the dominance of positive electron activity increases, leading to higher tool wear. In general, the polarity condition is determined experimentally using parameters such as current density and pulse duration. The electrode material should possess the following characteristics: excellent electrical and thermal conductivity, good machinability, high material-removal efficiency, resistance to wear, easy availability, low cost, and a high melting temperature [32,33].

2.3.6. Sparking Gap

The tool servo mechanism is significant for the effective operation of the EDM process. This mechanism also controls the establishment of the preset working gap between the electrode and the workpiece. Electromechanical systems (DC or stepper motors) and electrohydraulic systems are most commonly used to regulate the average gap voltage. For good performance, the gap distance's continuity and the system's response speed are critical. Backlash in the system is an undesirable characteristic. To respond to short cycles, the response speed must be high. The gap width cannot be measured directly but can only be inferred from the average gap voltage [34,35].

2.3.7. Flushing

In EDM, the fundamental characteristic properties of the dielectric fluid are high dielectric strength and rapid recovery after discharge, as well as effective quenching and flushing capability. Flushing is based on the efficient removal of molten metal debris from the spark gap. The material melting rate and tool life are influenced by the type of dielectric and the flushing method [2,36].

3. SURFACE MECHANICS IN DIE-SINKING EDM

3.1. Recast Layer

In the EDM process, the high-temperature effects generated during material removal from the workpiece cause the surface layer to melt and then rapidly resolidify. As a result of this cycle, a thin, recast layer forms on the workpiece surface. This layer, referred to in the literature as the recast layer, exhibits a thin, hard, brittle structure due to the high thermal gradients and rapid cooling conditions [37]. The surface layer formed during the EDM process is shown in Figure 4.

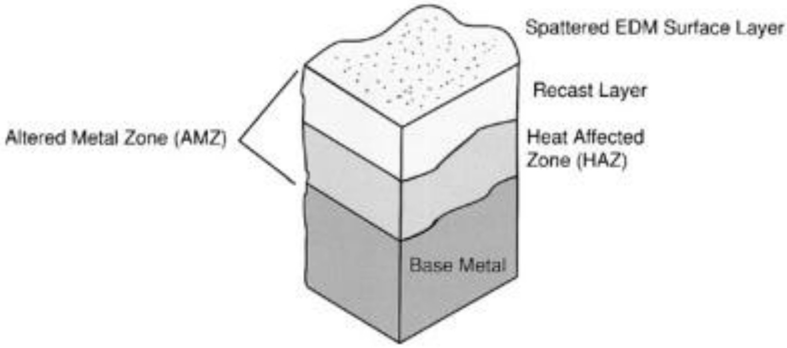

Figure 4. Surface layers after the EDM process [38]

As the molten material rapidly solidifies, a structure known as the "white layer" is formed on the surface. The thickness of this molten–recast layer is directly related to the applied pulse duration and pulse energy. Immediately beneath the white layer lies a Heat-Affected Zone (HAZ), where microstructural and chemical changes occur due to high-temperature exposure. The chemical composition and phase structure of this region are altered during the EDM process. Below the HAZ, a zone that has undergone micro- and macro-level plastic deformation due to twinning, slip, and phase transformations is present [39,40]. The EDM process causes permanent alterations not only on the surface but also in the subsurface regions. Above the unaffected base material, three characteristic layers are observed. At the top, there is an irregular surface layer in which recast metal residues and small amounts of electrode material particles are scattered. These dispersed surface residues can typically be removed with ease. Beneath this layer lies the resolidified white layer. The metallurgical structure and properties of this layer are significantly modified during the EDM process. The white layer forms as the molten metal rapidly cools and solidifies in the dielectric fluid, and it is characterized by its high hardness and bright surface appearance. However, this layer adversely affects surface integrity by facilitating the formation of microcracks. If the white layer is thick and not removed through surface finishing operations, surface damage may occur over time, depending on the service conditions [12]. At the lowest level, there is a third layer in which melting has not occurred, but microstructural changes have taken place due to thermal effects. This region exhibits a partially annealed structure due to thermal exposure. The depths of the resolidified layer and the HAZ are closely related to the material's thermal conductivity and the amount of energy applied. As the applied pulse current increases, the workpiece's melting rate increases. Accordingly, a greater amount of recast layer will form on the material surface [41–43]. The characteristics of these layers play a decisive role in surface integrity and mechanical performance. Although next-generation EDM machines can significantly reduce the thickness of the resolidified layer, it is not possible to completely eliminate the formation of the heat-affected zone.

3.2. Residual Stress in Recast Layer

The residual stresses formed on the material surface during the EDM process are not uniformly distributed throughout the depth of the affected layers; they differ between the recast layer formed after machining and the underlying HAZ. Typically, the recast layer on the surface carries a high level of tensile residual stress. In contrast, mild compressive or lower-tensile stresses develop within or beneath the HAZ to counterbalance this stress. This non-uniform surface stress distribution reflects the self-equilibrating behavior of residual stresses. The tensile stresses in the hardened surface layer are partially offset by mild compressive stresses in deeper regions, thereby maintaining overall force equilibrium at the surface. For engineering materials commonly used in industry—such as steel, aluminum alloys, titanium alloys, and nickel-based alloys—the

EDM process generally produces a surface layer that carries tensile residual stresses, accompanied by a shallow compressive stress region beneath it. The magnitude of these tensile stresses can be considerable, depending on the machining parameters; several studies have shown that residual stresses on EDM surfaces can approach the material's ultimate tensile strength (UTS). Indeed, measurements taken on workpiece surfaces have reported that the maximum residual stresses often reach levels close to the UTS of the material, and that increasing the discharge energy beyond this point does not further increase the stress but instead leads to stress relief through cracking and subsequent material damage [44,45].

The characteristics of the residual stresses on the workpiece surface depend on the applied machining parameters and the material type. Under high-energy EDM conditions, a thicker recast layer and a deeper heat-affected zone are produced; therefore, the maximum tensile stress may not occur at the surface but instead be located at the interface between the recast layer and the HAZ. Research has shown that under rough-machining conditions involving high current and long pulse durations, the maximum tensile stress often develops just beneath the surface, at the recast–HAZ boundary. In low-energy EDM operations, the recast layer is thinner, and as a result, the maximum stress typically forms at or very near the workpiece surface. Material properties also influence the residual stress state. While steels and most alloys develop tensile residual stresses on their surfaces after EDM, some materials may exhibit different behavior. Certain metal-matrix composites or specialized alloys may exhibit a mixed stress profile, with tensile and compressive stresses coexisting at the surface. Nevertheless, for common metallic materials processed by sinker EDM, the typical outcome is the formation of a recast layer carrying tensile residual stress at the surface, with a region of lower stress or mild compressive residual stress located beneath it [46–48].

When examined microstructurally, the recast layer is generally hard and brittle, as previously noted; in steels, it typically contains untempered martensite and carbide phases after EDM. The underlying HAZ, exposed to subcritical temperatures, may exhibit a partially tempered or annealed structure. In some cases, this can promote a more uniform distribution of stresses near the surface. However, suppose the recast layer is well-bonded to the underlying material. In that case, the tensile strain in the surface layer is constrained by the more ductile substrate, which contributes to the development of high tensile stresses at the recast–HAZ interface. Indeed, several studies have reported that the maximum tensile residual stress appears at the boundary between the recast layer and the HAZ, and that cracks frequently initiate in this region [49–52].

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FUSED DEPOSITION MODELING (FDM): FUNDAMENTALS, MATERIALS, PROCESS MECHANICS

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1. INTRODUCTION

Additive manufacturing is an advanced production technology in which a digitally created design model is transferred directly to production, and the final geometry is formed by successively depositing material in layered form. In this respect, it differs from conventional methods such as machining or casting,

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offering high flexibility and a design-oriented approach. This production technology enables the easy manufacture of complex shapes, reduces material waste, and allows cost-effective fabrication of application-specific products [1–3]. In this process, the computer-aided design (CAD) file is converted to a stereolithography (STL) file, and a cross-section is generated that contains details of each layer. Unlike conventional manufacturing methods, it enables the production of complex geometries while minimizing material waste. In sectors such as aerospace, defense, automotive, and medicine, it is increasingly preferred for its advantages in producing lightweight structures and specialized components. However, the novelty of the production technology, the limitations of the materials used, and the need to improve surface quality require further research and development to ensure this technology meets widespread industrial standards [4,5].

This method is based on the principle of depositing a thermoplastic filament, melted at a specified temperature, onto a surface in successive layers through an extruder that moves according to a digital model [6,7]. The FDM method enables precise control of numerous production-process parameters and allows the economical, rapid fabrication of parts with improved mechanical properties and complex geometries [8]. The interlayer bonding mechanisms occurring throughout the process, the rearrangement of polymer chains, the viscoelastic and thermo-rheological behavior of the material, and the thermal gradients and residual stresses formed during cooling directly determine the final mechanical, tribological, and dimensional performance of the produced part. In addition, fundamental process parameters such as nozzle temperature, build-plate temperature, printing speed, raster angle, infill density, and layer height shape the anisotropic mechanical character of FDM-produced structures and lead to direction-dependent behaviors, particularly under tension, compression, bending, impact, and fatigue loading. Furthermore, the microstructure of FDM-manufactured parts is significantly affected by numerous micromechanical factors, including void formation, interfacial bonding strength at material surfaces, fiber orientation within the filaments, and the degree of crystallization. Therefore, enhancing the functional performance of FDM manufacturing processes requires not only the optimization of macro-scale process parameters but also an understanding of material properties, such as the thermal properties of the polymers used. Considering these evaluations, the FDM production process stands out among contemporary manufacturing methods due to its low investment cost, high design freedom, rapid prototyping and production of customized or application-specific parts, efficient material use, and the ability to fabricate complex geometries with support structures. For this reason, it has become increasingly widespread in both academic research and industrial applications.

2. FUNDAMENTALS of FDM TECHNOLOGY

2.1. Working Mechanism of FDM

FDM manufacturing technology is a three-dimensional (3D) printing technique based on the principle of heating a thermoplastic filament to a semi-fluid state and extruding it through a nozzle onto a platform in layers. In an FDM printer, the filament is continuously fed through the extruder and nozzle. The nozzle moves along three axes according to G-code generated from CAD data, depositing material in layers to achieve the desired shape and dimensions. Each layer is placed on top of the previous one, forming the three-dimensional object defined by the design information. In this process, the thermoplastic nature of the filament allows the layers to adhere to each other and solidify at room temperature. The simple infrastructure, low cost, and ability to produce complex geometries have made FDM a widely preferred method for personal and industrial prototyping and manufacturing [7,9,10].

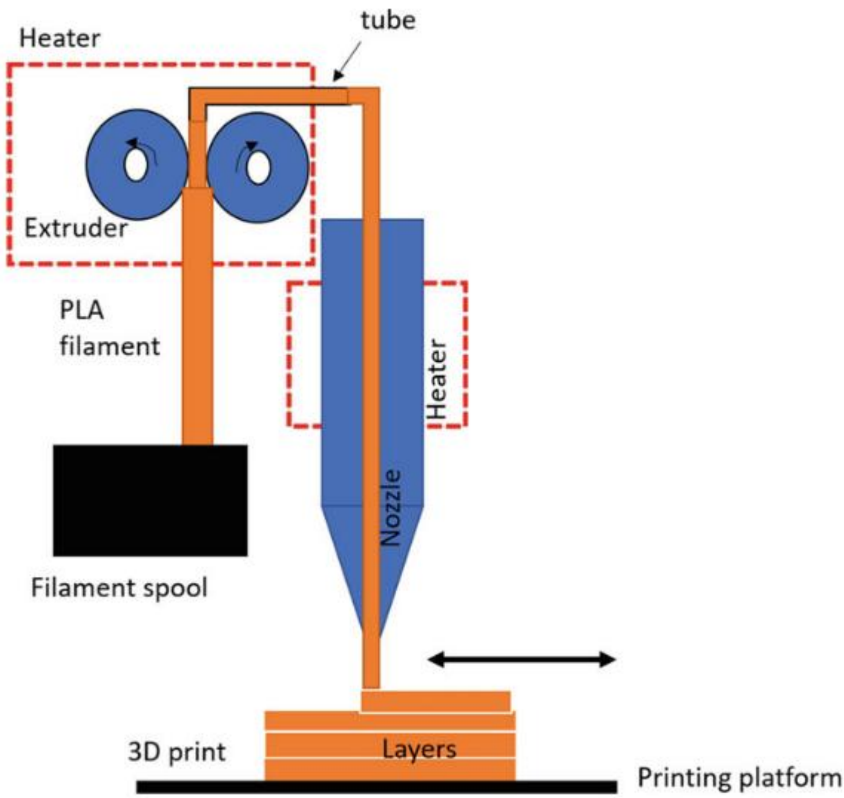

Figure 1. Principle of EDM [9]

In the FDM method, many process parameters determine the print quality and the quality of the produced part. In addition, the material's behavior is among the most critical factors determining the final mechanical properties. Variations in process parameters, such as nozzle diameter and temperature, printing speed, layer thickness, infill ratio, and printing orientation, directly affect interlayer bond formation, internal stress distribution, and the microstructural integrity of the manufactured part [11,12]. Since thermal gradients determine the rearrangement of polymer chains and the interdiffusion mechanism, the quality of adhesion between layers is one of the most critical factors governing part strength. In addition, porosity, road gaps, and irregular cooling behavior that may occur during the FDM process are significant issues. These problems can substantially affect not only mechanical performance but also tribological and dimensional stability. Therefore, the use of high-performance composite filaments, optimized printing parameters, and controlled cooling strategies is considered a fundamental approaches that enhance the suitability of FDM-produced components for functional industrial applications [13].

2.2. Thermo-Mechanical Behavior of Polymer Extrusion

The thermo-mechanical behavior of polymer extrusion in the FDM process is a fundamental factor that determines the quality, dimensional stability, and mechanical performance of the produced parts [14]. During extrusion, the polymer filament transitions from the solid state to a semi-fluid state as soon as it enters the heated nozzle. In this way, it exhibits both thermal softening and viscous flow behaviour [15,16]. At this stage, the fundamental material properties of the polymer, such as shear thinning, temperature-dependent melt viscosity, chain mobility, and elastic behavior, directly determine the flow stability within the nozzle and the quality of extrusion [14]. After exiting the nozzle, the material is subjected to a rapid cooling period. During this process, a complex thermal gradient forms within the material structure; the alignment of polymer chains, the rate of intermolecular diffusion, and the formation of interlayer bonding largely depend on this thermal behavior. In addition, due to rapid solidification and non-uniform cooling across the cross-section, undesired deformations such as internal stresses, shrinkage, and warping may occur. These effects significantly influence the dimensional stability and mechanical anisotropy of the produced part. A sufficient understanding of thermo-mechanical interactions is critical for preventing microstructural defects, such as porosity, road gaps, and weak interlayer adhesion. Therefore, optimization of process parameters such as extrusion temperature, printing speed, layer height, cooling conditions, and material modifications is essential. This approach is necessary for achieving higher mechanical strength, enhanced surface quality, and the production of functional FDM parts suitable for industrial applications [14,17,18].

2.3. Nozzle Motion Mechanics and Kinematic Structure

In FDM printer technology, the mechanics and kinematic structure of nozzle motion are highly important. They are among the most critical factors that determine print quality, surface condition, and interlayer alignment consistency. Any problem with the motion mechanics may cause the print to be defective or fail midway. In a typical FDM system, the nozzle moves over the build plate according to the toolpath information derived from the part's G-code. This motion is generally achieved through one of the Cartesian, CoreXY, or Delta kinematic configurations. These kinematic structures directly affect the nozzle’s acceleration, deceleration, speed profile, and positional accuracy along the three axes (X–Y–Z) [19,20]. When the effects of different kinematic structures on print quality and surface condition are compared, Delta-based printers achieve better surface quality. In contrast, CoreXY systems excel in dimensional accuracy [19]. Dynamic vibrations, inertial loads, and sudden speed variations occurring during motion cause path deviations, especially at high printing speeds. Additionally, they may lead to losses in corner sharpness and distortions in geometric tolerances. Moreover, the nozzle's positioning accuracy depends on mechanical and electronic components, including belt tension, linear guide rigidity, stepper motor resolution, and the performance of the motion control algorithm, all of which influence product quality. Since these dynamic–mechanical interactions determine the placement accuracy of the extruded polymer track, they directly affect the stacking quality of layers, the porosity of the internal structure, and the geometric integrity of the final part. Any issues encountered with this motion system or its components directly affect the quality of the printed product. Therefore, optimizing nozzle motion mechanics under appropriate parameters is highly important. Achieving this requires vibration damping and suspension strategies, advanced motion-control software, highly rigid frame designs, precise selection of kinematic configurations, and the use of high-quality components. These improvements play a critical role in enhancing FDM print quality and dimensional stability, particularly in engineering applications requiring high precision [19,21,22]. The mechanics and kinematic structure of nozzle motion are among the primary determinants of FDM print quality and dimensional stability. The selection of the kinematic configuration, vibration control, and mechanical–electronic optimizations is critical for producing high-precision, functional parts.

2.4. Layered Manufacturing Strategy and Geometric Constraints

The layered manufacturing strategy is a critical design approach that determines both geometric accuracy and functional performance in the FDM process. This strategy requires the simultaneous optimization of numerous process parameters. Layer thickness, printing orientation, infill density, infill pattern, nozzle movement paths, and support structure configuration are essential performance parameters that must be optimized [15,23]. The layer-by-layer material deposition method, a fundamental principle of layered manufacturing, inherently includes certain geometric limitations due to its characteristic nature. For example, overhangs exceeding a certain threshold (typically above 45°) tend to collapse when there is insufficient support beneath them. In such regions, it becomes necessary to create mandatory support structures to sustain these overhangs as required by the design. The necessity of creating these structures not only increases material consumption and production time but may also negatively affect surface quality, as the removal of supports during post-processing can leave marks [24]. In geometries with high surface curvature, the discrete and linear nature of the layers produces the so-called “stair-stepping” effect; this effect can be reduced, particularly by using a lower layer height, but it significantly increases the printing time. In complex internal volumes, thin-walled structures, and engineering applications requiring tight tolerances, it becomes difficult to align the infill paths with the constant track width. This may lead to microstructural defects such as local material accumulation, void formation, or insufficient bonding. In addition, the thermal distribution in irregular geometries with indentations and protrusions results in non-uniform regional thermal accumulation. This can cause shrinkage, warping, and structural distortion in the material [17,25]. Therefore, the proper formulation of the layered manufacturing strategy should be supported by appropriate layer-thickness applications, orientation-optimization algorithms, support-structure designs, functional slicing software, and thermal-simulation-based approaches. Such advanced strategies enhance the manufacturability of complex engineering geometries produced by FDM, improve surface quality, and make the structural integrity and mechanical properties of the parts more predictable and repeatable.

3. MATERIALS USED IN FDM

3.1. Thermoplastic Polymers

Thermoplastic polymers are macromolecules that soften under the influence of heat and solidify again when cooled. They can withstand repeated heating–cooling cycles. Since these materials, whose molecular structures may be linear or branched, do not contain chemical cross-links, they exhibit melting/flow behavior.

This property makes them ideal for melt–deposition–based layered manufacturing methods such as FDM [26].

3.1.1. Polylactic Acid (PLA)

It is a biodegradable thermoplastic polymer obtained from renewable resources and is one of the most commonly used filament materials in FDM manufacturing technology. Its low melting temperature (180–220 °C) and minimal warping behavior facilitate printing processes. It provides adequate stiffness and tensile strength from a mechanical standpoint, though its impact resistance is lower than that of some other thermoplastics. The thermo-mechanical properties of PLA are directly related to nozzle temperature and printing speed. When the selected parameters are used within appropriate ranges, interlayer bonding improves, and surface roughness is enhanced. A decrease in mechanical performance is observed when it is exposed to humid environments for extended periods. All these characteristics make PLA an ideal option for prototyping, educational applications, and functional parts subjected to low thermal loads. Although it is used in industrial applications, improvements in mechanical properties may be required depending on the specific use case [7,27,28].

3.1.2. Acrylonitrile Butadiene Styrene (ABS)

It is a thermoplastic polymer with high impact resistance and heat resistance, and it is widely used in FDM printing for the production of functional parts. For melting, the nozzle temperature is typically set to 220–250 °C. To prevent warping, the build plate temperature and the use of an enclosed printing chamber are essential for print quality. With appropriate parameter selections, surface quality and dimensional accuracy can be improved. ABS is a suitable material for FDM technology in applications that require strength and heat resistance [7,29].

3.1.3. Polyethylene Terephthalate Glycol-Modified (PETG)

PETG is a thermoplastic polymer that offers high impact resistance and chemical durability. In FDM printing, it is preferred for parts that require mechanical strength and, in particular, flexibility. During printing, the nozzle typically operates at 230–250 °C. Interlayer adhesion and surface quality can be improved through various printing parameters. Moisture control is significant for maintaining print quality. These properties make PETG a suitable material for functional applications that require flexibility [25,30].

3.1.4. Polyamide, Nylon (PA)

In FDM manufacturing technology, it is preferred for applications that require strength and wear resistance. From a mechanical standpoint, it exhibits high strength and good wear resistance. It is also a thermoplastic polymer used in parts that require flexibility. The nozzle temperature typically ranges from 240 to 260 °C. Moisture control during printing is critical to print quality. Interlayer adhesion and infill parameters directly affect the mechanical performance. All these properties make Nylon a suitable material for a durable, flexible, and functional part [31,32].

3.1.5. Polycarbonate (PC)

It is a thermoplastic polymer that provides high impact resistance, heat resistance, and dimensional stability. In FDM printing, it is preferred for producing parts that require high strength and temperature resistance. During operation, the nozzle temperature is typically 260–300 °C. All these properties make PC a suitable material for durable and functional parts [10,33].

3.2. Composite Filaments

They are obtained by reinforcing thermoplastic matrix materials with carbon fiber (CF), glass fiber (GF), or other reinforcing agents. Carbon-fiber-reinforced filaments such as PLA-CF and ABS-CF increase tensile and flexural strength, improve interlayer adhesion, and enhance dimensional stability. GF-reinforced materials, on the other hand, are preferred particularly to increase impact resistance and thermal stability. The mechanical and thermal performance of composite filaments is directly related to the reinforcement ratio, fiber length, fiber orientation, and FDM printing parameters.

3.2.1. Polylactic Acid – Carbon Fiber Reinforced (PLA-CF)

It is a composite filament material produced by adding carbon fiber to a low-melting, biodegradable PLA matrix. Carbon fiber reinforcement increases the mechanical performance of the structure, improves interlayer adhesion, and enhances dimensional stability [13,34].

3.2.2. Acrylonitrile Butadiene Styrene – Carbon Fiber Reinforced (ABS-CF)

It is a composite filament that enhances the mechanical properties of the high-impact-resistant ABS matrix by reinforcing it with carbon fiber. ABS-CF increases tensile and flexural strength as well as mechanical performance, strengthens interlayer bonding, and provides suitability for high-performance industrial parts. These properties make ABS-CF an ideal material for durable and functional components [35].

3.2.3. Glass Fiber Reinforced Filaments (GF-Reinforced Filaments)

They are obtained by reinforcing thermoplastic matrices such as PLA, ABS, or PC with glass fiber. Glass fiber reinforcement particularly increases impact resistance, thermal stability, and dimensional stability, enabling the production of high-load-bearing parts. These properties make GF-reinforced filaments suitable for high-strength components [10,36].

4. FDM PROCESS PARAMETERS

4.1. Nozzle Temperature and Thermal Effects

It is one of the most critical parameters of the FDM printing process. It affects print quality and directly influences mechanical properties. The nozzle temperature determines the filament's melting behavior, flowability, and interlayer adhesion. Low nozzle temperatures reduce interlayer bonding by insufficiently melting the layers, resulting in a decrease in tensile strength. On the other hand, high nozzle temperatures may cause excessive filament flow, dimensional deformation, and thermal degradation. Thermal effects also influence the rearrangement of polymer chains and crystallization behavior, thereby altering mechanical properties such as stiffness, modulus, and impact resistance. Therefore, selecting the optimal nozzle temperature is critical for maximizing both print quality and part performance, and it varies depending on the material type. All these factors demonstrate that nozzle temperature directly affects the mechanical and thermal performance in the FDM printing process [15,37].

4.2. Bed Temperature and the Warping Problem

The build-plate temperature is an important parameter that affects the dimensional accuracy and structural stability of parts produced in the FDM printing process. Thermoplastic materials used during printing tend to shrink as the layers cool. This effect is more pronounced in polymers with high thermal expansion, such as ABS and PC. Low build-plate temperatures cause the bottom layer to cool rapidly, leading to warping and corner lifting problems. When an adequate build plate temperature is provided, better adhesion between the first layer and the plate is achieved, internal layer stresses are reduced, and the dimensional accuracy of the print increases. In addition, the build-plate temperature influences the polymer's crystallization and glass transition behavior, thereby indirectly affecting mechanical properties. Therefore, selecting the correct build-plate temperature is critically essential for optimizing both print integrity and the mechanical performance of the final part [38].

4.3. Layer Height, Raster Angle, and Infill Structure

The layer thickness of the material deposited sequentially during FDM printing directly affects mechanical properties and surface quality. Thin layers increase interlayer adhesion, thereby enhancing tensile strength and providing a smoother surface. Thick layers, on the other hand, shorten the printing time but may reduce mechanical strength. The raster angle determines the orientation of the extruded paths relative to the loading direction and also affects the part's anisotropy. When the raster direction is parallel to the loading direction, tensile strength increases; at perpendicular or varying angles, stress distribution is altered, and flexural strength is influenced. The infill structure defines the internal geometry of the part and therefore determines its weight, stiffness, and energy absorption capacity; high infill density improves mechanical performance but also increases material consumption and printing time, while the infill pattern (grid, triangular, hexagonal) affects stress distribution and deformation behavior [39–41].

4.4. Printing Speed, Flow Rate, and Cooling Rate

Print speed, flow rate, and cooling rate play a decisive role in both mechanical properties and surface quality during the FDM printing process. As print speed increases, the filament may not fully melt or be adequately deposited onto the layers. Such an issue reduces interlayer adhesion and decreases mechanical strength. The flow rate controls the amount of material extruded; a low flow rate causes gaps between layers, while a high flow rate may lead to overflow and surface defects. The cooling rate affects the polymer's solidification process. Rapid cooling can increase interlayer stress and cause deformation, whereas properly controlled cooling improves both dimensional accuracy and mechanical performance. Optimizing these three parameters is critical for print quality and the structural integrity of the part [42–44].

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MECHANICAL PROPERTIES OF POLYMERS AS LIGHT WEAPON MATERIALS

FARUK GÜNER[1]

Introduction

Small arms have been integral to law enforcement agencies since their inception. Generally, a firearm comprises several primary components, including the frame, slide, and barrel. Among these, the frame material is critical to the weapon's performance and durability. Historically, firearm frames have been manufactured from three main material types: steel, aluminum alloy, and, more recently, polymer-based composites. The choice of material depends largely on the intended application and specific user requirements.

In the latter half of the 20th century, advancements in materials science facilitated the widespread adoption of polymer-based composite materials in engineering applications. While composites initially gained traction for their high strength-to-density ratios, they have since proven capable of outperforming traditional materials like steel and aluminum in various applications (Eryildiz & Akdoğan Eker, 2015). Consequently, the firearms industry has increasingly shifted toward polymer-based pistols. These frames offer significant advantages, including weight reduction, corrosion resistance, extended service life, and enhanced ergonomics.

A comparative analysis of frame weights illustrates these benefits. According to Karslı and Küçükömeroğlu (2017), a standard steel pistol frame weighs approximately 400 g, while an aluminum

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alloy frame averages 200 g. In contrast, a PA66 frame reinforced with 30% glass fiber weighs only about 120 g. Consequently, the total weight of the weapon varies significantly by material: steel-framed pistols average 1200 g, aluminum alloy pistols 1000 g, and polymer-based composite pistols approximately 750 g (Karslı & Küçükömeroğlu, 2017).

Beyond the frame, polymer materials are now utilized for various other components, such as the trigger, trigger safety, magazine body, and recoil spring guide. The popularity of polymer matrix materials stems from their high resistance to fatigue, impact, and thermal stress, as well as their suitability for rapid and economical production. One of the most significant manufacturing advantages is part consolidation; complex geometries can be molded as a single piece, reducing the number of required parts and assembly joints.

Despite these advantages, the market acceptance of polymer technology for pistols has been slower compared to rifles. However, the drive for competitive advantage and customer satisfaction has necessitated improvements in manufacturing methods and raw materials. Today, polymer weapons are increasingly preferred over their steel counterparts by both manufacturers and end-users due to their superior mechanical and thermal properties, as well as their cost-effectiveness.

This study examines the manufacturing methods of polymer-based small arm frames and analyzes the mechanical properties of the raw materials used in their production. Furthermore, it provides a comparative analysis of steel and polymer pistol frames based on specific technical criteria. The study aims to evaluate the advantages and disadvantages of polymer structures, presenting an assessment of their viability for both manufacturers and customers.

Polymer Applications in Firearm Frames

The materials engineering requirements for the defense and arms industry are rigorous. Ideally, composite materials utilized in firearm manufacturing must exhibit a high strength-to-density ratio, excellent formability, specific dielectric properties, and high resistance to corrosion and chemical degradation. Additionally, characteristics such as vibration damping and aesthetic versatility (colorability) are highly desirable.

The paradigm shift from traditional steel or aluminum-based weapons to composite-based systems is directly attributable to specific critical advantages. These advantages can be categorized as follows:

Durability and Operational Lifespan: Polymer composites demonstrate superior resistance to impact, wear, and environmental corrosion compared to traditional metals. This resilience significantly extends the service life of the firearm. Furthermore, the vibration-damping properties of polymers can contribute to recoil management, thereby potentially enhancing target accuracy and allowing for sustained performance during high-volume firing sequences.

Weight Reduction and Maneuverability: One of the primary drivers for polymer adoption is the reduction in mass. Polymer composite-based pistols are significantly lighter than their traditional metal counterparts. This reduction in weight mitigates operator fatigue and enhances the weapon's maneuverability and portability.

Cost-Effectiveness and Manufacturability: In competitive market conditions, production cost is a decisive factor. The utilization of polymer composites facilitates near-net-shape manufacturing (e.g., injection molding). This approach eliminates or drastically reduces the need for extensive and costly subtractive manufacturing processes (machining) required for steel or aluminum frames, resulting in a more economical production cycle.

Design Flexibility and Ergonomics: The inherent formability of polymer composites enables complex ergonomic designs that are difficult or cost-prohibitive to achieve through traditional metal machining. This design flexibility allows manufacturers to create user-centric interfaces, such as contoured grips and integrated accessory rails, directly within the molding process.

Advantages and Disadvantages

Below are the differences between a steel body and a polymer-based composite body weapon in general.

Advantages of steel-bodied weapons

1- Low Barrel Rise: In steel-framed pistols, the front of the receiver is particularly heavy. The upward torque generated during firing does not significantly affect the position of the barrel thanks to the weight of the front of the receiver. This means barrel rise is very low, allowing for more accurate shots.

2- Accuracy in Continuous Firing: This is directly related to low barrel rise. Thanks to low barrel rise, re-cocking the barrel after each trigger pull during continuous firing is quite simple. The superiority of steel-framed pistols is particularly evident during operational tactical fire, such as double-barreled shots.

3- High Heat Resistance: Steel-framed pistols can expand slightly when exposed to extreme heat or fired in large quantities, but they return to their original shape upon cooling. The results of temperature resistance tests of steel-structured guns are also much better compared to polymer-structured guns (composite guns).

Disadvantages of steel-bodied weapons

1- Weight: Steel-bodied pistols are quite heavy compared to their polymer counterparts. That's why these pistols are no longer used by many people as carrying weapons.

2- Rusting: Continuous attention and maintenance are required to prevent steel body guns from rusting. It is of great importance that scratches do not occur on these guns so that they do not rust. If any part of the gun is rusted, abrasions or pits may occur on the body surface.

Advantages Polymer Body Pistols

1- Lightweight Construction: Pistols with polymer frames are significantly lighter than their steel-framed counterparts. This feature makes polymer-framed pistols very easy to carry.

2- Recoil Absorption: While steel materials have almost no absorption capacity, polymer materials have quite good absorption capacity. This allows polymer-framed pistols to absorb some of the pressure exerted by the slide when fired. This reduces the recoil effect, albeit to a small extent.

3- Moisture Resistance: If steel-framed pistols are stored or left in a humid environment for a period of time, moisture begins to corrode the frame. However, polymer material is immune to moisture. Since polymer material does not rust like steel, polymer-framed pistols are extremely resistant to moisture.

4- Low Cost: The cost of manufacturing polymer parts is significantly lower than the cost of manufacturing and processing steel parts. Therefore, polymer-framed firearms are generally much cheaper than steel-framed firearms.

Disadvantages Polymer Body Pistols

1- Excessive Muzzle Rise: Pistols with polymer frames are quite lightweight. We mentioned the advantages of this above, but there is also a disadvantage to being lightweight. The upward rotational torque generated when the pistol is fired causes the barrel to rise. Due to the light weight of the pistol, the barrel rise is extremely high. Therefore, when firing multiple shots in quick succession with polymer-framed pistols, it takes time for the barrel to settle back into place, making it quite difficult to fire accurate shots in rapid succession.

2- Low Heat Resistance: Polymer-framed pistols may begin to expand when exposed to excessive heat or when fired repeatedly enough to significantly heat the frame. However, unlike steel-framed pistols, polymer-framed pistols do not return to their original shape after expanding and cooling. When polymer material heats up, it often loses its original shape and warps. As a result, the pistol may become inoperable.

The advantage of composite materials is that they combine the superior properties of their components. The primary property sought in the production and development of composite materials is strength.

Increased resistance to impact, fatigue, wear, and corrosion provides materials with significant advantages. Particularly in the arms industry, considering the operating principle of a weapon, resistance to impact, wear, and corrosion are among the most critical factors. High resistance to impact and wear will extend the weapon's lifespan and enable higher firing rates. High corrosion resistance is also an important feature that increases the weapon's lifespan. This is because weapons are constantly exposed to corrosive effects in different operating environments.

Other properties aimed to be developed with the production of composite materials include lightness, low cost, rigidity, aesthetic appearance, high temperature properties, and conductivity (thermal conductivity, electrical conductivity, and acoustic conductivity). All of the properties planned to be developed with the production of composite materials are of great importance in weapon materials, as they are in other materials. High fracture toughness is already an essential property for weapons operating under high-intensity repetitive loads. Lightweightness provides ease of use for weapon users, while low cost is very important for many industries in today's competitive environment. Considering the heating of weapons at high firing rates, high temperature properties are also of great importance.

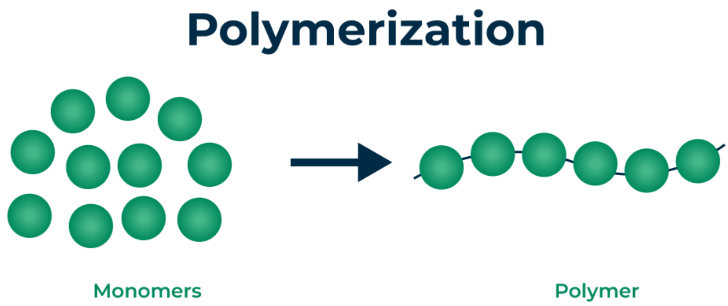
At this stage, the information to be obtained by making some determinations about the structure of the polymer material will facilitate the understanding of the production methods and the effects on the mechanical properties of polymer materials.

Structure of Polymers

Small-molecular-weight chemical molecules that are linked together in a specific order by covalent bonds are called monomers. In Greek, mono means single and poly means many. Monomers are the smallest molecules that repeat within a polymer. A molecule formed by the chemical bonding of two monomers is called a dimer, and a molecule formed by the bonding of three monomers is called a trimer.

A polymer is a large molecule formed by the bonding of many monomers together with covalent bonds under the influence of heat and pressure. Monomer units bond to each other through polymerization reactions to form a polymer molecule. A polymer molecule can contain dozens, hundreds, or even thousands of monomer units. A basic polymerization process is described in Figure 1.

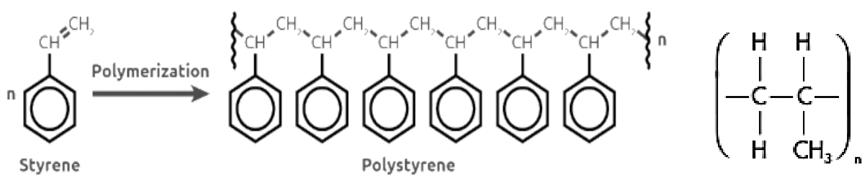
Figure 1 Definition of basic polimarization



Reference: "Polymerization," 23 Jul, 2025

Figure 2 shows a schematic representation of a more comprehensive polymerization process. Here, the conversion of the styrene sequence to polystrene polymer by polymerization process is shown.

Figure 2 a)Styrene to polystrene polimarization("What is polymerization and polymer synthesis?," 2025) b) Polyproplene (PE) crystaline



Reference: Ashby, 2005a

Polymers are large molecules. The Van Der Waals forces between them are also large. Therefore, the melting and boiling points of polymers are higher than those of monomers. This property also makes polymers harder, stronger, and more durable materials.

As the number of chains increases, the physical properties of polymers also change. For example, a polymer that can exist in liquid form when the number of chains is small will gradually increase in density and viscosity as this number increases, perhaps becoming a honey-like liquid, and for very high chain numbers, it may form a solid polymer. In order for the chain number to be increased to an infinite value as an upper limit, the chains must be cross-linked to each other. Polymers are called "linear linear" if their chains are connected to each other in the form of a long chain, "branched" if this chain has some side chains, and "call-bonded" polymers if a three-dimensional network structure is formed between the chains.

When energy in the form of heat is applied to a mass composed of polymer chains, an increase in the mobility of the polymer chains occurs. Initially, this mobility occurs in small segments of the polymer chain, but as the heat increases, it gradually encompasses larger segments and spreads throughout the entire chain. At this point, the polymer chains begin to slide over each other, and the solid polymer melts and flows.

Essentially, a solid plastic can be repeatedly heated and melted – cooled and solidified if it is thermoplastic, or if it breaks down when reheated after being shaped once with heat, it is thermosetting.

For all polymer materials, there is a temperature below which the polymer chain becomes immobile. This temperature is called the glass transition temperature (Tg). Above this temperature, there is sufficient thermal energy in the material to allow for regional folding movements of the polymer chains. Below the glass transition temperature, since the movements encompassing the entire polymer chain cease, the same material becomes inelastic, hard, and generally brittle.

Below the glass transition temperature, polymer materials are not fluid and exhibit Hookean elasticity. That is, at these temperatures, when polymer materials are stretched, they exhibit very little elasticity and can return to their original shape. This elasticity arises from the carbon-carbon bond angle in the stretched polymer chain being partially widened and strained by the tension. When the stress is removed, the carbon-carbon bonds return to their normal angles, and the material returns to its original dimensions.

Just above the glass transition temperature, when stress is applied to a polymer that is still in a solid state, partial alignment occurs in the polymer molecules, and the material stretches. When the stress is removed, the polymer chains return to their original positions and the material returns to its original dimensions. This condition is called viscoelasticity.

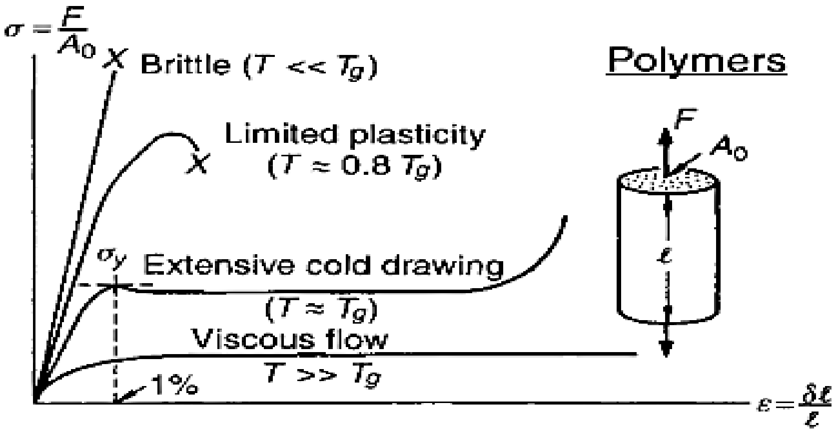
As the temperature continues to increase, the polymer material melts and begins to exhibit liquid behavior. As polymers melt, their viscosity increases. If pressure is applied to a molten polymer, the viscosity decreases.

The molecular weight of polymers is of great importance in the production of polymers and their industrial applications.

The molecular weight of polymers is much larger than that of monomer molecules. This large difference in molar mass results in differences in physical properties between polymers and molecules with fewer mer units. The molecular weights of solid polymers start from 10 000 and reach millions.

The useful mechanical properties of polymeric materials are based on their high molecular weight. If the molecular weight is below 5000-10000, there is no indication of mechanical strength. Mechanical strength increases rapidly when the molecular weight exceeds the values mentioned above. While a very high molecular weight is beneficial in terms of mechanical behavior, it also makes processability difficult. Commercial polymeric products that are both processable and have sufficient mechanical properties are desired to have a molecular weight between 10^4 and 10^6. In Figure 3 given below, the stress deformation behavior of a polymer material at glass transition temperature and at temperatures just below this temperature is expressed.

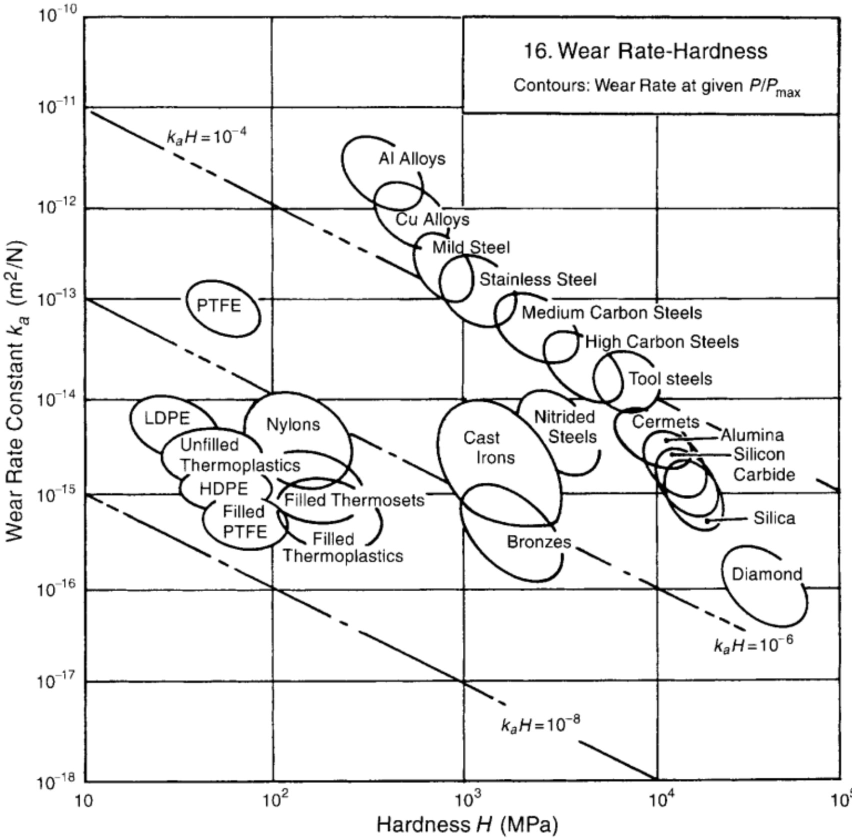
Figure 3 Stress-strain curve for a polymer via glass transition temperature



Reference:Ashby, 2005a

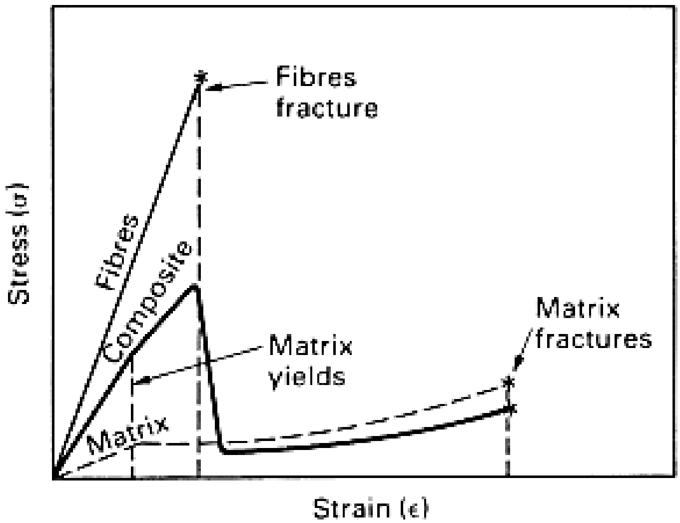
In firearm design, in addition to basic strength properties, wear resistance is an important parameter in the selection of polymers or other materials.In addition to wear associated with metal contact in firearms, wear also occurs due to pressurized gas.Figure 4 shows the relationship between wear resistance and hardness for different materials. The reason for determining hardness as the second variable is that the impact forces arising during the use of weapons can be expressed in terms of hardness. Figure 4 shows the relationship between wear resistance and hardness for different materials. The reason for determining hardness as the second variable is that the impact forces arising during the use of firearms can be expressed in terms of hardness.As can be seen in the figure, the wear resistance of alloyed metals is much higher than that of polymers and ceramics. The reason for choosing polymers is to create a composite structure. As can be seen in the figure, the wear resistance of alloyed metals is much higher than that of polymers and ceramics. In the selection of polymers, the formation of the composite structure,the load to be exposed to, and the number of repetitions are important parametersin wear resistance.

Figure 4 Relationship of wear resistance of materials with hardness



The use of polymers as defense industry materials is challenging due to their low wear and hardness resistance. Therefore, methods of reinforcement, which can be referred to as composite materials, have been developed to take advantage of the benefits offered by polymers. As shown in Figure 5, the fiber and fiber-class materials used as polymer additives are brittle materials with no significant flow. On the other hand, the amount of deformation of the polymer used as the matrix material is much higher. The material obtained by mixing fiber or fiber material in different ratios with the polymer matrix has a higher yield strength than the polymer and a higher tensile strength than the fiber.

Figure 5 The stree-strain curves of fibre, matrix and composite



Reference: Ashby & Jones, 1999

In firearm design, wear resistance is an important parameter alongside basic strength properties when choosing polymers or other materials. In firearms, wear occurs not only due to metal contact but also due to pressurized gas. Figure 4 shows the relationship between wear resistance and hardness for different materials. The reason hardness is determined as the second variable is that the impact forces arising during firearm use can be expressed in terms of hardness. As can be seen in the figure, the wear resistance of alloyed metals is much higher than that of polymers and ceramics. In the preference for polymers, the formation of the composite structure, the load to be exposed to, and the number of repetitions are important parameters in wear resistance. Mechanical engineers adhere to a rule in practical applications, which is to avoid materials with a plane strain fracture toughness (K_{1C}) below 15 MPa.m$^{1/2}$. Almost all metals commonly used in the market are above this limit, ranging from 20 to 100 MPa.m$^{1/2}$. White cast iron and some powder metallurgy products cannot meet this requirement, whereas ordinary engineering ceramics have values in the range of 1-6 MPa.m$^{1/2}$ and are the preferred materials when sensitive choices are required in applications.

Unfortunately, polymers as engineering materials fall below these values, ranging between 0.5-3 MPa.m$^{1/2}$. Despite this extremely low plane strain fracture toughness, polymers are widely preferred in engineering applications.

When a brittle material deforms, it deflects elastically until it breaks. The stress value at which this occurs is calculated using the following equation (Ashby, 2005b).

$$\sigma_f = \frac{C\ K_c}{\sqrt{\pi a_c}}$$

Equation 1 shows that Kc is an appropriate fracture toughness, the length of the largest crack in the material, and C is a geometry-dependent constant typically around 1. As can be understood from the equation, high fracture toughness will increase load capacity, but some designs have energy limitations, some have deflection limitations, and some have geometric limitations. An important criterion underlying the preference of polymers as firearm materials is the C parameter in this equation. The variability of the parameter indicates the variability of material strength. It is clear that polymers offer more design freedom than metals. Their spring-like properties, high angular, parallel, and axial flexibility, and good shock absorption properties offer many opportunities that can be exploited in engineering design.

Polymer materials are under the influence of different forces during their use. Knowing the mechanical properties, which we express as reactions to these effects, has an impact on many details from design to raw material manufacturing.

The first and most important value to be known is the tensile stress, from which the yield stress, which indicates the transition of the material from the elastic to the plastic region, can be derived as a function of this value. A third parameter that emerges from this is elasticity. It is an important engineering parameter that expresses the magnitude of the elastic deformation region. It is a parameter that shows how much of the deformation resulting from the applied stress can be recovered and to what degree elastic deformation can be achieved. Ductility, which is frequently used, is a value different from elasticity, explained by two parameters: elongation and fracture shrinkage. Elongation is the increase in length of the standard tensile specimen before breaking, while breakage shrinkage is the ratio of the change in cross-sectional area of the tensile specimen to its initial cross-sectional area.

As with metals, polymers also deform when stresses below the yield stress are applied for long periods of time. This mechanical property, referred to as creep, is a value that must be carefully calculated under working conditions such as high repetition counts. For this purpose, a sudden load of a magnitude that will not deform the polymer is applied to the polymer. The polymer undergoes elongation when subjected to this deformation effect for a long time, and the polymer deforms. The suitability of the developed polymer for firearm designs must be investigated by monitoring the amount of deformation over time. Since polymers have a chain structure and contain folded chains, after a while, these chains begin to slide over each other under the effect of the load, and plastic deformation occurs due to elongation. Therefore, the chain formation in the internal structure of polymers is also important in firearm use.

In addition to these, hardness, which is a measure of the resistance of the material's surface to indentation, toughness, which is a measure of the energy required to break the material and is measured by the area under the stress-strain curve, and the impact resistance of materials to sudden impact are important mechanical properties.

Sampling

The parameters to be considered in determining the material to be used for manufacturing a light weapon to operate at peak efficiency are ranked in order of importance as follows: Modulus of elasticity, Strength, Impact resistance, Wear resistance, Dimensional stability at temperature, Hardness, Water absorption resistance, Corrosion resistance, Density, and Cost.

In terms of processing, polymers can be divided into thermoplastics and resins using FDM and photopolymerization AM technologies. In FDM, PLA; polyamides (PA), ABS, and high-impact polystyrene (HIPS); PC, ABS, PLA, TPLA, PA, and TPU; and nylon have been used. While process parameters such as print temperature and bed temperature are well known for these materials, others are largely application-dependent. All these polymer materials are relatively inexpensive and flexible compared to other engineering materials. Therefore, polymers are used in many defense industry applications, ranging from armed unmanned aerial vehicles to simple prototyping, from high impact resistance to high performance requirements, and from dynamic to bio-inspired (Colorado, Cardenas, Gutierrez-Velazquez, Escobedo, & Monteiro, 2023).

An examination of today's light weapon industry reveals that certain polymer groups are clearly preferred. Among all commercially available polyamide-based polymers, PA66 has the highest melting point and is a material group with high mechanical strength values since it does not contain side chains or interchain cross-links on the main chain.

Amorphous polymers are not preferred in weapons. This is because amorphous materials are sufficiently brittle at low temperatures. Glass fiber reinforced PA66 is the most commonly used polymer in light firearms. The most important characteristics of PA66 in firearm manufacturing are as follows: hardness, toughness, good thermal stability, flame retardancy, electrical resistance, chemical resistance, lightness, low cost, and suitability for mass production.

In addition to being strong and durable, they possess good mechanical and tribological properties. They have high corrosion resistance. They are used in the machine industry, in gear wheels, sliding bearings, and in the defense industry.

PA66 also has the highest melting point. It has a semi-crystalline structure. PA 66 melts at 265 degrees and has a continuous use temperature of 120 degrees. As with PA 6, there is a wide variety of products available with different viscosity values, reinforced with glass fiber and similar fibers, rubberized, with high thermal resistance, mineral-filled, flame-retardant, and UV-resistant.

PA 66 has high strength and hardness. It is resistant to thermal deformation. It exhibits excellent resistance to repeated stress and sudden impacts. It also has very high flexural and tensile strength, a low coefficient of friction, and is the most suitable material for working under load. Elastomers are added to increase its impact resistance, while glass fiber is used to reinforce its strength, hardness, and fatigue resistance. It has effective dielectric properties. It exhibits excellent resistance to lubricants, fuels, hydraulic fluids, paints, cleaning chemicals and detergents, aliphatic and aromatic solvents. It also has resistance to aqueous solutions and salts. It exhibits excellent resistance to hot water and even steam. (Karslı, 2016).

Numerous experimental studies are conducted in the production of firearm barrels. Tests such as density, hardness, tensile strength, impact, corrosion, water absorption, and impact resistance are performed.

The main body, grip, magazine base, magazine spring, slide, front sight, trigger, cover retaining part, needle retaining part, needle spring protector, and needle cap of some locally produced polymer composite-based pistols are manufactured from polymer-based composite materials.

For parts in light weapons that operate under low stress values and are not expected to have high dimensional stability, glass fiber reinforced PA66 composite material at a level of 30% can be used for more economical manufacturing. Increasing the fiber reinforcement in composite materials linearly increases the strength and hardness of the composite material. However, the highest strength and hardness values are achieved with 40% carbon fiber reinforced PA66 material. The glass fiber reinforcement ratio is increased to 25-30% in the main body part, which is of critical importance in weapons and is exposed to high-intensity repeated impacts depending on the weapon's operating system, while other parts have a glass fiber reinforcement of 15-25%.

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