UNIVERSITA' DEGLI STUDI DI MODENA E REGGIO EMILIA
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Ph.D. THESIS
IN INDUSTRIAL AND ENVIRONMENTAL ENGINEERING
(Mechanical and Vehicle Engineering from XXXVI cycle)

Predictive models of plastic deformation and mechanical analysis simulation applied to highly stressed components: engine connecting-rod.

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0. Abstract

This thesis focuses on the predictive modeling of mechanical properties of steel components obtained by forging and machining, applied to engine connecting rods, which are critical components in converting reciprocating motion into rotary motion in internal combustion engines.

The research presents a comprehensive analysis of the evolution of the connecting rod, from its ancient origins to its modern applications, emphasizing the significance of material selection, manufacturing techniques, and simulation methodologies in enhancing its performance.

Subsequently, materials used for connecting rods manufacturing are studied, analyzing the transition from early materials like different types of carbon steel and alloys, up to the latest composites and powder-originated solutions.

The thesis further explores modern manufacturing techniques, including forging in its different versions, CNC machining and sintering, which have significantly improved the precision and quality of connecting rods. The role of heat treatments in enhancing the mechanical properties of these components is also discussed, with a particular focus on quenching, tempering, and annealing processes.

A key aspect of the research is the application of Finite Element Analysis (FEA) in predicting the mechanical properties of connecting rods under various process conditions, depending on how the part is manufactured and making process alternatively selectable in industrial scale.

The use-case study involves the production and mechanical properties prediction of a 20kg engine connecting rod using open-die forging simulation versus close-die forging: the simulation results provide insights into effective strain distribution, fiber trends, and potential improvements in the design and manufacturing processes.

In conclusion, this thesis contributes to the field of mechanical engineering by providing a detailed understanding of how predictive modeling can optimizing the design, testing and manufacturing phase of new versions of highly stressed engine components.

Method introduced can lead to a reduced time-to-market and lower development costs for critical-to-assembly parts, since manufacturer can select the most convenient process, instead of relying on traditionally used ones.

1. Introduction

1.1 Background, context and industrial application

Large-bore engines are used in ship-power and generative power plants, as generator for electricity and co-generator for heat and electrical energy.
Tipically, large engines have bore size from 180 to 500mm (4 stroke type, common industrial application), with single cylinder power from 250 up to 1.200kW.
Major players in this field produce up to 5.000 cylinders/year in the whole large-bore sector of running engine models, developing in parallel minimum 1 engine version per year, aiming to achieve improved performance (fuel consumption optimization, higher output rate or service availability).

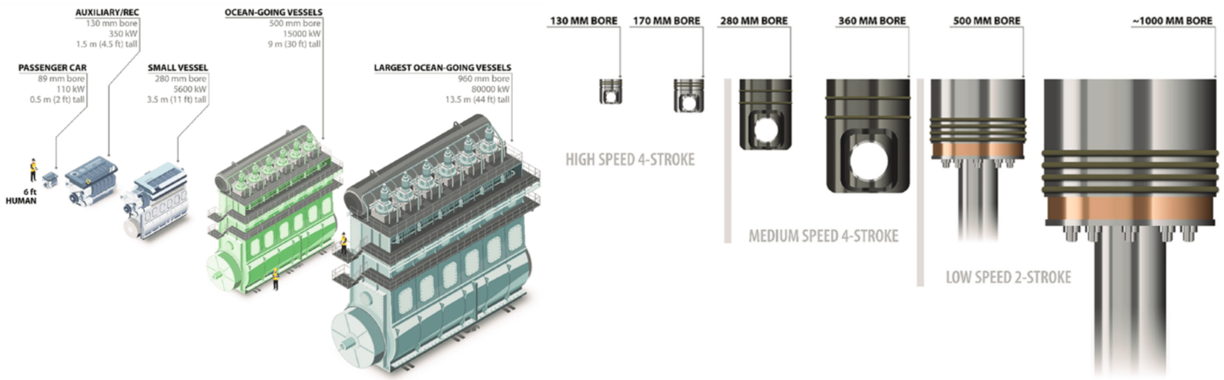


Figure 17. large bore engine examples (4 stroke on the left, 2 strokes on the right)

1.2 Problem Statement: Prototyping con-rods with open-die

For the reason mentioned above, con-rod development phases should use different process, making sure that mechanical properties and behaviour is well predicted and convergent between each step:

- First prototype for single cylinder engine requires quick realization and low capital expenditure → open-die forging process
- Pilot lot of parts might require some technical improvement in material/shape/features coming from Single Cylinder Engine application and still requires short lead-time and low investment, as design might again change → open-die forging process

- Serial production batches requires low unit cost, while equipment lead-time can be developed in parallel to sampling stages → close-die forging process
  Since design is frozen and approved by field test reports on pilot lot, final production equipment can be developed so to produce mass quantities of parts.

For these types of engine, **connecting rod size** weight range goes from 20 up to 700kg.
While engine development take 3-5 years time to market spam to be developed, several prototyping steps are done to prove the design choices and test the actual reliability of each engine:

- Single cylinder engine (S.C.E.) dry-test: cynematism verified, with no gas/injection.
- S.C.E. firing, checking the actual
- Multi-cylinder test from 500-4.000h, testing the actual performance and reliability.

Connecting rod is one of the key components to be developed (together with crankshaft, cylinder head and fuel injection system) and checked during the development phase; full development of con-rod can take several months and high investment.
Taking as example 150mm bore engine, con-rod weight is approximately 20kg size.
As seen in the introduction, 2 main process can be used to produce connecting rods:

1. Close Die Forging → near net shaping → partial CNC machining

Figure 18. close-die forging example (from case-study)

2. Open Die forging → rough shaping → full-profile CNC machining

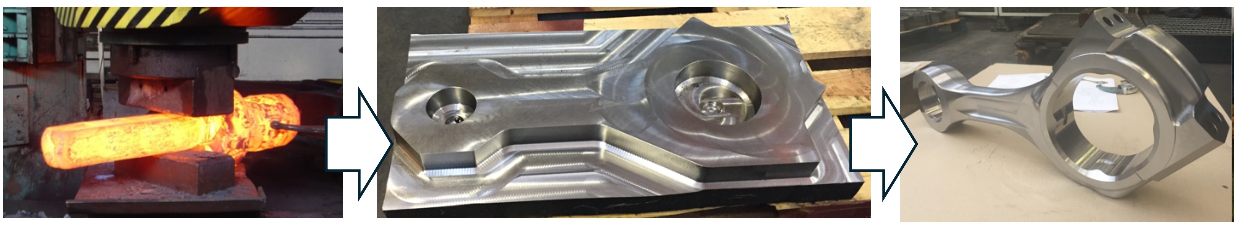


Figure 19. open-die forging example (from case-study)

While close-die forging is the most efficient and cheap process for industrial scal production, since near-net shape reduce forging input weight and machining time/cost, it involves:

- High capital expenditure: forging equipment can cost up to 5.000€ each kg weight of the con-rod
- Long development time: forging equipment can take up to 6 months to be studied and manufactured
- Low flexibility in design change: one manufacturing and forging equipmens is realized, con-rod profile and design cannot be changed or improved even if field test show weak points.

1.2.1 Samples for new engines

Industrial problem of this case is that samples and pilot lot are produced typically with final equipment of close-die forging, meaning long development time and high initial cost, with low possibility to change the design during development phase, as final forging tools are manufactured. For industrial application, best case would be introducing the possibility to produce initial sample in low quantity and short time (1-10 pcs range) knowing in advance that mechanical properties and fatique behaviour will be aligned to final product made by close-die forging.

1.2.2 Parts for service: fast production

The possibility to produce small quantities of parts (by open-die forging) with same properties of industrially close-die forged properties would allow also to produce parts for service and revamping applications.

Large bore engines are typically in operations for more than 30 years and they overtake several steps of maintenance and overhauling: in case of damages, or after 30-40.000h operations, some model of engine require a full substitution of con-rod parts together with other wear equipment.

As OEM producers of engines keep spare parts on stock for 15-20 years, it frequently happens that spare parts are needed and close-die forging equipment is not anymore available and production of small quantities of parts become expensive and time-absorbing due to new equipment (9 months, up to 100.000€ Capital Expenditure).

The possibility to produce service parts from open-die forging, predicting and selecting mechanical properties so to make the parts suitable for use in parallel to close-die forged con-rods would make the solution very interesting for all players in spare parts market.

1.3 Research Objectives, Significance of the study

Using predictive studies and FEM analysis, the target is to predict final properties of the part in terms of:

- Grain size and fiber orientation

- Mechanical properties
- Hints on fatigue behavior, to be tested on field at industrial level

This application will allow to select the most convenient process based on time, initial investment and cost, controlling the process parameters in order to obtain the needed mechanical process.

Also, trial and error phases will be reduced if mechanical properties can be predicted and selected from the design phase, instead of repeat sampling stages which ab

1.4 History of connecting rod

In the realm of mechanical engineering and engine design, the connecting rod stands as a pivotal element that has played a fundamental role in converting reciprocating motion into rotary motion. This chapter aims to delve deeply into the history of the connecting rod, from its ancient origins to its modern-day applications in internal combustion engines and beyond. Through meticulous analysis, we endeavor to comprehend the evolution of this component within the context of mechanical engineering and technological advancement.
The history of the connecting rod is inherently intertwined with the development of mechanical engineering and the industrial revolution. Understanding the historical trajectory of the connecting rod is crucial for fully appreciating technological progress in the realm of engines and machinery.

1.4.1 Historical origins of the connecting rod and its development through the centuries

The history of the connecting rod traces its roots back to ancient civilizations, where human ingenuity began shaping simple mechanics to meet every day needs and primitive industrial tasks. The earliest traces of connecting rods date back to ancient civilizations such as Egyptian, Greek, and Roman, where archaeological findings suggest a primitive use of mechanisms involving the principle of the connecting rod. Even during the time of ancient Egyptians, machines and devices were discovered, including hand mills for grinding grain or flour, which may have employed primitive connecting rods to convert the rotary motion of the crank into linear motion to drive the mills [1]. Ancient Greece also made significant contributions to the development of similar mechanisms, as evidenced by ancient texts and writings of historians such as Herodotus and Ephorus of Cyme. Greek inventions, such as the Antikythera mechanism, believed to have been used for astronomical and calendrical purposes, may have employed connecting rods or similar mechanisms for motion transformation. Similarly, the Romans utilized advanced engineering techniques to build machines and devices to perform tasks requiring complex movements, such as textile production or metalworking. During the Middle Ages and the Renaissance, the knowledge and engineering techniques developed by previous civilizations continued to evolve. However, practical applications of connecting rods during this period remained primarily limited to manufacturing and craftsmanship [2]. During the Renaissance, with the resurgence of interest in science and technology, there was renewed interest in mechanical engineering and practical applications of physics. However, despite these developments, the use of connecting rods remained largely confined to limited contexts and specific applications. With the advent of the Industrial Revolution in the 19th century, the connecting rod underwent an unprecedented transformation, becoming a key component in industrial machinery and early steam engines. The advent of steam engines represented a turning point in mechanical engineering during the Industrial Revolution. The connecting rod played a crucial role in this context, transforming the reciprocating motion of the piston generated by steam into a usable rotary motion to power industrial machinery and equipment [3]. The introduction of steam engines into factories and mills led to a growing demand for efficient mechanisms for motion transformation, stimulating the development and widespread adoption of connecting rods in steam engines. During the Industrial Revolution, numerous technological advancements occurred that influenced the design and operation of connecting rods. The use of new materials, such as steel, allowed to produce stronger and more durable connecting rods capable of withstanding higher workloads [4]. The introduction of new machining techniques, such as milling and forging, allowed to produce more precise and uniform connecting rods, improving the efficiency and performance of steam engines. Connecting rods found wide application in a range of industrial applications, from driving textile machinery and mills to propelling locomotives and ships. Steam locomotives represented a convergence point for many innovations in mechanical engineering, including the optimization of connecting rods to improve the efficiency and performance of engines [5]. The evolution of the connecting rod during the Industrial Revolution had a significant impact on the economy and society of the time. Innovations in mechanical engineering and industrial production helped improve the efficiency and productivity of factories and industries, stimulating economic growth and the expansion of national and international markets through railway transportation [6]. Connecting rods played a crucial role in transforming the thermal energy generated by the combustion of coal into usable mechanical work to power industrial machinery and equipment, thereby contributing to the growth and development of the industrial economy [7].

1.4.2 Internal combustion engines

The evolution of internal combustion engines represents a pivotal chapter in the history of mechanical engineering and the automotive industry. From simple prototypes to sophisticated and highly efficient machines, internal combustion engines have undergone a continuous and significant process of development over the decades. In this context, the connecting rod has played a crucial role, as it is one of the fundamental components that converts the reciprocating motion of the pistons into useful rotary motion for driving vehicles and machinery.

The early 19th century marks the birth period of internal combustion engines. The Belgian inventor Étienne Lenoir is considered one of the precursors of this technology, having developed the first functional internal combustion engine in 1859. Lenoir's engine, known as the "gas engine," used coal gas as fuel and operated on the principle of internal combustion. However, this early model was inefficient and impractical for widespread use.

Subsequently, in 1862, Alphonse Beau de Rochas, a French engineer, developed the four-stroke thermodynamic cycle, which still forms the basis of modern internal combustion engines. This cycle, known as the Beau de Rochas cycle, involved four phases: intake, compression, power, and exhaust. The adoption of this cycle significantly contributed to the efficiency and performance of internal combustion engines. [7]

One of the pivotal points in the history of internal combustion engines is represented by the work of the German Nikolaus Otto. In 1876, the German inventor built the first functional four-stroke engine. This engine, known as the "Otto engine," was the precursor to modern gasoline engines and revolutionized the automotive industry and mechanical engineering. Otto's engine used the four-stroke cycle and employed gasoline as fuel, introducing a more economical and efficient alternative to the steam engines that dominated at the time.

Over the years, internal combustion engines have undergone numerous improvements and optimizations. The 20th century witnessed an acceleration in the production and use of internal combustion engines, with the introduction of advanced technologies such as electronic fuel injection, electronic engine control, and the use of lightweight alloys to reduce weight and improve performance.

In this context of technological development, the connecting rod has maintained its importance as an essential component, transmitting the reciprocating motion of the piston into rotary motion that drives the vehicle or machinery. Its function has been crucial in ensuring the proper transmission of motion and maintaining synchronization between the piston and the crankshaft. Its design and operation have been continuously refined over time to improve engine efficiency and performance. [7]

The advent of internal combustion engines has had a revolutionary impact on society and the global economy. These engines have made possible the mass production of vehicles and machinery, revolutionizing the transportation and industrial production sectors.
The introduction of new technologies, such as direct fuel injection and the use of lightweight materials to reduce engine weight, has contributed to improving engine efficiency and performance.
The analysis of the origins of the connecting rod reveals an intricate path of technological development and innovation in the field of mechanical engineering. From ancient civilizations to industrial revolutions, the connecting rod has continued to play an essential role in the transfer of motion and the evolution of modern machines and engines.

1.5 Materials used in connecting rods

The analysis of materials used in the production of connecting rods throughout history reveals a path of continuous development and innovation in engine engineering. Since its earliest manifestations, connecting rods have been subjected to a constant search for optimal materials and manufacturing techniques to ensure reliable and durable performance.
The early connecting rods were often made of materials such as wood or iron, providing some strength but were prone to rapid deterioration and failures. With the advent of the industrial revolution, progress in metallurgy and production processes allowed the introduction of forged steel connecting rods, which offered greater strength and durability compared to previous materials.
The evolution of internal combustion engines during the 19th and 20th centuries led to further improvements in the materials used in connecting rods. The adoption of advanced steel alloys enabled the production of lighter and stronger connecting rods, enhancing the overall performance of engines. Additionally, the introduction of connecting rods made of lightweight alloys such as aluminum and titanium helped reduce the engine's weight and improve fuel efficiency. Moreover, the possible use of composite conrods has been introduced as well.
However, the selection of materials for connecting rods is not limited solely to their mechanical strength but also includes considerations such as thermal conductivity, corrosion resistance, and ease of processing. Optimizing the material properties of connecting rods is essential to ensure reliable and durable performance over time. For example, connecting rods made of aluminum alloys offer excellent thermal conductivity, reducing the risk of engine overheating, while stainless steel connecting rods are highly resistant to corrosion, making them ideal for marine or industrial applications. [8]
The analysis of the materials used in the production of connecting rods throughout history reflects a constant commitment to innovation and optimization of the performance of internal combustion

engines. From the early wooden or iron connecting rods to modern lightweight and durable alloys, progress in materials and manufacturing techniques has significantly contributed to the evolution and reliability of engines.

1.5.1 Carbon and Alloy Steels

Figure1 Steel conrod for small-bore engine

Among the most common materials used to produce connecting rods, carbon and alloy steels hold a predominant position, thanks to their exceptional mechanical properties and wide availability in the market.

Carbon and alloy steels are a common choice for manufacturing connecting rods due to their relatively low cost, ease of manufacturing, superior mechanical properties and market availability. Carbon steels are ferrous alloys with a carbon content of less than 2%, characterized by a combination of strength, ductility, and toughness. These properties make carbon steels suitable for a wide range of applications, including connecting rods in internal combustion engines. Alloy steels, on the other hand, are characterized by the presence of other alloying elements such as chromium, manganese, nickel, and molybdenum, which impart greater strength and hardness compared to carbon steels. Alloy steels like chromium-molybdenum steel are particularly suitable for high-performance applications that require superior fatigue and corrosion resistance.

Connecting rods made from carbon and alloy steels are widely used in a variety of applications, from the automotive industry to aerospace. These connecting rods are employed in internal combustion engines of production vehicles, such as cars, trucks, and motorcycles, where they offer an optimal balance of performance, strength, and cost. Carbon steels are particularly suitable for non-high-performance engines, where strength and durability are still crucial. Alloy steels, on the other hand, are preferred in high-performance engines, such as those used in sports and racing vehicles, where performance takes priority over cost. Additionally, connecting rods made from carbon and alloy steels find applications in other industries, such as aerospace and naval industries, where strength and lightness are essential for application success. [9]

The design and manufacturing of connecting rods in carbon and alloy steels require careful consideration of mechanical stresses and specific engine performance requirements. The design of connecting rods must account for factors such as maximum load, maximum engine speed, and expected engine lifespan. Furthermore, the manufacturing of connecting rods requires the use of advanced machinery and production processes to ensure maximum precision and the best possible quality. The use of techniques such as CNC machining and CAD modeling enables highly precise design and manufacturing, ensuring compliance with design specifications and optimal performance in the engine. [10]

Connecting rods made from carbon and alloy steels represent a reliable and versatile choice for a wide range of internal combustion engines.

1.5.2 Light alloys

Figure 2 Aluminum (left) and titanium (right) conrods

The creation of connecting rods using aluminum and its alloys in mechanical engineering has garnered significant attention due to the advantageous properties these materials offer. The use of aluminum in connecting rods primarily stems from its light weight, which directly translates to reduced reciprocating mass in the engine, leading to improved performance and efficiency. Notably, aluminum alloys can reach high strength-to-weight ratios, an essential aspect for the demanding operational conditions of internal combustion engines.

Aluminum's low density (approximately one-third that of steel) ensures that when it is used to fabricate connecting rods, the result is a substantial reduction in the weight of the reciprocating components. This reduction contributes to lower rotational inertia, allowing the engine to accelerate more rapidly and achieve higher RPMs with less effort. [11] Lower reciprocating mass is particularly beneficial in high-performance and racing engines, where every ounce of weight reduction can lead to significant competitive advantages.

Moreover, aluminum alloys can sustain high-strength conditions due to advancements in material science, particularly in formulations such as 7075-T6, which combines aluminum with zinc,

magnesium, and copper to achieve superior mechanical properties. These high-strength alloys exhibit tensile strengths that can exceed those of some steels, thereby making them suitable for the high-stress environments experienced by connecting rods during engine operation.
Additionally, aluminum's excellent thermal conductivity allows it to dissipate heat more effectively than steel, thus preventing overheating and minimizing the risk of thermal fatigue. This property helps maintain dimensional stability and prolongs the lifespan of the connecting rods under continuous and strenuous operation. Furthermore, aluminum naturally forms a protective oxide layer that grants it superior resistance to corrosion compared to iron and steel, which is particularly advantageous in the chemically aggressive environment of an internal combustion engine.
In addition to mechanical properties, the corrosion resistance of aluminum alloys makes them ideal for the harsh environments inside combustion engines where exposure to fuel, oil, and other corrosive agents is routine. Aluminum forms a naturally protective oxide layer that guards against corrosive damage, extending the service life of the components even under continuous exposure to potentially harmful substances.
The use of aluminum also comes with certain drawbacks. Primarily, aluminum alloys tend to have lower fatigue strength compared to high-strength steels. This can lead to durability issues under the cyclic loading conditions experienced in engine components, necessitating more frequent inspection and potential replacement. [12] Additionally, the manufacturing process for aluminum connecting rods can be more complex and costly. Aluminum alloy components often require precise control of the casting and forging processes to achieve the desired mechanical properties and to avoid defects such as porosity or inclusions that can compromise the component's integrity.
In summary, while aluminum connecting rods offer substantial benefits in terms of weight reduction, thermal management, and corrosion resistance, they also present challenges related to fatigue strength and manufacturing complexity. These factors must be carefully balanced to optimize the performance and durability of high-performance engines.

1.5.3 Composite materials

Figure 3 - Composite conrod [4 - Website]

The application of composite materials in the manufacturing of connecting rods presents an innovative approach that could revolutionize the field of mechanical engineering. Composite materials, such as carbon fiber reinforced polymers (CFRP), offer significant advantages over traditional materials like aluminum alloys and steel. One of the primary benefits of composites is their high strength-to-weight ratio, which results in a substantial reduction in the mass of the connecting rod. This reduction not only enhances engine efficiency but also contributes to lower fuel consumption and reduced emissions. Additionally, composites exhibit excellent fatigue resistance, surpassing that of conventional metals, which is crucial for the longevity and reliability of engine components. [13]

Despite their strength, composites are often more costly due to complex manufacturing processes and the expense of raw materials. Moreover, they can be sensitive to environmental conditions, such as moisture and temperature variability, which may affect their performance and durability over time.

In comparison to traditional materials like aluminum—all renowned for their light weight and good corrosion resistance—and steel—celebrated for its high strength and durability—composites stand out in specific applications but require careful consideration regarding their limitations and costs. [14]

Table 1. Comparison table of materials

Property	Composite Materials (CFRP)	Aluminum Alloys	Steels
Density (g/cm³)	1.5-2.0	2.7	7.8
Tensile Strength (GPa)	1-5.5	0.1-0.5	0.3-2
Fatigue Resistance	Excellent	Good	Very Good
Corrosion Resistance	Variable	Excellent	Moderate to Poor
Thermal Conductivity (W/m·K)	25-48	150-200	40-60

Certain composite materials exhibit high-temperature stability, ensuring both dimensional stability and mechanical integrity under the intense thermal conditions within an engine. This, combined with their inherent corrosion resistance, reduces maintenance requirements and extends the service life of components. Furthermore, composites provide substantial benefits, including significant weight reduction, enhanced strength, and superior fatigue resistance, which are critical for high-performance applications. [15]

However, the use of composites in connecting rods presents several challenges and disadvantages. The manufacturing processes, such as autoclave processing, resin transfer molding, or filament winding, are typically more complex and costly than those for conventional metals. These methods require precise control over variables to achieve the desired material properties, and any inconsistencies can lead to defects that compromise the structural integrity of the component. Additionally, the anisotropic nature of composite materials means their mechanical properties can be directionally dependent, necessitating meticulous design and analysis to ensure reliability under all loading conditions.

Moreover, the repair and recycling of composites are less straightforward than for metals, adding to the cost and complexity of their use. Despite these challenges, ongoing advances in material sciences and manufacturing technologies are mitigating some of these disadvantages, making composites an increasingly viable option for high-performance engine components.

While composites offer substantial advantages, the complexities associated with their manufacturing and their direction-dependent properties present notable challenges. These challenges must be effectively addressed to fully capitalize on the potential of composites for use in engine connecting rods. [16]

Summarizing, selecting a material for conrods requires a deep knowledge of materials properties and of the project requirements, and it can be conducted also using dedicated software, as shown in figure 4 concerning high performance conrod materials as a function of the applied force (F) and length (L) of the conrod, requiring that no buckling occurs and fatigue resistance is maximized.

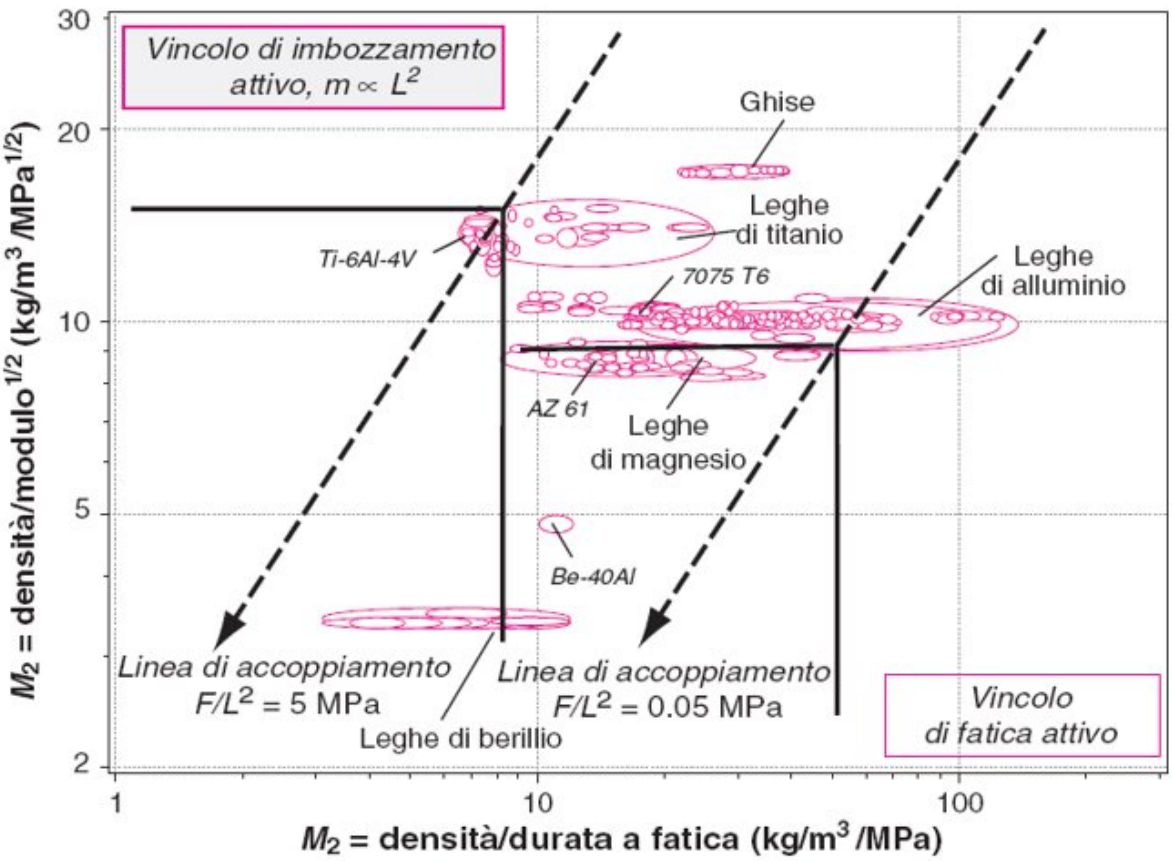


Figure 4 material selection chart for conrods

However, manufacturablity of the conrod, and in particular its splitting, are also mandatory requirements for the material selection.

1.6 Evolution of deformation and machining techniques

1.6.1 Forging

Forgings are categorized through various criteria, initially distinguished by the general classifications of open die and closed die. Further classification is based on the close-to-finish factor, which denotes the amount of material (cover) that necessitates removal by machining to meet the dimensional and detail specifications of the final part. Additionally, forgings are categorized according to the type of forging equipment utilized in their production, such as hammer upset forgings, ring-rolled forgings, and multiple-ram press forgings.
Among these classifications, those rooted in the close-to-finish factor are most closely linked to the inherent properties of the forging, including strength and resistance to stress corrosion. Generally,

forgings requiring minimal machining to meet final-part requirements tend to possess superior properties. Consequently, a finished part machined from a blocker-type forging typically exhibits mechanical properties and corrosion characteristics inferior to those of a part derived from a close-tolerance, no-draft forging.

It should be noted that reducing the amount of material requiring machining from the forging usually leads to increased die costs. Moreover, the capacity requirements of equipment may need to be elevated to produce a forging that is essentially net forged or closer to finished dimensions. [17]

1.6.1.1 Open die forging

Open die forging, also known as flat die or hammer forging, involves compressing the workpiece between a ram and an anvil or between two dies.

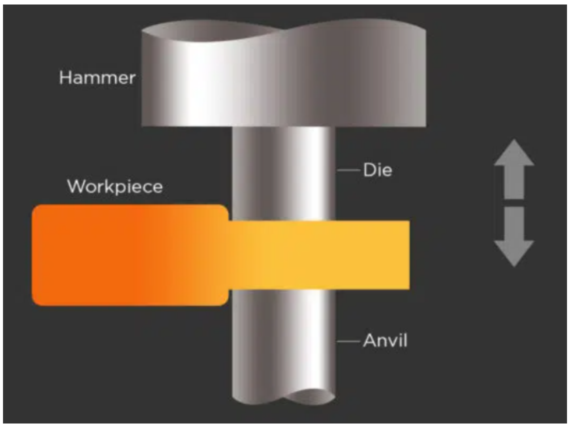


Figure 5. Open die forging process [1 - Website]

This process can be performed manually or by using power hammers. The anvil remains fixed at the bottom while the ram provides motion in both directions. In open die forging, the working surfaces of both the anvil and ram are flat and horizontal, restricting material flow in the lateral direction. The ram, typically a hefty falling weight, operates above the rigid support known as the anvil block. The upper die is mounted on the bottom of the ram, while the lower die is mounted on the top of the anvil.

Various die shapes, including concave and convex surfaces, are employed as needed for shaping the workpiece. The metal workpiece is heated above its recrystallization temperature, typically ranging from 1900°C to 2500°C.

Open die forging encompasses three main types of operations:

1. **Cogging**, also referred to as drawing down, involves thinning the stock at one end by hammering the workpiece with flat dies, resulting in a reduction in stock thickness and an increase in length.

2. **Edging and fullering**: Fullering is a primary forging operation in which concave and convex-shaped dies elongate the bar or workpiece along its length while decreasing the cross-section.
3. **Upsetting**: This forging operation involves increasing the lateral cross-section perpendicular to the axis of the applied force, while reducing the length of the workpiece. The phenomenon of barrelling may occur due to uneven material flow, with greater flow at the center than nearer to the dies, caused by friction. Upsetting in forging can be classified into three types: full upsetting, head upsetting, and central upsetting.

Open die forging presents several advantages in the manufacturing process. Firstly, it employs **uncomplicated tooling**, which simplifies the production setup and reduces associated costs. Moreover, it offers cost-effectiveness when compared to closed die forging methods. Additionally, open die forging provides versatility in shaping, allowing for a diverse array of geometries to be achieved. It is particularly well-suited for forging bars or slabs with circular, rectangular, or hexagonal cross-sections. Furthermore, it finds extensive application in repair or maintenance scenarios.

However, open die forging also entails certain drawbacks. One notable limitation is that it typically yields forgings with **lower accuracy** compared to closed die forging techniques. This reduced precision is often attributed to the reliance on the operator's skill level to achieve desired outcomes. Additionally, open die forging is best suited for smaller production runs, as it may not be as efficient for large-scale manufacturing processes. [18]

1.6.1.2 Closed die forging

Closed die forging is a forging method wherein cavities in the form of impressions are cut into the die block.

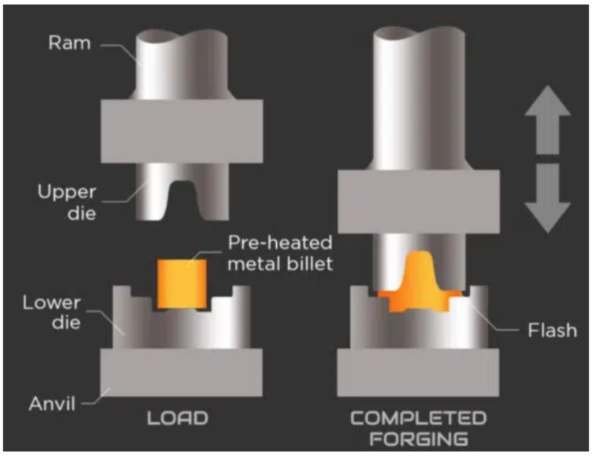


Figure 6. Close die forging process [1 - Website]

The dies utilized can be single or multi-impression, depending on the product requirements. These closed dies are meticulously machined to produce forgings with precise dimensions. During the operation, the heated metal piece is placed on the lower die block, and a machine hammer delivers blows to shape the metal according to the die's final dimensions. The lower die is mounted on the anvil, while the upper die is on the hammer. Excess metal escapes as thin fins or flash, and all forging operations are performed within a single die block.

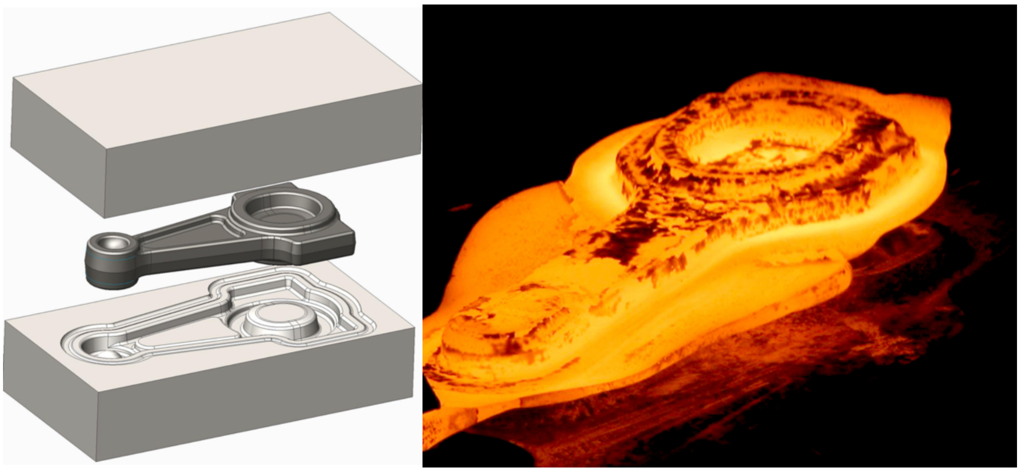


Figure 7. Close die forging example [1 - Website]

The closed die forging process demands meticulous attention to process parameters and tooling techniques due to the precision required for component manufacturing. Compared to conventional forging processes, closed die forging primarily focuses on producing **near-net or net-shape components** through precision forging techniques. The die is sealed shut by the punch or supplementary closing mechanisms during deformation. Multi-acting presses, spring assemblies, or independent closing devices are utilized to ensure the necessary pressure during deformation.

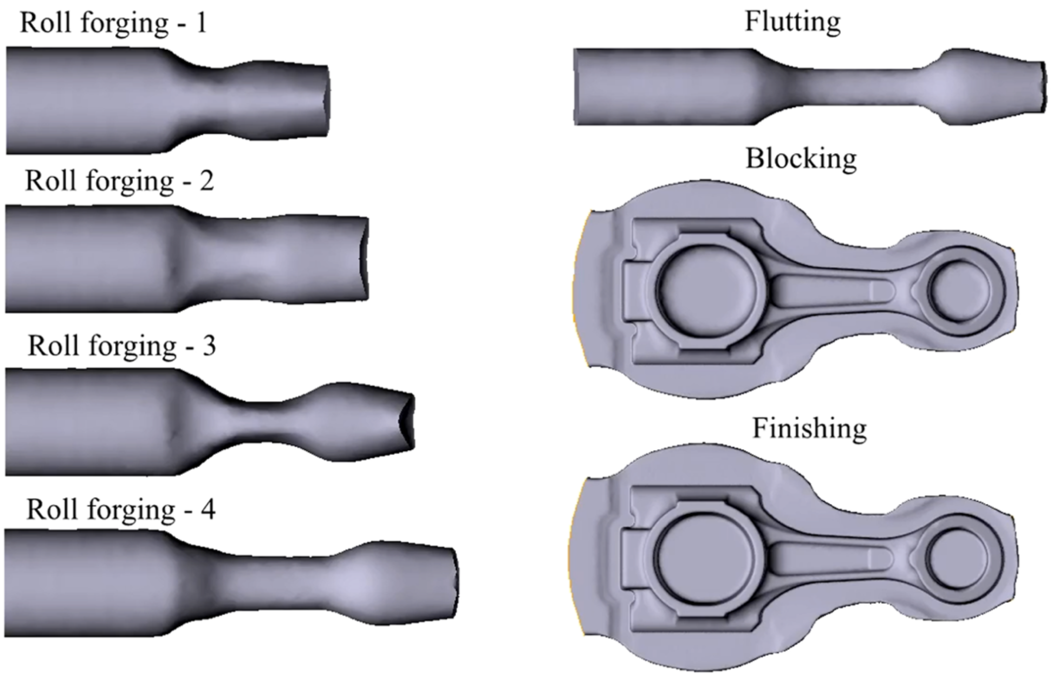


Figure 8. Close die forging main steps [1 - Website]

In situations where the punch cannot fully seal the die due to radial form elements like helical gearings, segmented dies or additional closing elements become necessary. Horizontally segmented dies leverage ram movement and spring assemblies to provide closing pressure, while vertically segmented dies require specialized devices to convert vertical press loads into horizontal closing forces during use in single-acting presses. [19]
Main phases and

1. Initial Heating Stage:

- The steel billet is heated in a furnace to a temperature range between 1150°C to 1250°C.
- Uniform heating ensures the billet reaches the forging temperature, minimizing temperature gradients within the material.
- The billet is soaked at the desired temperature to achieve a homogenous temperature distribution.

2. Transfer to Die [upsetting]

- The heated billet is quickly transferred from the furnace to the forging press.
- During transfer, there is a slight temperature drop due to exposure to ambient air.
- The transfer time is minimized to maintain the high temperature necessary for effective forging.

3. Initial Contact with Dies:

- The billet is placed in the lower die and the upper die begins to close.

- Initial contact causes a rapid temperature drop on the surface of the billet due to heat transfer to the cooler dies.
- The core of the billet remains close to the initial forging temperature, while the surface cools rapidly.

4. Deformation Stage [preform]:

- As the dies close, the billet undergoes plastic deformation.
- Deformation generates heat due to the work done on the billet, increasing the temperature locally.
- The highest temperature is observed in regions experiencing the most deformation.

5. Temperature Distribution:

- The temperature distribution within the billet becomes non-uniform.
- Hot spots develop in areas of intense deformation, while less deformed regions cool.
- The dies continue to extract heat from the billet, particularly at the interfaces.

6. Final Forging Stage [final form]

- The forging process is completed as the billet takes the shape of the connecting rod.
- The surface temperature of the forged part is significantly lower than the core.
- The temperature gradient can lead to residual stresses within the forged part.

7. Ejection and Air Cooling:

- The forged connecting rod is ejected from the die.
- It begins to cool in ambient air, with the surface cooling more rapidly than the core.
- Air cooling is uneven, potentially leading to thermal stresses and the need for post-forging heat treatment.

8. Trimming: After close-die forging, excess material known as flash forms along the parting line of the connecting rod:

- The forged connecting rod is transferred to a trimming press.
- The trimming press consists of a set of dies specifically designed to match the profile of the forged part, made of high-strength tool steel to withstand the forces involved

- The upper trimming die descends onto the forged part, applying pressure to shear off the flash.
- The excess material is separated cleanly along the parting line.

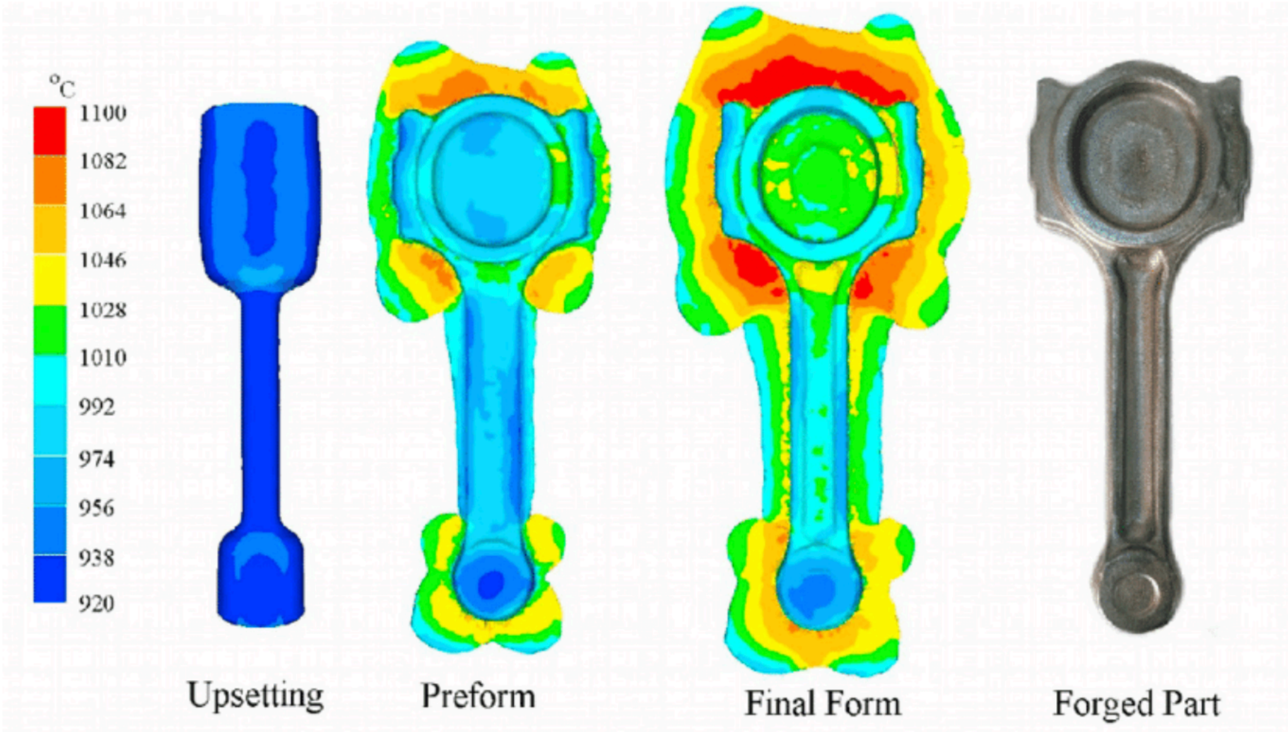


Figure 9. Close die forging temperature diagram [1 - Website]

Closed die forging stands out as a highly advantageous method within the manufacturing landscape. Its proficiency in crafting intricate and elaborate shapes with utmost precision is remarkable. Furthermore, it facilitates the production of large batches of identical components with exceptional accuracy, thus lending itself seamlessly to mass production scenarios. Unlike its counterpart, open die forging, closed die forging streamlines operations by eliminating the need for extensively skilled personnel, thereby curbing labor expenses. Additionally, the efficiency gains are palpable, as closed die forging typically boasts **shorter production times** compared to open die forging.
Despite its numerous merits, closed die forging does come with its share of challenges. Notably, the substantial **investment** required for **tooling** poses a significant financial hurdle, particularly impacting smaller-scale productions. This cost factor often renders closed die forging economically unviable for low-volume outputs, where the expenses may outweigh the benefits. Furthermore, meticulous planning is essential to determine the optimal material input into the die, ensuring minimal wastage and achieving desirable forging outcomes. [18]

1.7 CNC machining

In recent years, the application of Computer Numerical Control (CNC) machining for the manufacturing of connecting rods has gained significant attention within the field of mechanical engineering. CNC technology has demonstrated superior precision and repeatability, which is crucial in the context of high-performance automotive components such as connecting rods. CNC machined connecting rods exhibit enhanced mechanical properties, including improved tensile strength and fatigue resistance, compared to those manufactured using traditional forging methods. Furthermore, the flexibility of CNC machining allows for intricate geometries and customizations that are often unattainable with conventional techniques. [20] However, this advanced manufacturing method is not without its disadvantages. The high initial investment in CNC machinery and the associated software, along with the need for highly skilled operators, can considerably elevate production costs, making it less viable for low-volume manufacturing. Additionally, CNC machining often results in longer production times due to its subtractive nature, which involves the gradual removal of material from a workpiece, as opposed to near net shape manufacturing methods that require less finishing work. CNC machining can introduce microstructural inconsistencies and residual stresses due to the material removal process, potentially affecting the component's lifespan under cyclical loading. [21]

Despite these challenges, the advantages of CNC machining, such as precision, customization, and superior mechanical properties, highlight its viability and potential for widespread adoption in the production of connecting rods in the automotive industry.

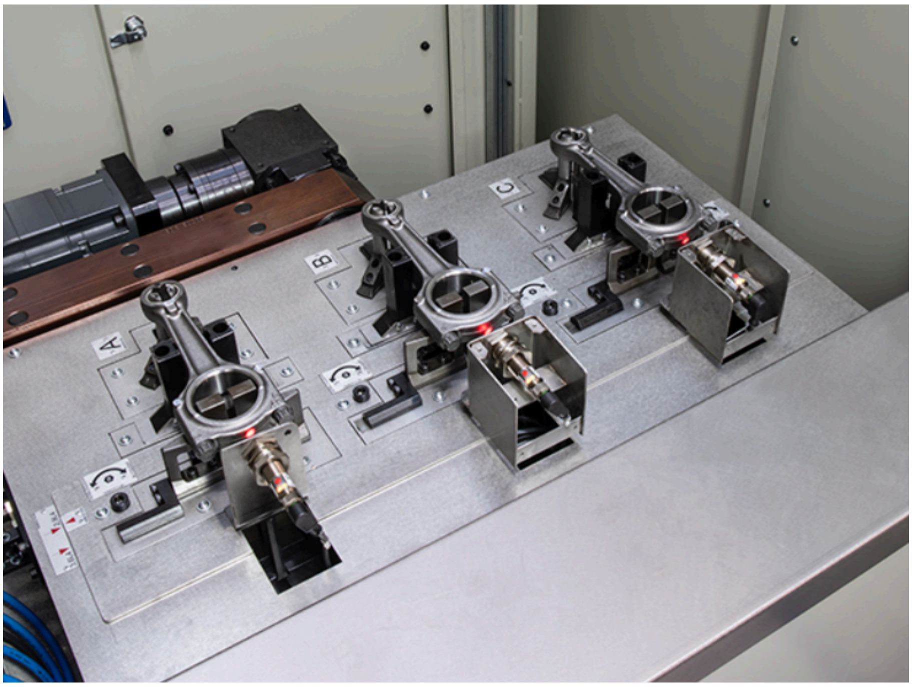

A
B
C

Figure 10. connecting rod CNC machining

1.8 Sintering

The production of connecting rods via sintering, a method rooted in powder metallurgy, has gained traction for its ability to engineer high-performance components with unique microstructural characteristics. Sintering involves compacting powdered metal into a desired shape and subsequently heating it to a temperature that is just below its melting point, thus allowing particles to bond to form a monolithic parts This process yields a microstructure that is remarkable for its homogeneity and fine grain size. Sintered connecting rods exhibit excellent mechanical properties such as high wear resistance and a superior strength-to-weight ratio, essential for the stringent demands of modern internal combustion engines. Additionally, sintering provides notable design flexibility, making it feasible to create intricate geometries that are either difficult or cost-prohibitive to achieve through traditional forging or casting methods. [22]

One of the prominent advantages of sintering is its capacity for near-net shape manufacturing, which minimizes material wastage and reduces the need for extensive post-processing. This efficiency could translate into significant cost savings, especially when scaled to mass production, despite the higher initial costs associated with high-quality metal powders and specialized sintering equipment. Furthermore, the process allows for the incorporation of alloying elements directly into the powder mix, thus enabling the tuning of material properties such as hardness, strength, and wear resistance to meet specific application requirements.

Despite these compelling advantages, there are notable drawbacks to the sintering process. One of the critical issues is the inherent porosity that can remain within the sintered components. Residual porosity can adversely affect the fatigue resistance of the connecting rods, potentially leading to premature failure under cyclical loading conditions, which is a significant concern for high-stress engine components. Another challenge is the potential for anisotropy in mechanical properties caused by the directional nature of powder compaction, which can result in variability in performance characteristics depending on the orientation of the load. [23]

Furthermore, the relatively slower production rates compared to forging and the necessity for precise control over the sintering environment add layers of complexity and cost to the manufacturing process.

Yet, ongoing advancements in powder metallurgy are addressing many of these issues. For instance, improved powder fabrication techniques are leading to powders with better sphericity and lower impurity levels, which in turn produce sintered parts with fewer defects and greater uniformity. Additionally, innovations in sintering technology, such as hot isostatic pressing (HIP) and spark plasma sintering (SPS), are being explored to reduce porosity and enhance mechanical properties. [24] These methods apply additional pressure during the sintering process, promoting better particle bonding and reducing internal voids, thereby significantly improving the fatigue life and overall performance of sintered connecting rods.

While the sintering process for manufacturing connecting rods presents challenges such as residual porosity and higher initial costs, its advantages in terms of weight reduction, material efficiency, and the ability to create complex geometries cannot be overstated. Advances in sintering technology continue to mitigate its disadvantages, making it a promising alternative to conventional manufacturing methods. The ongoing research and development in this field, suggest that sintered connecting rods will play a vital role in the future of high-performance engine components.

Figure 11. connecting rod from synthering.

1.9 Heat treatments

Heat treatment processes, such as quenching, tempering, carburizing, and annealing, are critical in the metallurgical engineering of steels, enabling the customization of their microstructural and mechanical properties to meet specific application requirements. Quenching involves rapid cooling from the austenitization temperature, typically utilizing mediums such as water, oil, or air, to induce the formation of martensitic structures, thereby increasing hardness and strength. Following quenching, tempering is employed to mitigate the brittleness of martensite by reheating the steel to a sub-critical temperature, facilitating the formation of tempered martensite which enhances toughness while maintaining adequate hardness. Carburizing, or cementation, is a surface hardening process where steel is exposed to a carbon-rich environment at elevated temperatures, allowing carbon atoms to diffuse into the surface layer, thus creating a hardened exterior while retaining a ductile core. Annealing, on the other hand, involves heating the steel to a specific temperature followed by controlled cooling, aimed at homogenizing the microstructure, reducing hardness, and enhancing ductility and machinability. In the subsequent sections, the techniques will be examined in greater detail, exploring their underlying metallurgical principles, processing parameters, and resultant microstructural and mechanical transformations.

1.9.1 Quenching

Quenching is a critical process in the heat treatment of steel, playing a pivotal role in determining the material's microstructure and mechanical properties. Quenching involves rapid cooling of heated steel to achieve desired mechanical properties. The success of the quenching process relies on controlling the cooling rate to promote the formation of specific microstructures, such as martensite. The choice of quenching medium, including water, oil, or air, significantly influences the cooling rate and subsequent microstructural changes. Water quenching is one of the most used techniques due to its high cooling rate. Water quenching results in rapid cooling, promoting the formation of martensite, a hard and brittle microstructure. However, excessive cooling rates can lead to distortion and cracking of the material. Therefore, careful control of the quenching parameters, such as agitation and temperature, is essential to mitigate these issues and achieve the desired properties. Oil quenching offers a slower cooling rate compared to water quenching, resulting in a less severe transformation of microstructures. However, the slower cooling rate may also lead to incomplete transformation and the formation of undesirable microstructures. To optimize the oil quenching process, it’s necessary to adjust parameters such as temperature and viscosity to achieve the desired balance between hardness and toughness. Air quenching involves cooling the steel using ambient air, resulting in the slowest cooling rate among the three quenching methods. Air quenching is preferred for low-alloy steels and applications where minimal distortion is desired. However, the slower cooling rate may limit the formation of martensite, leading to lower hardness compared to water or oil quenching. [25] Preheating the steel to higher temperatures before air quenching to enhance the transformation kinetics and achieve adequate hardness. In recent years, advancements in quenching techniques have led to the development of novel approaches to improve the efficiency and effectiveness of the process. Quenching is a vital process in steel heat treatment, influencing the material's microstructure and mechanical properties. Through careful selection and control of quenching parameters, such as quenching medium, temperature, and agitation, it is possible to tailor the properties of the quenched steel to meet specific application requirements.

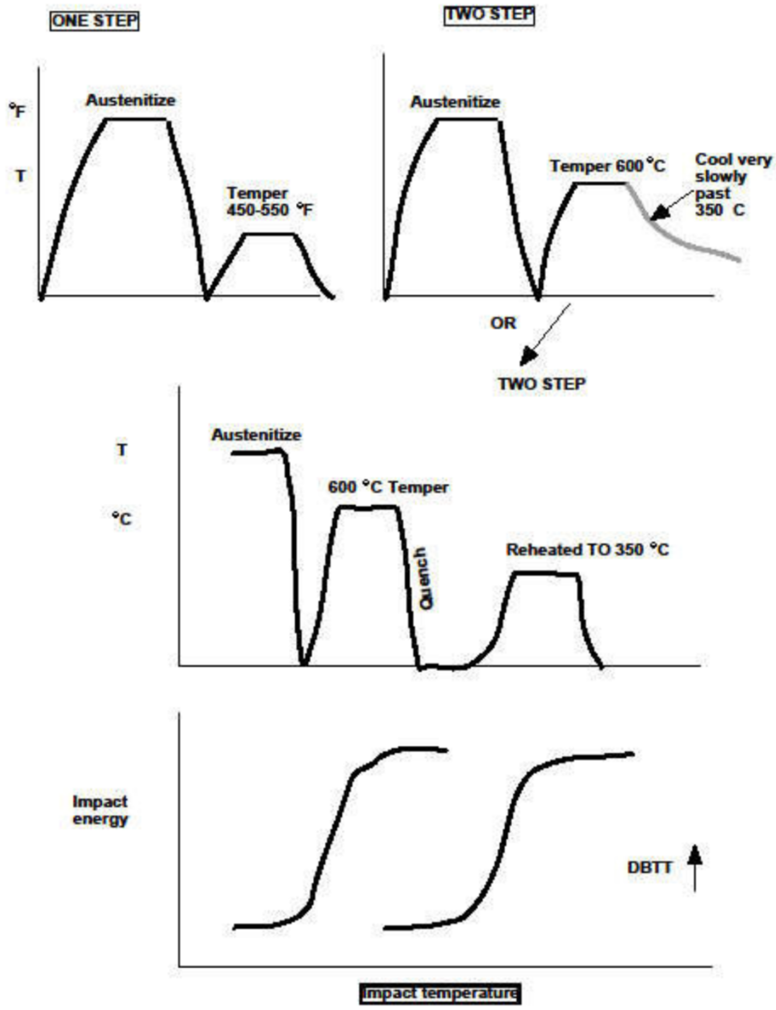


Figure 12. Quenching+ tempering diagram (2 options) for 42CrMo4.

1.9.2 Tempering

Tempering, a pivotal process in metallurgy, holds significant importance in enhancing the mechanical properties of steels. Tempering, commonly referred to as heat treatment, is integral to steel processing, particularly in improving toughness and ductility while maintaining hardness. The process involves reheating quenched steel to precise temperatures, followed by controlled cooling.

This facilitates the transformation of retained austenite and the precipitation of carbides, contributing to enhanced mechanical properties. The mechanisms underlying tempering are complex, involving phase transformations and diffusion-controlled processes. The redistribution of alloying elements and the formation of dislocations play crucial roles in determining the final microstructure and mechanical properties of tempered steels. [26]

Various tempering processes are employed in industrial settings, each offering unique advantages. Traditional tempering, involves heating the steel to temperatures between 200°C and 600°C, followed by air cooling. This process allows for the precipitation of fine carbides and the refinement of the microstructure, resulting in improved toughness and ductility. In contrast, cryogenic tempering, involves subjecting the steel to extremely low temperatures, typically below -100°C, to enhance martensite transformation and refine the microstructure further. This process has been shown to improve wear resistance and dimensional stability in steels, particularly in tooling and automotive applications.

Tempered steels find widespread applications across various industries, including automotive, aerospace, and manufacturing. The use of tempered steels in the production of critical components require high strength, toughness, and wear resistance, such as gears, bearings, and springs. Additionally, tempered steels are utilized in structural applications where a balance of strength and ductility is essential, such as in construction and infrastructure projects. [27]

Recent advancements in tempering techniques have focused on improving process efficiency and product performance. It's possible to apply surface modification techniques, such as plasma nitriding, in combination with tempering to enhance surface hardness and wear resistance. [28]

Tempering is a critical process in steel heat treatment, enabling the enhancement of mechanical properties to meet specific application requirements. Through a comprehensive understanding of tempering mechanisms and processes, coupled with advancements in technology and materials science, researchers and engineers can continue to innovate and improve the performance of tempered steels across diverse industrial applications.

1.9.3 Case hardenening

Case hardening, particularly through carburizing, is a pivotal heat treatment technique employed to enhance the surface properties of steel, making it a cornerstone in mechanical engineering for components that must endure high stress and wear. Carburizing involves carbon diffusion into the surface layer of low-carbon steel at high temperatures, followed by a quenching process, which results in a hardened outer case and a tough, ductile core. The methodologies of carburizing are diverse, ranging from pack carburizing, gas carburizing, and liquid carburizing to more advanced methods like vacuum and low-pressure carburizing. These latter techniques offer enhanced control over carbon potential and case depth, resulting in superior uniformity and reduced distortion compared to traditional methods

The primary properties imparted by carburizing include a significant increase in surface hardness and wear resistance, which are critical for high-performance applications such as gears, camshafts, and drive shafts. Carburized gears exhibit excellent load-bearing capabilities and resistance to surface fatigue, which substantially extends their service life under cyclic loading conditions. The hardened surface protects against abrasive and adhesive wear, while the softer core absorbs impacts and resists breakage. This combination of properties enhances the overall durability and reliability of the component. [29]

However, carburizing is not without its disadvantages. The process involves high temperatures and potentially prolonged exposure times, which can lead to undesired distortion and dimensional changes in the treated parts. Such thermal stresses necessitate post-treatment machining to restore the exact dimensions and tolerances, adding to the overall cost and complexity of the production (Bong, 2017). Moreover, traditional carburizing processes, especially gas carburizing, use hydrocarbon atmospheres, which can pose environmental concerns due to carbon emissions and require strict control to prevent carbon precipitation and soot formation.

On the other hand, advanced carburizing techniques like vacuum and low-pressure carburizing have been developed to mitigate some of these issues. These methods operate under controlled environments, reducing the risk of oxidation and decarburization while providing better uniformity of the case depth. Advances in LPC, for instance, utilize computer control to maintain precise carbon potential and cycle times, enabling higher repeatability and minimizing part distortion [29]. Additionally, these methods can be more environmentally friendly, as they use less energy and emit fewer pollutants compared to traditional carburizing processes.

Furthermore, the flexibility of carburizing techniques allows for tailored case depths and carbon gradients to meet specific performance requirements for various applications. This adaptability is particularly advantageous in the automotive and aerospace industries, where components are subjected to varying operational demands. Advanced simulation and modeling tools aid in optimizing the carburizing process parameters, ensuring maximum efficiency and consistency. The use of computer simulations in carburizing allows for the precise prediction of carbon diffusion profiles and thermal behavior, thereby enhancing the overall quality of the treated parts.

Despite these advancements, challenges remain. The significant initial capital investment required for advanced carburizing systems, such as vacuum furnaces, can be a barrier for smaller manufacturers. Moreover, the complexity of these systems necessitates specialized knowledge and rigorous maintenance to ensure optimal operation. Additionally, the high energy consumption associated with long carburizing cycles can lead to increased operational costs, although advancements in hybrid and rapid carburizing techniques are working to address these inefficiencies.

Carburizing represents a vital heat treatment process in mechanical engineering, offering substantial improvements in surface hardness, wear resistance, and fatigue life of steel components. While traditional carburizing methods pose certain drawbacks such as distortion and environmental impact, the development of advanced technologies like vacuum and low-pressure carburizing have significantly enhanced the process's precision, efficiency, and sustainability. Continuous innovation and the integration of simulation tools are set to further optimize carburizing processes, solidifying their role in the future of high-performance steel treatment.

1.9.4 Annealing

Annealing is a pivotal heat treatment process employed to modify the properties of steel, aimed at improving its mechanical performance and facilitating further manufacturing processes. This technique involves heating the steel to a specified temperature, maintaining it for a defined period, and then cooling it gradually, often within a controlled environment. The primary purposes of annealing are to reduce hardness, improve ductility, relieve residual stresses, and refine the microstructure, which collectively enhance the material's machinability and overall workability. There are several methodologies of annealing, including full annealing, process annealing, and spheroidizing. Full annealing, which involves heating the steel to its austenitizing temperature and then cooling it slowly in the furnace, transforms the material into a homogeneous, fine-grained structure that possesses optimal ductility and softness. Process annealing, conducted at lower temperatures, aims to restore ductility in work-hardened steels, thereby facilitating further cold working operations. Spheroidizing, which typically involves prolonged heating cycles, is designed to produce a spheroidal or globular form of carbide precipitates within the steel matrix, significantly enhancing its machinability.

One of the foremost benefits of annealing is the considerable enhancement in materials' ductility and toughness. For example, annealed steels demonstrate significantly increased toughness and reduced brittleness, making them more resilient under dynamic loads and less prone to fractures during further processing and in-service use. Annealing also homogenizes the chemical composition and refines the microstructure, leading to consistent and predictable mechanical properties, which are crucial for high-precision engineering applications. Additionally, annealing alleviates internal stresses induced by prior manufacturing steps, thus preventing warping, cracking, and other defects that might arise during subsequent operations.

Despite its benefits, annealing presents several challenges and disadvantages. The process is typically time-consuming and energy-intensive, particularly when dealing with large or complex components that require prolonged heating and slow cooling cycles. These extended cycles contribute to higher operational costs and reduced throughput in industrial settings. [30] Furthermore, if not conducted under carefully controlled conditions, annealing can lead to surface oxidation and decarburization, which may degrade the steel's surface properties. This necessitates the use of controlled atmospheres or protective coatings to mitigate such effects, further increasing the complexity and cost of the process.

Recent advancements in annealing technologies have sought to mitigate these drawbacks and enhance the efficiency and effectiveness of the process. Innovations such as Rapid Thermal Annealing (RTA) and Controlled Atmosphere Annealing (CAA) are noteworthy developments. RTA involves short, high-temperature cycles, drastically reducing the total processing time while still achieving the desired microstructural transformations. This method is particularly advantageous for thin sections and specialized applications where time efficiency is critical. CAA, on the other hand, utilizes environments with precisely controlled gas compositions, which virtually eliminate oxidation and decarburization, thus preserving the surface integrity of the steel components. This approach not only improves the quality of the annealed product but also reduces the need for post-treatment surface finishing. [31] In terms of applications, annealed steels find extensive use across various industrial sectors. In the automotive industry, for example, annealed steel sheets are preferred for their enhanced formability and are used in stamping and deep-drawing processes to produce complex body parts and structural components. In the aerospace sector, annealed materials are employed to fabricate components that require superior toughness and fatigue resistance. The construction and oil & gas industries also benefit from annealed steel pipes and fittings, owing to their improved weldability and resistance to stress corrosion cracking.

Annealing remains a cornerstone in the thermal treatment of steels, providing substantial improvements in material properties such as ductility, toughness, and stress relief, thereby enhancing the overall manufacturability and performance of steel components. While the process is not without its challenges, ongoing advancements in annealing methodologies, such as RTA and CAA, are addressing these issues, making the process more efficient, cost-effective, and environmentally friendly. These developments underscore the evolving nature of heat treatment technologies and their critical role in modern engineering applications.

1.101 Plastic deformation of steels

Plastic deformation in steels is a critical phenomenon that underpins the mechanical behavior and performance of structural components in various engineering applications. This process involves the permanent change in shape of the steel when subjected to stresses exceeding its elastic limit, which is dictated by the movement and interaction of dislocations within the crystal lattice. Historically, the theory of dislocations, introduced by Orowan, Polanyi, and Taylor, has provided a framework to understand how plastic deformation occurs at the atomic level. [32] The stress-strain curve is a fundamental tool used to characterize the deformation behavior, where the transition from elastic to plastic deformation is marked by the yield point.

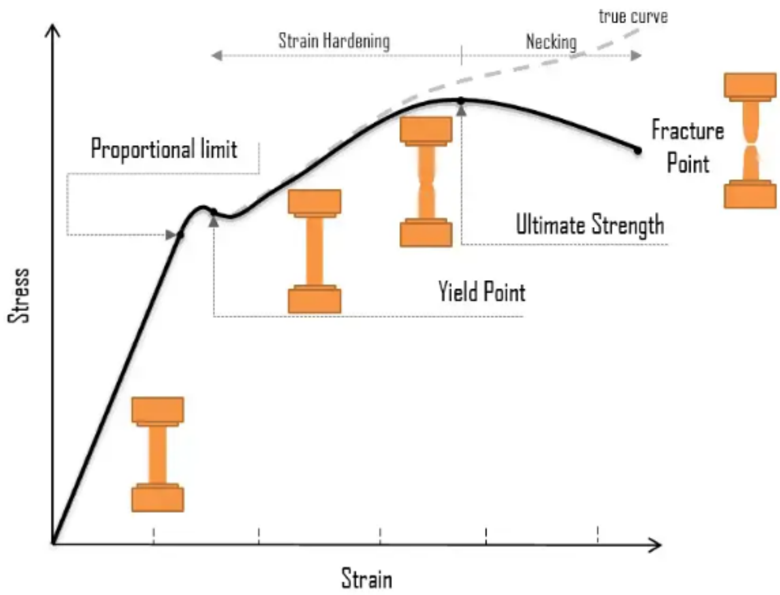


Figure 13. Stress-strain curve (low carbon steel) [2 – website]

Dislocation motion, facilitated by slip and twinning mechanisms, plays a pivotal role in the plastic deformation of steels. Slip occurs along specific crystallographic planes and directions, while twinning, a less common mechanism in steels, involves a reorientation of the crystal lattice.

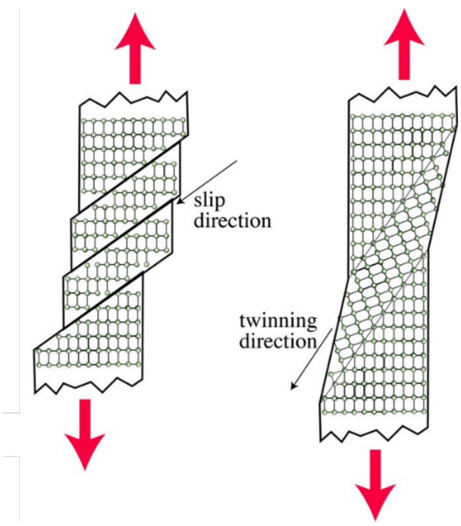


Figure 14. Motion of atoms during slip and twinning mechanisms simulated by an applied tensile stress [3 – website]

The study of these mechanisms is essential for comprehending the genesis of plastic deformation and the resultant microstructural changes within the material. The fracture point is the point at which the material physically separates due to strain. At this point, the strain reaches its maximum value and the material fractures, even if the corresponding stress is lower than the ultimate strength. Ductile materials have a fracture strength lower than the ultimate tensile strength (UTS), while in brittle materials, the fracture strength is the same as the UTS. If a ductile material reaches its UTS in a load-controlled scenario, it will continue to deform without additional load application until it ruptures. However, in a displacement-controlled loading situation, the material may deform and relieve the load, preventing rupture. [33]

1.5.1 Factors influencing plastic deformation

The plastic deformation of steels is influenced by a multitude of factors, including chemical composition, microstructure, temperature, and strain rate. The alloying elements present in steel, such as carbon, manganese, and chromium, significantly impact its mechanical properties by altering the crystal structure and dislocation dynamics. For instance, carbon atoms can hinder dislocation movement by creating pinning points, thereby increasing the steel's yield strength through solution strengthening.

The grain size, determined by the steel's microstructure, also plays a crucial role; finer grains provide more grain boundaries, which act as barriers to dislocation motion, enhancing the material's strength according to the Hall-Petch relationship. [34] Temperature is another critical factor; at elevated temperatures, steels exhibit increased ductility due to enhanced dislocation mobility and dynamic recrystallization processes. Conversely, low temperatures can lead to embrittlement and reduced formability The strain rate, or the rate at which deformation is applied, influences the material behavior as well. High strain rates can result in increased strength and reduced ductility due to the limited time for dislocations to bypass obstacles, whereas low strain rates allow for more significant dislocation motion and interactions, promoting ductility. [33] These factors collectively determine the plastic deformation behavior of steels, necessitating precise control and optimization to achieve desired mechanical properties for specific engineering applications.

1.5.2 Plastic deformation in connecting rods

Plastic deformation in engine connecting rods is a critical aspect of mechanical behavior under high-stress conditions. The connecting rod is a crucial component in an internal combustion engine, subjected to complex loading cycles that involve both axial and bending stresses. These loading conditions can induce significant plastic deformation, particularly during peak engine operations.

Understanding the fundamentals of plastic deformation in connecting rods involves examining the material properties, microstructural characteristics, and the mechanics of dislocation movement under high stress.

Microstructurally, connecting rods are typically made of high-strength alloys such as forged steel or aluminum, selected for their superior combination of strength, fatigue resistance, and manufacturability. The dislocations and grain boundaries within these materials play a vital role in accommodating plastic strain. Under high cyclic loads, dislocation movements are constrained by grain boundaries, leading to work hardening and eventual stabilization of the microstructure.

Axial loads, arising from the combustion pressure, and bending stresses, resulting from the rod's geometry and dynamic forces, interact to produce complex stress states. The stress-strain behavior of the material under these conditions can be characterized using finite element analysis (FEA). Studies have demonstrated the application of FEA in predicting plastic deformation patterns in connecting rods, revealing critical regions susceptible to failure. [35]

Additionally, the cyclic nature of engine operation necessitates considerations of fatigue life and crack initiation. The Morrow and Coffin-Manson equations are often employed to model low-cycle fatigue behavior, which combines elastic and plastic strain components for more accurate life predictions. Utilizing these models, engineers can predict the lifespan of connecting rods based on their deformation characteristics, improving reliability and performance.

The fundamentals of plastic deformation on engine connecting rods involve an intricate interplay of material science, mechanical stress analysis, and advanced computational modeling. A deep understanding of these principles is essential for designing durable connecting rods capable of withstanding the rigorous demands of high-performance engines.

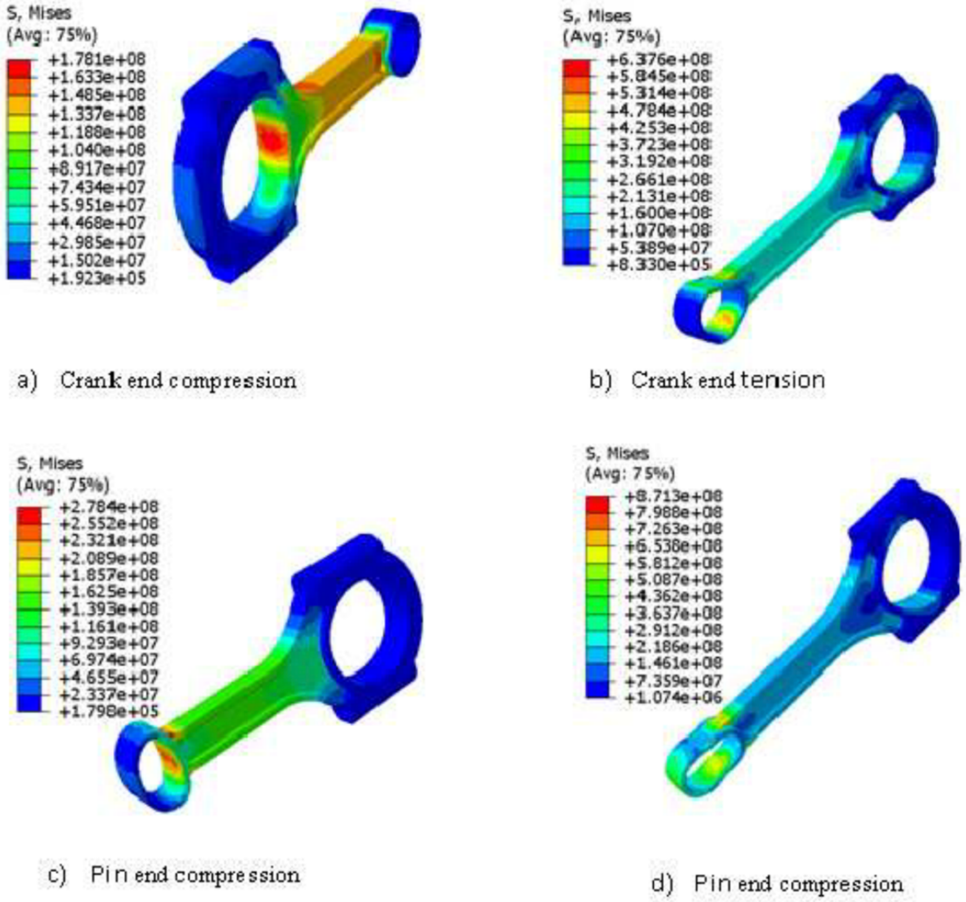


Figure 15. Von Misses stresses contour for actual connecting rod [3 – website]

2. Method and tools: Deform™ and FEA

DEFORM is an advanced finite element analysis (FEA) software that is instrumental in simulating plastic deformation processes, particularly in the forging of high-performance mechanical components such as connecting rods. These components are vital in internal combustion engines, transmitting power from the piston to the crankshaft. Accurate simulation of their forging process is essential to improve performance and ensure reliability under high-stress conditions.
In [37] they utilized DEFORM to simulate the forging of connecting rods, providing detailed insights into the stress-strain relationships and thermal conditions during plastic deformation. The software's capability to model material flow accurately is crucial for predicting defects like underfilling, laps, and internal voids, which can compromise the structural integrity of the component. DEFORM's precision helps optimize forging parameters such as die temperature, ram speed, and lubrication to achieve superior product quality.
The thermal conditions during forging significantly influence the grain structure and mechanical properties of the forged component. DEFORM's ability to accurately simulate thermal gradients

allows engineers to predict and control microstructural evolution. The software also incorporates advanced material models that consider strain rate, temperature, and phase transformations, offering a comprehensive view of the forging operation.

DEFORM's advanced algorithms enable precise modeling of anisotropic properties, optimizing process parameters to enhance the mechanical performance of the final product. DEFORM's post-processing capabilities allow for detailed analysis of the simulated forging process. Engineers can visualize the distribution of stress, strain, and temperature within the component, identify potential zones of weakness, and make data-driven decisions to mitigate these issues. This approach reduces the need for costly physical trials, accelerating development and improving manufacturing efficiency.

In summary, DEFORM is a state-of-the-art FEA software crucial for simulating and optimizing the forging processes of high-performance mechanical components, such as connecting rods. Its sophisticated modeling capabilities provide a deep understanding of thermomechanical phenomena, significantly contributing to the development of components with enhanced performance and longevity.

The plastic deformation process in DEFORM can be described using the Hill's flow rule of plasticity:

$$\sigma = K * \varepsilon^{m} * (1 + (1 - R) * \sqrt{\varepsilon} * \cos(3\theta))$$

where:

- σ is the flow stress,
- K is the flow coefficient,
- ε is the total strain,
- m is the flow exponent,
- R is a parameter that describes the flow directionality,
- θ is the angle between the flow direction and the direction of maximum strain.

The Hill's flow rule considers the crystal structure and grain orientation of the material to more accurately model the plastic behavior of metals in complex deformation situations. This constitutive law is integrated into the DEFORM software to enable a more realistic simulation of metal deformation during the processing. This equation forms the basis for modeling material behavior during plastic deformation. DEFORM uses such equations along with advanced numerical methods to simulate and optimize the forging process. [38]

Moreover, the heat conduction during the thermal cycles of forging can be represented by the heat diffusion equation. This equation describes how heat energy diffuses through a material over time. The heat diffusion equation is a partial differential equation and is given by:

$$\frac{\partial T}{\partial t} = \alpha * \nabla^{2T}$$

Where:

- $\frac{\partial T}{\partial t}$ is the rate of change of temperature with respect to time,
- α is the thermal diffusivity of the material,
- ∇^{2T} is the Laplacian of the temperature field which represents the spatial distribution of temperature in the material.

This equation governs the heat transfer process during forging operations and helps in predicting how the temperature evolves within the material as a function of time and spatial location. By solving this heat diffusion equation, the DEFORM software can simulate the thermal behavior of the material during forging processes and accurately predict temperature distributions, thermal gradients, and heat flow patterns within the workpiece. [38]

DEFORM integrates these mathematical models to provide a comprehensive analysis of the forging process, enabling engineers to optimize manufacturing parameters and improve the quality and performance of forged steel components.

2.1 Applications and advancements in modeling

Insights gained from studying plastic deformation in steels have significant implications for various industrial applications. In the automotive industry, enhanced ductility and strength are critical for forming processes used to manufacture intricate body panels and structural components. High-strength steels, such as Dual-Phase (DP) and Transformation-Induced Plasticity (TRIP) steels, are engineered to leverage controlled plastic deformation for superior crashworthiness and weight reduction, which are essential for improving fuel efficiency and safety. [39] In aerospace, steels must withstand extreme stress and fatigue conditions, making the understanding of plastic deformation vital for the design of components like landing gear and turbine blades. Here, steels are often subjected to rigorous thermal and mechanical cycles, necessitating materials that can endure high stresses while maintaining structural integrity.

Recent advancements in computational modeling and simulation provide powerful tools for predicting and optimizing the plastic deformation behavior of steels. The Finite Element Method (FEM) is widely employed to simulate the stress-strain response under various loading conditions, offering insights into the material's deformation mechanisms and potential failure modes. Constitutive models, incorporate parameters like strain rate, temperature, and microstructural attributes to predict the plastic behavior more accurately. Recent research focuses on integrating micromechanical models with **FEM to capture the influence of microstructural features**, such as

grain size and dislocation density, on macroscopic deformation behavior. [40] Additionally, advancements in multiscale modeling frameworks enable the study of plastic deformation from the atomic scale, through dislocation dynamics, to the continuum scale, facilitating a comprehensive understanding of the material behavior. These modeling approaches not only enhance the predictive capabilities but also reduce the need for extensive experimental testing, thereby accelerating the development and optimization of new steel grades with tailored properties for specific applications.
Plastic deformation in steels is a multifaceted subject that encompasses fundamental theories, influencing factors, state-of-the-art experimental techniques, and advanced modeling approaches. Understanding these aspects is critical for the design and optimization of high-performance steel components in various engineering applications. The integration of experimental observations with computational models offers a robust approach to studying deformation mechanisms and predicting material behavior, driving innovations in steel manufacturing and application. Continuous research and development in this field are essential to meet the ever-evolving demands of modern engineering challenges. [41]

2.2 Finite Element Analysis (FEA)

The Finite Element Method (FEM) stands as one of the most powerful and versatile numerical techniques in engineering and computational science. Its widespread application across various disciplines, from structural analysis to fluid dynamics and electromagnetics, underscores its importance in modern engineering design, analysis, and optimization processes.
Finite Element Analysis (FEA) can trace its origins back to work by Russian Canadian Alexander Pavlovich Hrennikoff in 1941 and German-American mathematician Richard Courant in 1942. Hrennikoff introduced a structural approach where a flexible medium, such as an aircraft, was represented by collections of beams and bars. Both pioneers share a common key concept: the discretization of a continuous domain into a set of smaller, distinct sub-domains, generally known as elements. The seminal contributions of these individuals laid the foundation for what would become the modern Finite Element Method. Initially developed for structural analysis, FEM has since evolved to encompass a broad spectrum of engineering disciplines, including thermal analysis, fluid dynamics, electromagnetics, and multiphysics simulations. [42]
At its core, the Finite Element Method revolves around the discretization of a continuous domain into a finite number of smaller, interconnected subdomains or elements. These elements, typically simple geometric shapes such as triangles or quadrilaterals in 2D and tetrahedra or hexahedra in 3D, collectively form a mesh that approximates the original domain**.** The primary objectives of FEM include:

1. Discretization: this process involves dividing the continuous domain into finite elements. The choice of element type and mesh density significantly impacts the accuracy and computational cost of the analysis. Common element types include linear and quadratic elements, each offering a trade-off between computational efficiency and solution accuracy.
2. Interpolation**:** interpolation functions, also known as shape functions, are used to approximate the behavior of the solution within each element based on nodal values. These functions facilitate the mapping of nodal values to any point within an element, enabling the evaluation of the solution at arbitrary locations.
3. Assembly**:** the assembly process involves formulating the global system of equations by assembling the elemental equations based on boundary and continuity conditions. This step typically involves the application of numerical integration techniques to evaluate element stiffness matrices and load vectors.
4. Solution**:** once the global system of equations is formulated, it is solved to obtain the numerical approximation of the solution. Various solution techniques, including direct solvers, iterative solvers, and specialized algorithms tailored to specific problem types, may be employed based on the nature of the problem and the desired computational efficiency.
5. Post-processing**:** post-processing involves analyzing and interpreting the results obtained from the finite element analysis. Visualization tools, contour plots, and graphical representations aid in understanding the behavior of the solution, identifying critical regions, and extracting engineering insights. [43]

This structured approach to FEA has not only advanced the precision and quality of engineering designs but has also streamlined the design process in various commercial applications. By using FEM, the time required from the conceptual stage to production has significantly decreased, highlighting the importance of leveraging the growing capabilities of modern computing to achieve high levels of accuracy in engineering analysis and design.

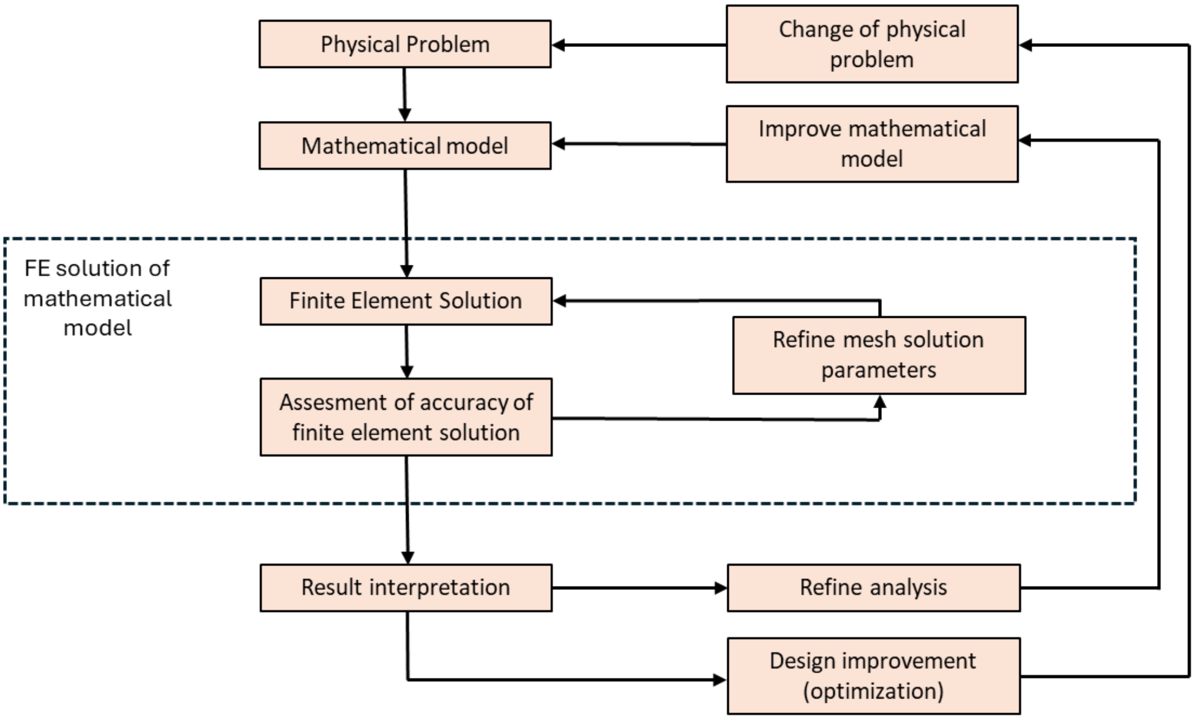


Figure 16. Process of Finite Element Analysis [42]

The versatility of the Finite Element Method lends itself to a wide range of engineering applications, including but not limited to:

1. Structural Analysis**:** Prediction of stresses, strains, and deformations in mechanical components and structures.
2. Heat Transfer Analysis**:** Evaluation of temperature distributions and thermal gradients in solid bodies and fluid domains.
3. Fluid Dynamics**:** Simulation of fluid flow phenomena, including laminar and turbulent flow, heat transfer, and multiphase flows
4. Electromagnetics**:** Modeling and analysis of electromagnetic fields, including static and dynamic behavior, electromagnetic interference, and antenna design
5. Multiphysics Simulations**:** Integration of multiple physical phenomena, such as fluid-structure interaction, thermal-electrical coupling, and acoustics.

As computational capabilities advance at an unprecedented pace, the Finite Element Method is set to assume an increasingly significant role in engineering design and analysis. Nevertheless, the journey forward presents both challenges and opportunities that merit careful consideration.
One notable area is High-Performance Computing. To accelerate simulations and manage ever more complex models, it becomes essential to leverage parallel computing architectures and cloud-based resources. This evolution not only promises to enhance the efficiency of engineering workflows but also to significantly reduce the time and cost associated with computational analyses

Another critical focus is the Modeling of Advanced Materials. As new materials such as composites, nanomaterials, and biomaterials emerge, developing robust constitutive models and material characterization techniques becomes paramount. These advancements will facilitate the application of FEM to a broader range of materials, thereby fostering innovation across various engineering disciplines

The integration of FEM with Data-Driven Approaches represents a transformative opportunity. By combining FEM with machine learning and data-driven techniques, it is possible to enhance predictive capabilities, optimize designs, and automate the generation and tuning of models. This synergy not only improves accuracy but also streamlines the engineering design process, leading to smarter and more efficient solutions. [44]

Finally, the field of Uncertainty Quantification and Reliability Analysis cannot be overlooked. Incorporating probabilistic methods and uncertainty quantification techniques is crucial for assessing the reliability and robustness of FEM predictions, especially in the presence of input uncertainties and model assumptions. This approach ensures that FEM-based analyses are not only precise but also trustworthy and resilient under varying conditions.

As we stand on the cusp of a new era in computational engineering, the Finite Element Method is poised to evolve and expand its horizons. By addressing these challenges and embracing the corresponding opportunities, FEM will continue to be a cornerstone of engineering innovation and excellence. [45]

2.2.1 Software features and main algorithms

Ansys is among the more frequently used software in the market for Finite Element Analysis (FEA). Ansys, Inc. produces a comprehensive suite of computer-aided engineering (CAD) products, though it is best known for Ansys Mechanical/Multiphysics. The FEA tool Ansys is a standalone analysis tool that incorporates preprocessing, solving, and post-processing segments. Additionally, Ansys supports user-programming; the tool's Command Language includes a thousand commands that can be utilized to program or modify mesh, geometry, boundary conditions, and other features. When performing FEA in Ansys, users can operate in either interactive or batch modes. The batch mode requires the input of commands for analysis execution and is mainly used by those proficient in the Ansys Command Language. Conversely, the interactive mode involves graphical input methods for data entry and option selection. [46]

Abaqus is a powerful tool with a user-friendly interface that allows for the creation of two-dimensional sketches and three-dimensional objects. Once boundary conditions are applied, these can be transferred to the simulation section of the software, which is divided into various stages. These stages include geometry creation, material property definition, and mesh generation, each serving distinct purposes. The CAE module generates the input file, while additional modules handle problem evaluation. The latest versions of Abaqus perform the analysis, sending results back to the CAE module for researchers to visualize the problem's progress. Abaqus Viewer is a separate software for visualizing outcomes. CAE is used for both pre-processing and post-processing and offers a range of capabilities for studies in acoustics, structural damage, fracture, and failure analysis. Abaqus Standard and Explicit are implicit and explicit solvers, respectively. Standard employs an implicit approach, ideal for static analysis and slow dynamic events requiring accurate stress results. Explicit, on the other hand, uses an explicit scheme, suitable for evaluating highly nonlinear systems with transient loads. [47]

SOLIDWORKS is widely used for modeling individual parts and assembling them for evaluation. It is particularly popular for modeling complex structures and assemblies, with nearly 3.5 million licenses sold globally. SOLIDWORKS provides a user-friendly environment for modeling, assembling, and analyzing. It is capable of handling metal fatigue, pressure vessel analysis, and thermal structural assessments. Recently, SOLIDWORKS has gained the capability to analyze nonlinear problems. Like other similar tools, it allows researchers to validate the performance and safety of a product under deformation loads and material conditions, ensuring the product's quality.

Inventor, a product by Autodesk, is like SOLIDWORKS. It is a self-contained software suite with built-in modules for parts, assembly, drawing, and presentation. Inventor encompasses all stages from creating a structure to its assembly and subsequent analysis. It also features a simulation environment where FEA can be performed. [47]

The table outlines some of the available capabilities and features of the specified software. However, it is important to note that over time, certain parameters or functionalities may change and potentially become obsolete. The comparison presented was based solely on the data provided in Table 2, though it should be acknowledged that there are additional features not included in this analysis, which could be similar or different across the various products.

Table 2. Comparison of competencies of the following products: Abaqus, Ansys, SOLIDWORKS and Inventor

	Abaqus (CAE)	**Ansys**	**SOLIDWORKS**	**Inventor**
Self-contained	No	Yes	Yes	No
Graphical geometry modeler	Includes	Includes	Includes	Includes
Graphical manual meshing	Includes	Includes	No data	Includes
CAD import	Capable	Capable	Capable	Capable
Units aware	No	Yes	No data	No data

Linear static	Performs	Performs	Performs	Performs
Nonlinear - large displacements	Performs	Performs	Performs	Performs
Nonlinear - contact	Performs	Performs	Performs	Performs
Transient linear	Capable	Capable	Capable	Capable
Transient onlinear	Capable	Capable	Capable	Capable
Natural frequency	Capable	Capable	Capable	Capable
Linear buckling	Capable	Capable	Capable	Capable
Acoustic	Capable	Capable	Not Capable	Not Capable
Heat transfer	Capable	Capable	Capable	Capable
Electric/magnetic	Capable	Capable	Not Capable	Capable
Fluid flow	Capable	Capable	Not Capable	Capable
Fluid structure interaction	Capable	Capable	Not specified	No data
Solid elements	Capable	Capable	Capable	Capable
Shell elements	Capable	Capable	Capable	Capable
Price	Limited free	Limited free	Not free	Both

Reviewing the table, it is evident that the selected software packages have notable similarities, although there are some minor differences. The first two packages, Abaqus and Ansys (CAE and Mechanical respectively), share identical capabilities except for self-contained modules and unit-aware components.

Furthermore, both software packages are available in two options: a full version and a limited free version. The limited version restricts the number of allowable nodes, making it unsuiv for complex analyses that require larger mesh generation. Consequently, this version is more appropriate for simpler analyses with smaller meshes.

Inventor Nastran also shares similarities with Abaqus and Ansys (CAE and Mechanical respectively). It offers a student version with a three-year free license. The only significant difference is its lack of acoustic analysis capabilities.

SOLIDWORKS stands out as the only software in the list without a free license option, and it has some limitations compared to the other products. Specifically, it does not support acoustic analysis, electric/magnetic field simulations, or fluid flow analyses. However, SOLIDWORKS excels in modeling and assembly capabilities when compared to the other three software packages. It is often used to create models or assemblies of individual parts, which can then be transferred to Abaqus (CAE), Ansys (Mechanical), or Inventor Nastran for further analysis.

ANSYS

ANSYS, commonly known as ANSYS Mechanical or ANSYS Multiphysics, is a widely used finite element analysis (FEA) software. The academic variations of these commercial products are known as ANSYS Academic Research, ANSYS Academic Teaching Advanced, Introductory, and other versions. ANSYS is a versatile tool for finite-element modeling used for numerically solving various mechanical problems. ANSYS is a powerful multipurpose analysis tool applicable in a broad spectrum of engineering disciplines. [48] Before employing ANSYS to develop an FEA model of a physical system, certain questions must be answered based on engineering judgment and observation:

2. What are the objectives of this analysis?
3. Should the entire physical system be modeled, or just a portion of it?
4. How detailed should the model be?
5. What should be the refinement level of the mesh?

Balancing computational cost against result accuracy is crucial when addressing these questions. The ANSYS software can be used effectively and appropriately by considering the problem type, time dependence, nonlinearity, and modeling simplifications. This type of analysis can address various structural issues such as static, modal, fatigue, transient dynamic analysis, shape optimization, harmonic analysis, eigenvalue buckling, and heat transfer analysis. [49] [42]

3. Con-rod sample production and mechanical properties prediction

3.1 Case-study with 20kg engine con-rod for 2MW Engine

Common and representative engine application for new con-rod is in the range of following parameters:

- Total Electric power output: 2 MW @ 1.200rpm, 50Hz
- Configuration: 16 cylinders V (125 kW per cylinder)
- Weight: 20 kg con-rod (displacement 446mm, main bore 184mm, pin-bore 95 mm)
- Material 42CrMo4+QT

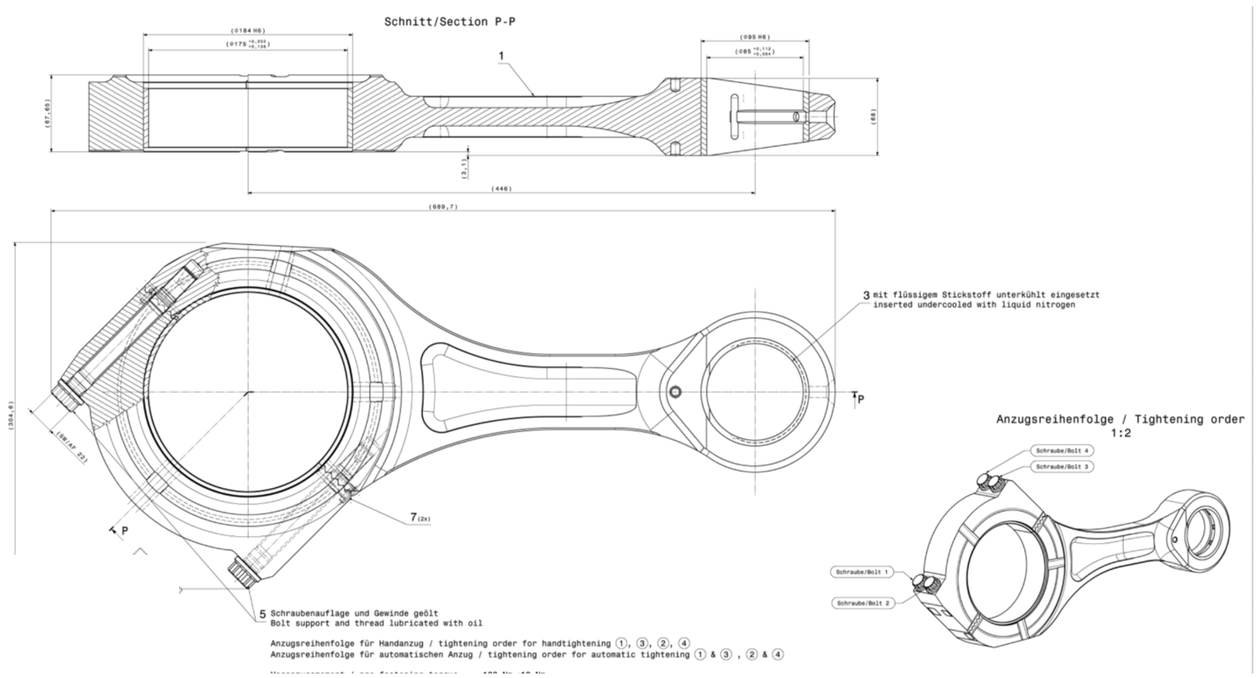


Figure 20. manufacturing drawing of case-study con-rod

This application takes typically 2-3 years of product development of the whole engine design, requiring several million € investment in research, development and prototyping to achieve requested performances (in terms of output, consumption and emission class).

Once main features of the engine are designed, detailed component definition starts in parallel with prototypes production.
The most critical components to develop in this type of engines are thermally and cinematically stressed parts::

- Con-rods
- Crankshaft
- Cylinder head
- Fuel injection and piston module

Taking into account con-rod as focus of this study, the realization of samples can take from 9 up to 12 months to be developed with traditional techniques (close-die forgings + machining), with relevant capital expenditure to have serial production equipment ready for the sampling stage (0,1mln€ range).

The possibility to realize sample(s) with open-die forging solution would represent a much shorter lead-time (3-6 months) and lower capital expenditure (0,01mln€ range), including the possibility to change the final design of the part based on samples result, since no final equipment has been realized.

The only option to chose the (convenient) open-die solution is to prove that both process lead to comparable and predictable result in terms of mechanical properties of the components, so that testing the open-die proto equals the test on close-die.

3.2 Simulation of con-rod production and predicted properties

In order to compare productive process of con-rod, simulating material, fiber, grain size and mechanical properties behaviour, typical process parameters were selected:

- Close-die forging with 32 MN/mm industrial hammer
- Open-die forging with standard and diffused hydraulic press (<40mTon power)

With following heat treatment as shown below:

CLOSED DIE:
- starting temperature: 1200°C
- close-die equipment temperature 300°C
- hammer: counterblow 32x10^6 N-mm
- lubricated dies, with shear coefficient 0,3 and convection 5 N/sec/mm/C
- starting shape: bill 130x130x340 forged in central shape 90x50 , total lenght 560 mm
- number of hammer hits : 30
- hot trimming and air cooling
- quench tempering as for 42CrMo4 (see next chart)

OPEN DIE:
- open-die press, with manual manipulator
- starting temperature 1200°C
- starting shape: Full ingot RQ60 da 6400kg cut 80kg (square, average lenght 640mm)
- hydraulic press 3.000 ton , descent speed 15 mm/s
- 4 steps forging, with 3 intermediate heating sessions to 1.200°C
- plane tool forging length L=450 mm, estimated temperature 200°C
- press movement stroke 200mm and deformation 50 mm
- quench tempering as for 42CrMo4 (see next chart)

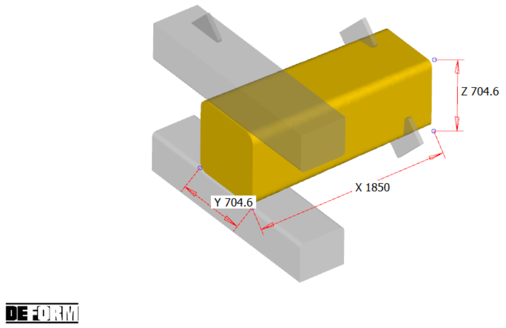
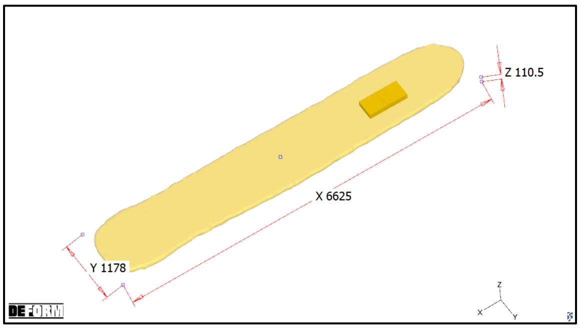
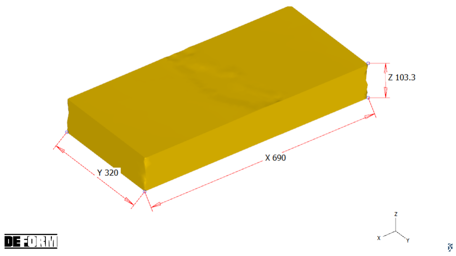
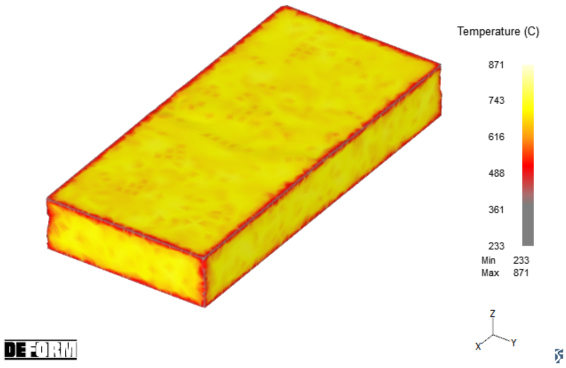
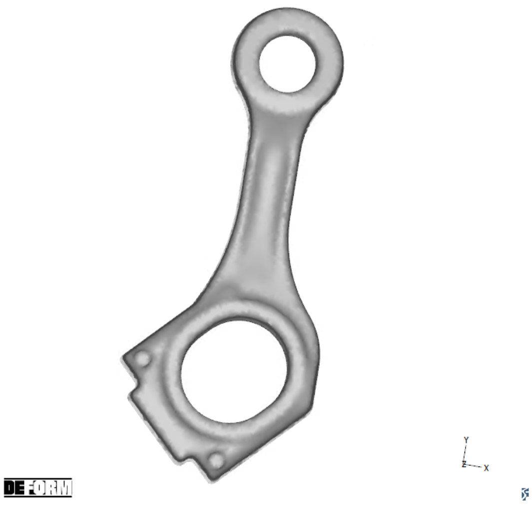
SOFTWARE SIMULATION:

- Deform Version 13.1.1
- Simulation type: lagrangian
- Mesh: tethreaedral
- Software solution: Spares, Spooles [SParse Object Oriented Linear Equations Solver]

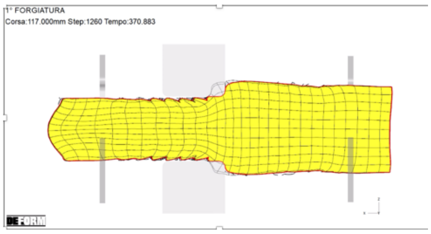
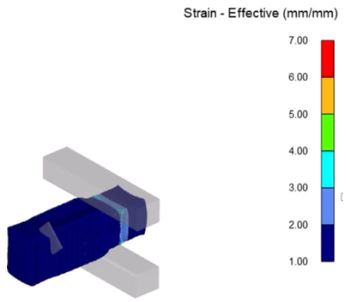
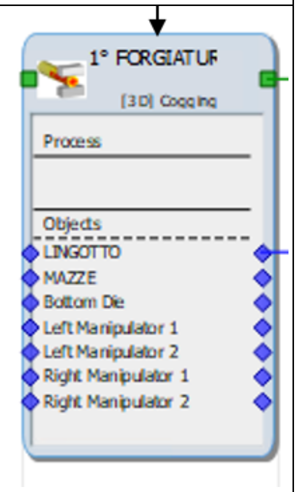
Table 3. Process parameters

	OPEN-DIE (C.M.F. spa)	**CLOSE-DIE (Riganti Forging spa)**
Material	42CrMo4	42CrMo4
Final machining shape	1851601-11-200-E01 (similar to 1850601-11-2001)	1851601-11-200-E01
Pre-machined shape	G0004993-C	G0004375
Starting material shape	Full ingot RQ60 da 6400kg cut 80kg (square, average lenght 640mm)	bill 130x130x340 forged in central shape 90x50 , total lenght 560 mm
Tasso di riduzione finale	RR=11:1	Variable in section, from 2 tp 7-8:1
Indicazione della dimensione media del grano del semilavorato	G9, certif 281030_14305	5-8
TT dopo stampaggio	tempering 850°C x 4h relief 555 x 7h (heating curve70°C/h)	Normalized 890 °C quench tempered (- heating 870 °C – quench in polymer/oil- relief 570°C)
Tool geometry	N/A (free forge)	Standard tool for industrial hammer
Temperatura iniziale di forgiatura	1200°C	1200°C
Indicazione sulla tipologia di pressa	Hydraulic press	Counterblow hammer 32.000 Kgm

3.2.1 Open-die forging process, main steps:

Ingot under hydraulic press 	Representative deformed shape after forging 
Forged portion cut by saw 	Heat treatment simulation 
Near net-shape after profile machined by CNC 	

3.2.1 Open-die forging simulation steps and effective strain diagram

<table>
<tr><th>Phase</th><th>Fiber trend
(Deform™)</th><th>Effective Strain
(Deform ™)</th><th>FEA status</th></tr>
<tr><td>1st forging</td><td>
</td><td>
</td><td>
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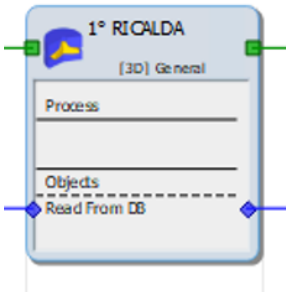
<tr><td>Heating</td><td></td><td></td><td>
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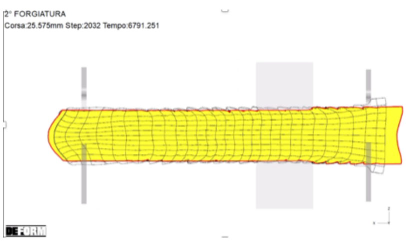
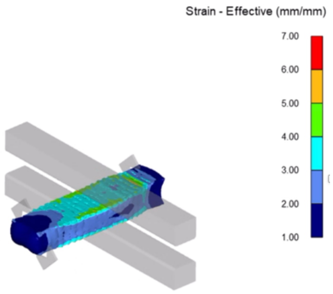
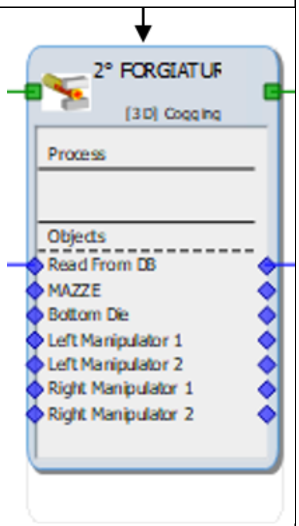
<tr><td>2nd forging</td><td>
</td><td>
</td><td>
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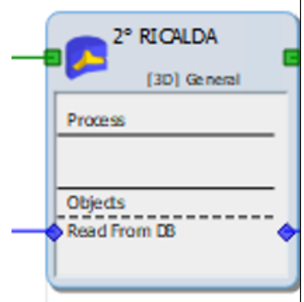
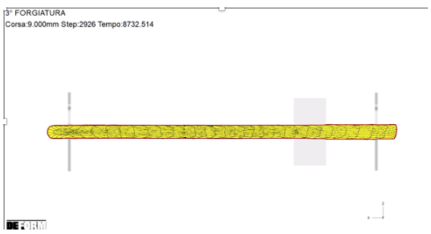
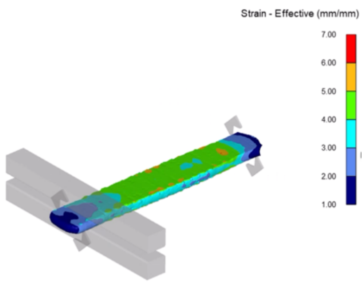
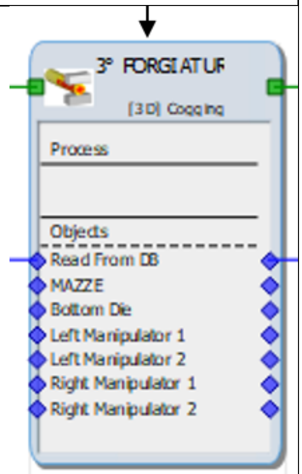
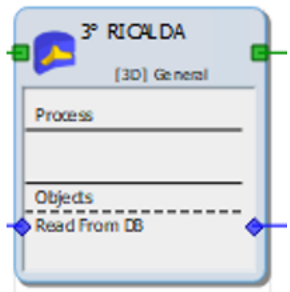
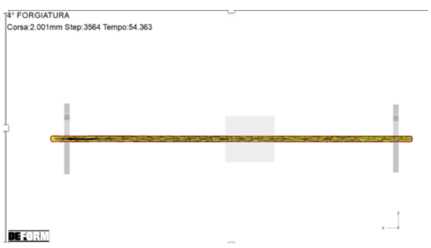
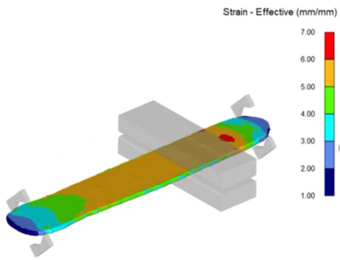
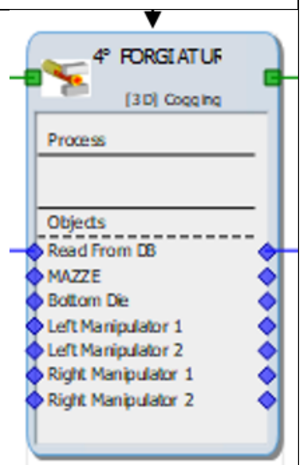
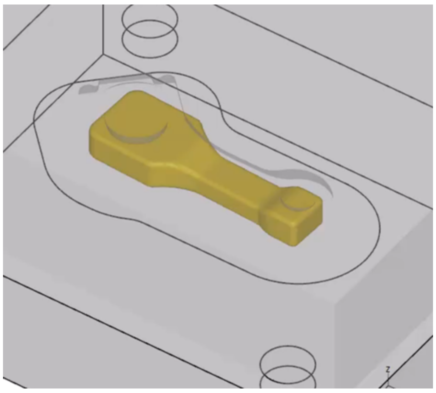
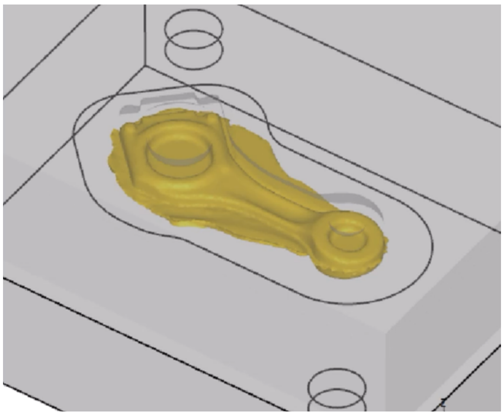
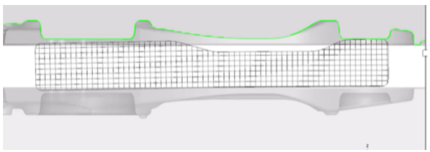
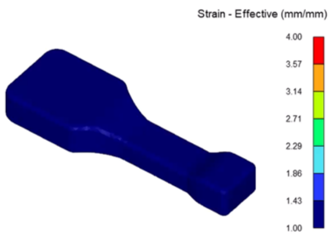
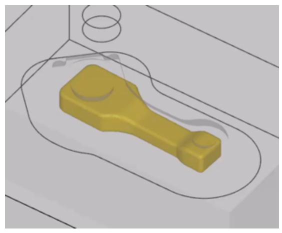
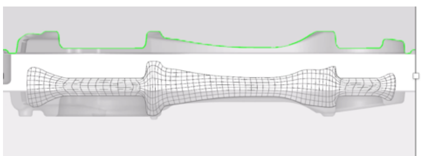
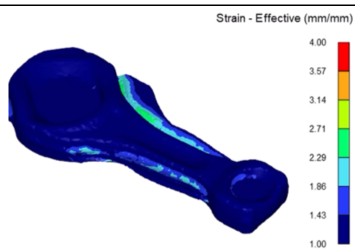
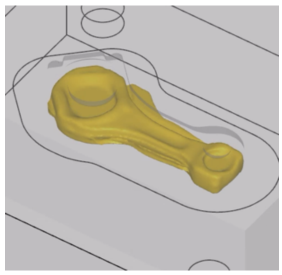
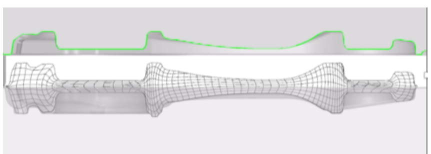
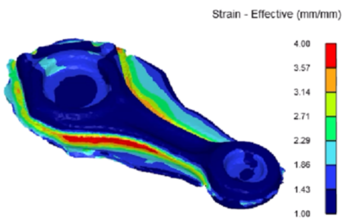
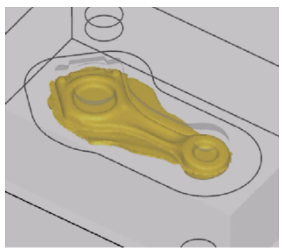
Heating			
3rd forging			
Heating			
4th forging			

3.2.2 Close-die forging process, main steps:

Preformed shape under forging die	Representaive deformed shape after forging
	

3.2.3 Close-die forging simulation steps and effective strain diagram

Phase	Fiber trend (Deform™)	Effective Strain (Deform ™)	FEA status
Initial stage			
20 seconds forging (50%)			
Final stage			

3.3 Results: Simulation of con-rod production and predicted properties

3.3.1 Final fiber trend in open-die is shown in picture:

As shown in picture 16, close-die fiber orientation is better aligned to the shape of the shaft, thanks to the near-net shape deformation given by the equipment, while open-die is aligned to the deformation process developed in axial direction.

Thanks to the cut process (chapter 2.5.1) done in the same direction of con-rod axis, open-die shows anyhow the correct orientation of the fiber.

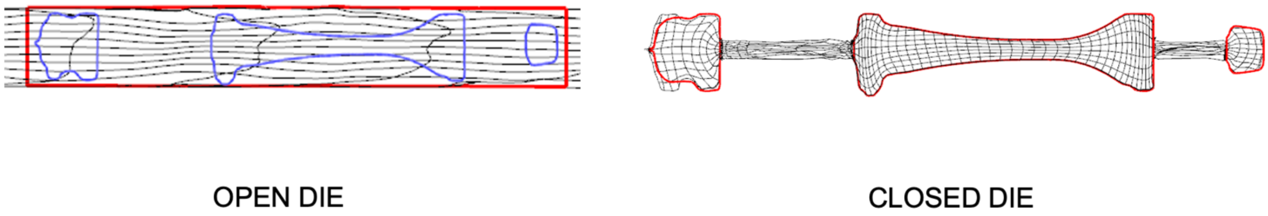


Figure 21. fiber orientation comparison

3.3.2 Effective strain comparison

As shown in picture 17, open-die show a much better forging ratio and effective deformation (6-7mm/mm) than close-die (1-2mm) thanks to the higher deformation given by the press and starting block of square size.

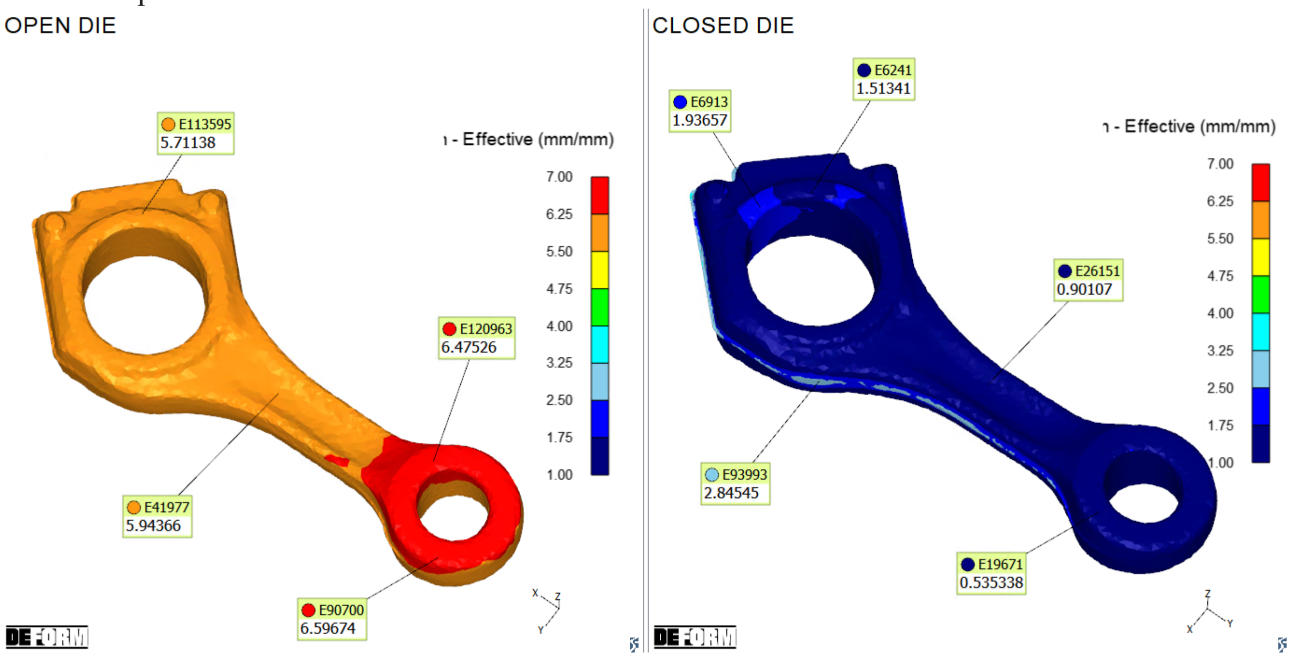


Figure 22. effective strain comparison

3.3.3. Residual stress comparison

While open-die grants a fully omogenous distribuzion of residual stress close to 0 MPa, close-die highlights remaining stressed points close to the crank and pin bores (up to 150MPa) due to a less omogenous deformation.

This could represent a risk for mechanical performance of the con-rod, even if way below critical values for 42CrMo4.

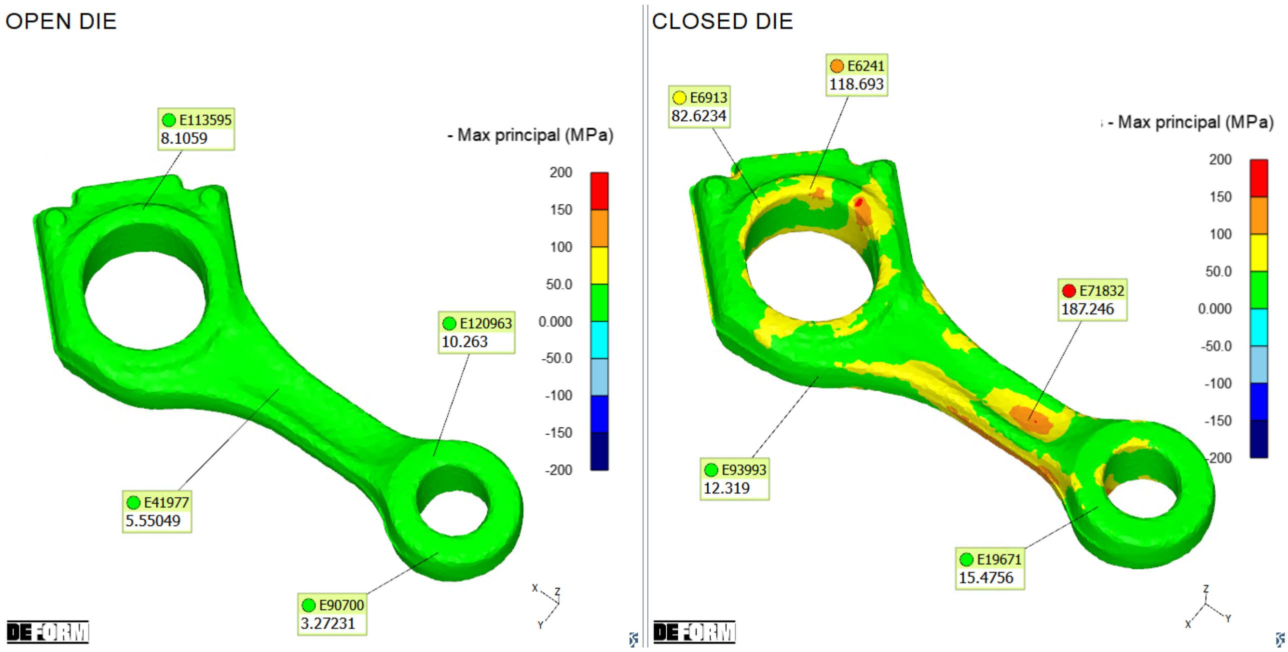


Figure 23. residual stress comparison

3.3.4 Grain size comparison

Thanks to the lower deformation and heat treatment, grain size show better result on close-die (12 microns average) compared to open-die (50-60microns average) resulting in better properties for the close-die option.

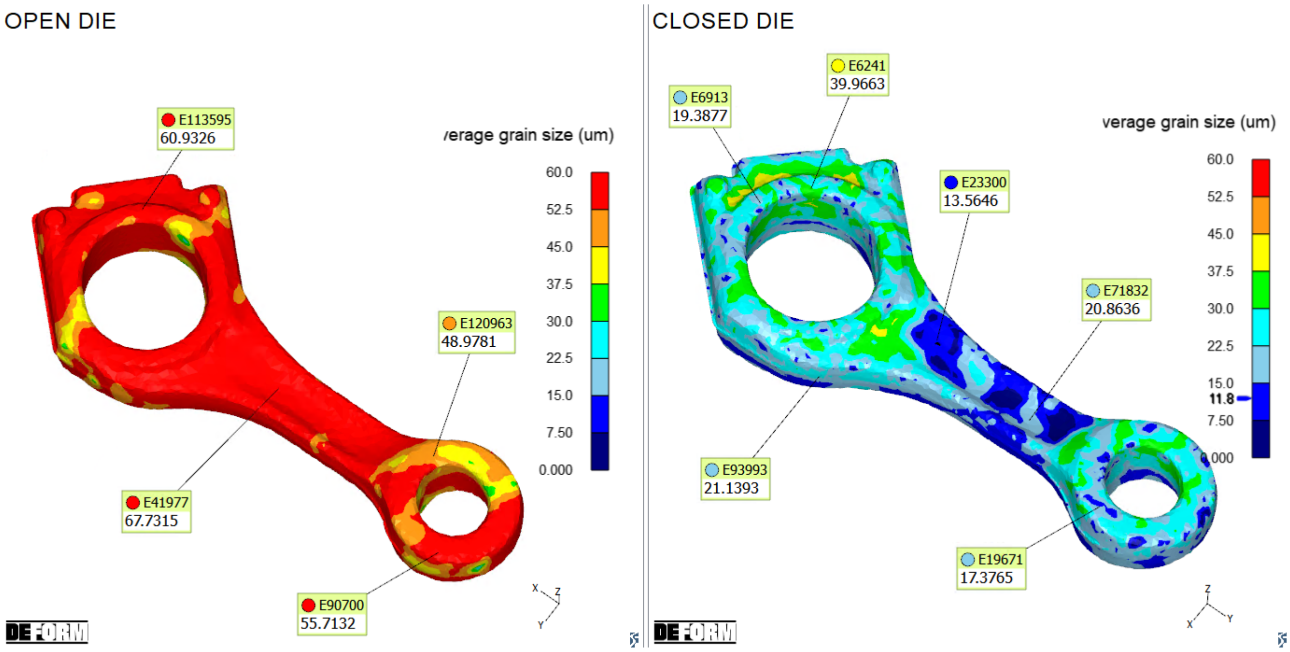
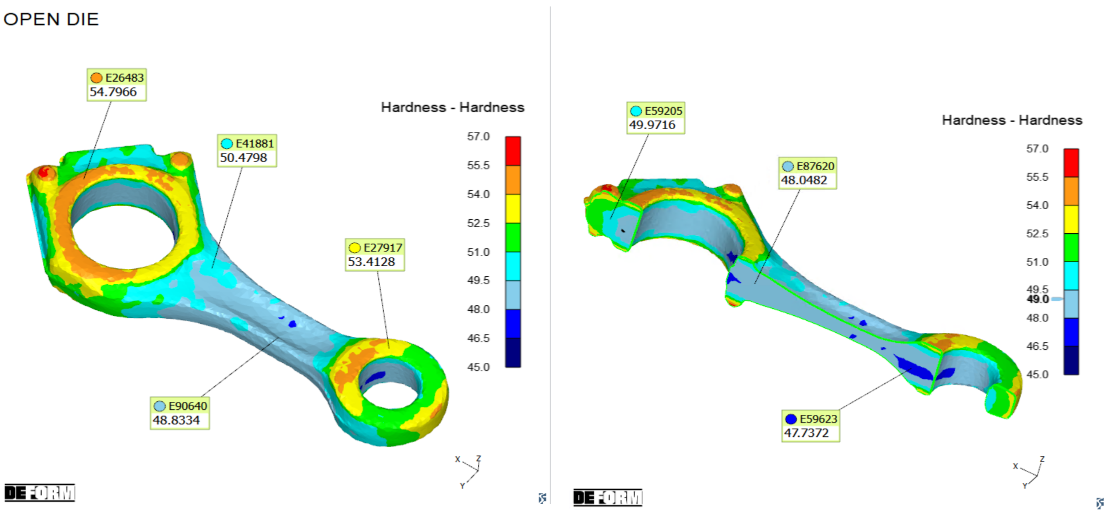


Figure 24. Grain size comparison

3.3.5 Hardness comparison

As last feature, hardness shows alignment of properties between close-die and open-die.



CLOSED DIE

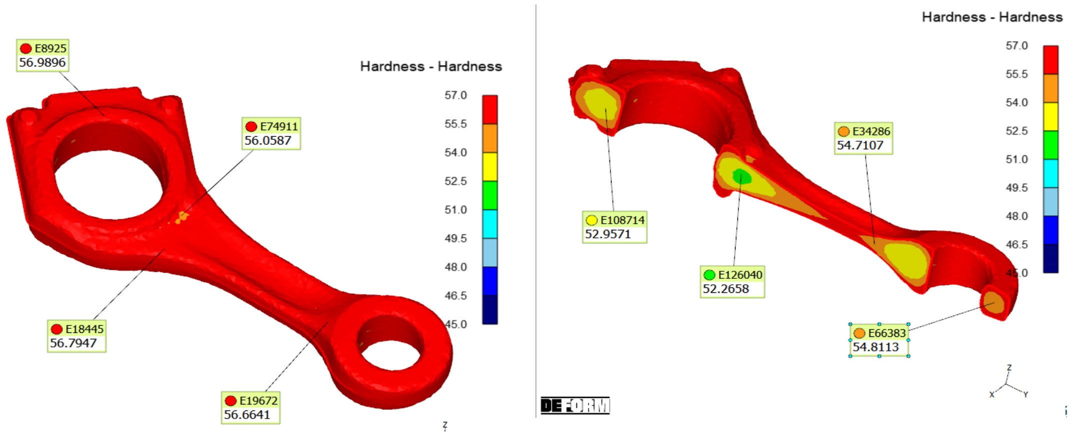


Figure 25. Hardness Rockwell C (HRC) comparison

4. Conclusions

Summarizing the features compared, and assigning a quality score (0 = poor; 100 = best) in agreement with Deform team and aligned to historical best practices, manufacturing process looks aligned and comparable in terms of final result. See Picture 21 for parameters.

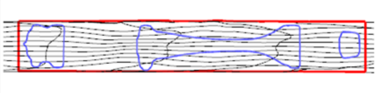
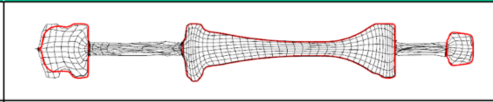
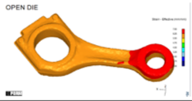
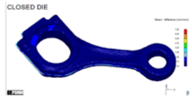
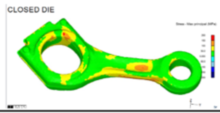
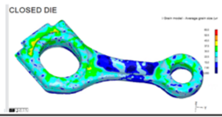
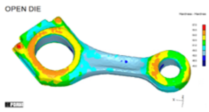
	OPEN-DIE		CLOSE-DIE	
Fiber Orientation		25		100
Strain effettive		100		0
Residual stress		100		25
Grain size		50		100
Hardness		50		100
	Total quality score:	**325** / 500		**325** / 500

Figure 26. Quality score

This study, while it might be confirmed by the company with field test on samples, show the possibility to use the two alternative processes (open-die and close-die) as alternative solutions, selecting the most appropriate for each application:

- Open-die and full machining process for samples and service parts (quick, low Capital Expenditure, less efficient)
- Close-die for serial production (longer development, capital expenditure, more efficient once launched)

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