Forged Automobile Engine Crankshaft

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Introduction

This paper will detail design specifications of an automobile engine crankshaft, an important part of combustion engines that converts linear piston motion into rotational energy to power the vehicle. This paper will discuss quenched and tempered versus micro-alloyed steels as competing material options, ultimately identifying the Q&T material AISI 4140 as an appropriate selection due to its strength, fatigue resistance, durability, and capacity for chemical case hardening. AISI 4140 will be used in the forging process to ensure toughness and minimize product defects. For the optimization of performance, the design specifications will focus on fatigue strength, using rotating bending tests and S-N curve analysis to determine and evaluate the product's endurance. Industry research will be included to assist in the choice of advanced materials and processes to help refine the overall operation, reduce defects, and improve efficiency/cost-effectiveness.

Materials

Cast Iron vs Steel Alloys

Material selection for an automobile crankshaft is first determined by the manufacturing method. Cast iron is employed in casting, while steel alloys are utilized in forging. Casting is cheaper and easier for high-volume production but significantly inferior in mechanical properties [1], [2]. Cast iron is much more brittle than steel alloys, making it more prone to cracking and failure under the high dynamic and static loads crankshafts experience [3]. This brittleness can be exacerbated by casting defects such as voids, which are difficult to detect [2]. In contrast, forged steel alloys have superior strength, and toughness, and obtain a uniform grain structure when compressed under high pressure during forging. These attributes make forged steel alloys the preferred choice for applications requiring efficiency, power, and safety, such as in commercial passenger vehicles [1].

Types of Steel Alloys

Two families of steel alloys are most relevant for modern forged crankshaft manufacturing: quenched and tempered (Q&T) alloys and micro-alloys (MA). Q&T alloys are typically medium-carbon steels with alloying elements such as chromium, molybdenum, manganese, silicon, and more [1], [4]. Their composition is designed to achieve high strength and toughness through heat treatment. After forging, Q&T alloys are quenched in water or oil to form a super hard martensitic structure that yields a high tensile strength but also brittleness; it is then tempered to relieve internal stresses, reducing brittleness and improving toughness [4]. In contrast, MA's contain small amounts of vanadium, titanium, and/or niobium. Instead of rapid quenching and tempering, MA's alloys are cooled slowly in a controlled manner, allowing small, uniform grains to form. This process results in high hardness and toughness without requiring reheating and also reduces distortion and therefore machining needs [1], [4]. By eliminating/reducing these steps, MA alloys reduce production time and cost significantly, with one study showing that MA alloys may lower production costs by 11–19% at volumes exceeding 300,000 units. However, this comes at a performance cost, as Q&T alloys outperform MA alloys in their mechanical properties, which are critical when considering crankshaft failure [4].

Failure and Fatigue Strength

Crankshaft failure results in not only economic losses due to repair costs but also life losses if failure occurs during engine operation. Several studies have illustrated that the most prevalent cause of crankshaft failure is fatigue, caused by the cyclical nature of the extreme torsion, bending, and shear loads it is typically subjected to [5]. Over time, these loads cause crack initiation and propagation at points of high-stress concentration, leading to fracture [5]. Thus, it is imperative that the material selection and treatment prioritize fatigue in addition to tensile strength. Q&T alloys excel in this area, possessing not only higher tensile, but also fatigue strength, illustrated by their outperforming MA's in reverse rotating bending fatigue tests [4]. While processes such as induction hardening and rolling fillets can improve the tensile and fatigue strength of MA's, they still don't match those of Q&T's [4]. Additionally, these extra steps would lessen MA's cost and production speed advantage, further highlighting the superiority of Q&T's for high-performance/load applications.

Nitriding

In addition to the aforementioned methods of induction hardening and rolling, Q&T's are suitable for chemical case hardening methods like nitriding that elevate their fatigue and wear resistance even further. Nitriding entails exposing a steel part to a hot atmosphere (~500-580°C) which is rich in nitrogen in the form of ammonia (NH3) for 40 to 100 hours. The ammonia decomposes into nitrogen and diffuses into the steel's surface where it expands the iron lattice and reacts with iron and alloying elements to form stable nitrides [1], [4]. This process immobilizes dislocations, resulting in higher hardness on the surface which increases resistance to wear like scratching and chipping, reducing stress concentration and therefore crack initiation [1], [5]. Yet, the properties of the crankshaft's core are unaffected, so it doesn't impact overall toughness. Additionally, by generating a compressive state in the surface, the part's rotating bending strength is greatly improved [4]. The alloying elements such as aluminum, chromium, and molybdenum present in Q&T steels are critical for effective nitriding. Aluminum contributes to surface hardness, chromium enhances layer thickness, and molybdenum suppresses "temper embrittlement" [1]. In comparison, MA alloys lack sufficient concentrations of these elements, making them unsuitable for nitriding. The capacity for nitriding is a unique advantage of Q&T alloys; however, because it is very time-consuming and therefore expensive, nitriding is generally reserved for very high performance/sport vehicles [1], [4].

Our Selection

Selecting the appropriate material for a forged automotive crankshaft depends on cost, performance, and production efficiency. Micro-alloys are cost-effective and adequate for many applications, but Q&T alloys are essential for higher-performance applications. Given the automotive industry's push for increased engine efficiency and power, the mechanical advantages of Q&T alloys are becoming increasingly necessary [4]. With this in mind, we have selected AISI 4140, a medium-carbon steel with the following composition:

- ❖ Carbon: 0.38–0.43%
- ❖ Chromium: 0.8–1.1%
- ❖ Manganese: 0.75–1.0%
- ❖ Molybdenum: 0.15–0.25%
- ❖ Silicon: 0.15–0.3%
- ❖ Phosphorus: ≤0.035%
- ❖ Sulfur: ≤0.04% [6]

A medium-carbon steel like AISI 4140 is an appropriate choice that yields high strength and heat treatment response, yet retains greater ductility than a high carbon alternative [3]. Chromium, molybdenum, and manganese all improve hardenability through heat treatment, enabling the crankshaft to handle high stresses [3]. For instance, when quenched at 850°C and tempered at 540°C, AISI 4140 achieves a tensile yield strength of 1,110 MPa [6]. Additionally, chromium enhances wear and corrosion resistance, molybdenum increases high-temperature strength and reduces brittleness, manganese boosts tensile strength and impact resistance while minimizing sulfur-induced brittleness, and silicon improves heat resistance to thermal shocks [3]. All of these effects will improve the shaft's resistance to fatigue. Finally, the inclusion of phosphorus and sulfur enhances machinability for easier, more cost-effective finishing; it should be noted that their restriction to low content is critical to avoid adverse effects like heightened brittleness [1], [3]. Overall, AISI 4140 has a low alloying percentage, which will keep material costs down; yet, its composition synergistically addresses crankshaft needs, balancing strength, toughness, wear resistance, and machinability.

Nitrocarburizing

To target crankshaft materials' greatest weaknesses, fatigue and wear, we will use chemical case hardening in addition to quenching and tempering. However, to optimize performance and production efficiency, we propose innovating standard material treatment through nitrocarburizing, a modified version of the nitriding process. Nitrocarburizing introduces carbon into the nitrogen-rich atmosphere, allowing both elements to diffuse into the steel. This process achieves surface hardening within 15 minutes to 6 hours, significantly faster than traditional nitriding [1]. While the resulting surface layer is shallower (~0.1 mm), it still provides great fatigue and wear resistance effects, and the reduced processing time lowers production costs and increases output, making it much more economically viable for high-volume manufacturing and high performance [1].

Conclusion

By selecting AISI 4140, applying quenching and tempering, and incorporating nitrocarburizing, we ensure that our forged crankshafts achieve an optimal balance of strength, toughness, wear resistance, and cost-efficiency. This approach tackles the current shortcoming/bottleneck in crankshaft material selection of competing cost and performance outcomes. AISI 4140 is a robust choice for high-performance crankshafts that compromises with the industry's need for economic and scalable production.

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Manufacturing Process

As previously mentioned, we intend to use forging to manufacture the automobile engine crankshaft. Forging offers a product with high strength, durability, and good fatigue resistance. Forging results in an aligned grain structure that follows the shape of the crankshaft, which drastically improves the mechanical properties compared to the alternative options of manufacturing [1]. This makes the resulting product perfect for high-stress applications like that of an engine crankshaft.

Overview of the Forging Process

To begin the process, a rod or “billet” of the given material is prepared and cut to the desired size. The billet is then heated in a furnace to a temperature that allows the material to become malleable, but not yet a liquid - usually around ~2,200℉ [2]. At this stage, it is essential that heating is applied uniformly to avoid any potential uneven deformation or thermal stresses. The heated billet is then placed into the associated die, where it is “hammered” to deform it into the shape of the crankshaft profile predetermined by the die. During the hammering/compaction process, excess material is squeezed out “at its mating lines” [2]. The excess material then gets trimmed to make sure that the part matches the shape of the die. The trimmed crankshaft is heat-treated (quenched and tempered) to improve its hardness and toughness. The forged crankshaft then undergoes precision machining to match the dimensions and tolerances required for the desired assembly.

Why Forging?

The most common manufacturing methods for engine crankshafts are billet, forging, and casting. Forging is the most practical method for crankshaft manufacturing because it creates an optimal balance of strength and cost [3]. Cast crankshafts are inexpensive for mass production but lack durability and are more likely to house internal defects. Billet crankshafts are more durable but are much more expensive and time-consuming to produce, as they utilize CNC machining to shape the part from a solid billet. Because forging results in a continuous grain structure, it can eliminate most internal defects and dislocations/voids, which leads to a stronger, denser product [1], [3], [4]. Overall, forged crankshafts offer the best combination of strength and reliability. They provide superior durability compared to cast crankshafts at a lower cost than billet crankshafts.

Production Rate

Forging's production rate depends on the complexity of the crankshaft design, the level of automation in the production process, and the equipment used [5]. In a setup that is mostly/highly automated, several crankshafts can likely be produced per hour [3]. For a production that is mostly done manually, the process can be labor-intensive and take longer than an hour. Source [6] found that the cycle time for one example of a mostly by-hand forging process was 92.73 minutes. Regardless of whether or not the process is fully automated, forging allows for a high-volume manufacturing process to be feasible. Each of the operations listed in the "Overview" section has variable cycle times, but are all relatively similar in length. Heating, forging, and cooling are likely to take the longest, with trimming, heat treatment, and machining being the quickest [2], [3].

Tooling and Setup Cost

The forging process requires many tools, and access to proper equipment can carry a significant cost. The material cost may represent up to 50% of the production costs [7]. During the process of heating the billet for it to become malleable, it is important to monitor the temperature. As temperature changes have a "significant impact on product quality during the production process," it is important to have the crucial equipment for precise temperature monitoring [8]. Heating the billet to temperatures exceeding 2,000℉ also requires the proper devices, die materials, and cooling systems [9]. This can be incredibly expensive but is essential for acceptable product creation. Depending on the specific quality of the crankshaft, the die can be custom-made - and therefore come with a steep cost. For example, custom dies and high-capacity presses for a heavy crankshaft are required, which means the overall tooling cost will increase [9]. The machining used at the end of the forging process to shape and finalize the part for production can also be expensive. The process of making the crankshaft can be quite costly as one source states that the "initial cycle time was 92.73 min for processing of crankshaft" [6]. The longer the cycle time, the higher the expenses on labor and machine operation [6]. Ultimately, machining and shaping are expensive but necessary for the mass production of crankshafts.

Potential Defects

Although forging may be one of the most effective ways to create an engine crankshaft, there exists the possibility of defects. Issues such as underfill defects account for the majority of defect causes. "Jamshedpur-INDIA revealed more than 80% rejections and rework, including several underfilling, overlapping, and foreign substances" [8]. Underfill exists when the material does not fully occupy the die cavity and can be caused by inaccurate die geometry or insufficient press capacity [9]. Flash formation is another significantly occurring deformation source."The flash ratio for complicated geometries like crankshafts can reach up to 50% and more" [7]. Proper material reduction, or a flashless forging process can minimize flash formation and reduce costs.

How to Improve the Forging Process + Innovation

Improving the forging process would ultimately mean the reduction of costs, and the minimization of defects that could occur. As said previously, flash formation tends to be a major defect that happens during forging. The study, "Influence of the Forming Angle in Cross Wedge Rolling on the Multi-directional Forging of Crankshafts", indicates that increasing the form angle is a direct cause of flash formation. This ultimately causes a material loss and a longer post-forging processing time [10]. To deal with this issue, flashless forging can be done to minimize flash formation and material loss. Multi-directional forging addresses this issue by combining the die movement in both the vertical and horizontal directions [10]. Figure 1.1 below illustrates the die movement involved in this process.

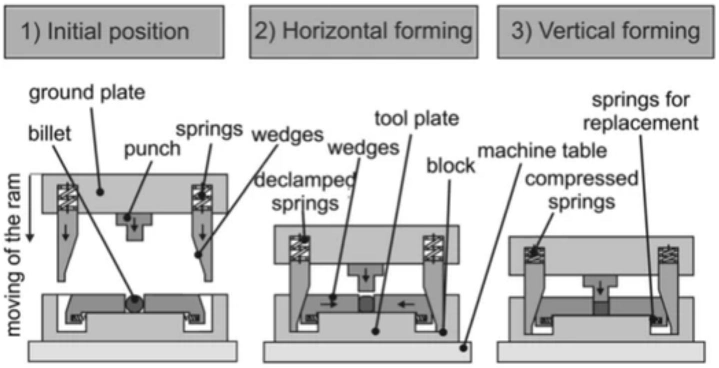

Figure 1.1 [10]

Multi-directional forging can be more costly due to the need for specific sliders and wedges. However, reducing flash formation leads to energy savings, as less material is needed to be heated, and there is a faster processing time, which ultimately improves cost efficiency. Another way to optimize the forging process is to use Finite Element Analysis to simulate the process chain. This reduces the necessity for physical trials and saves time and resources [7]. The process of flashless forging as stated previously, can be optimized using FEA, and with specific simulation parameters, “a new process chain for flash reduction will be designed” [7].

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Measurements

Property to be Tested: Fatigue Strength

The function of an automobile crankshaft in a combustion engine is to turn the linear motion of the pistons into rotational motion. The crankshaft of a car engine goes through cyclical loading during engine use causing repeated stress, which creates material fatigue, leading to cracks, fractures, or eventual failure. Thus, we chose to focus on testing the fatigue strength. Ensuring that the crankshaft can withstand repetitive stresses without failing is needed for the reliability and longevity of the engine. Accurately testing the fatigue strength of the crankshaft is important to ensure engine damage or unsafe vehicle performance does not occur. Therefore, evaluating the crankshaft's fatigue strength is essential to confirm its durability under the dynamic loads it will experience during normal operation. The results from this test also inform our material selection, manufacturing processes, and design improvements.

ANSYS for Preliminary Testing

ANSYS is a powerful computational tool used for finite element analysis (FEA) which plays a crucial role in the preliminary testing and evaluation for our crankshaft design. Using ANSYS, we plan to make simulations to model the physical behavior of crankshafts under various loading conditions, providing insights into the structural integrity, fatigue life, and overall performance, all before conducting any physical tests. This simulation-based approach offers significant advantages in terms of cost, time, and the ability to explore various design alternatives.

Prototype models can be created in other software such as Solidworks and imported to ANSYS for analysis. Within the scope of ANSYS, there is the ability to simulate fatigue loading. After meshing the part and applying boundary conditions, these tests can be conducted [1]. By conducting these simulations, we can predict the locations most susceptible to fatigue failure, such as stress concentration points and areas of high tensile stress, and adjust the design accordingly to improve durability, all before creating a physical model. ANSYS also allows for the incorporation of advanced material models, including those that account for material inhomogeneity or anisotropy, which can provide more accurate predictions for complex crankshaft materials [1]. Within our simulations, we can set the material to be AISI 4140 to better model the current crankshaft design. By using ANSYS as a preliminary testing method, we can significantly reduce the number of physical prototypes required, thereby saving both time and resources. The results from these simulations can help guide the physical testing process, ensuring that the crankshaft design undergoes rigorous evaluation based on potential weak points identified through the FEA.

The Rotating Bending Fatigue Test

We plan to use the rotating bending fatigue test to assess the fatigue strength of the crankshaft by subjecting it to alternating bending loads while constantly rotating it at a fixed speed. This test simulates the cyclical loading the crankshaft experiences during engine operation, helping to identify the point where material failure or cracking begins. The test setup includes a high-precision fatigue testing machine capable of applying variable loads to replicate the bending, torsional, and axial stresses encountered in a real engine. Hydraulic or servo-controlled actuators simulate these fluctuating loads, while strain gauges placed on critical points of the crankshaft will monitor stress distribution and crack initiation [2]. We will place strain gauges on key stress concentration areas, such as fillet radii, journals, and keyways, based on ANSYS predictions for maximum stress points. The loading protocol will consist of sinusoidal or triangular waveforms, replicating the alternating tensile and compressive forces that occur during engine cycles [2]. The frequency of loading will be adjusted to simulate typical engine speeds, ranging from 1 Hz to 100 Hz. The test will continue for a predefined number of cycles, typically up to 1 million cycles or until the first signs of crack initiation are detected [3]. This test method closely replicates the real-world operational conditions of the crankshaft, however, there exists a second half to the testing process. The evaluation of the results of the rotating bending fatigue test is shown through S-N curve analysis.

S-N Curve Analysis

The S-N curve analysis, complementing the rotating bending test, quantifies the relationship between applied stress levels and the number of cycles to failure, providing critical insights into a crankshaft's fatigue life under real-world conditions. This analysis involves plotting the relationship between the applied stress (S) and the number of cycles to failure (N), creating a curve that helps us understand the crankshaft's durability under repeated loading. We will subject the crankshaft to varying levels of stress during fatigue testing leading to the identification of the critical stress ranges where fatigue failure is likely to occur [4]. Post-test evaluation generates the S-N curve to assess fatigue strength, identify failure modes, such as crack propagation and surface fatigue, and determine the fatigue limit. These analyses help guide our material and design improvements, ensuring reliable performance under operational stresses.

Challenges of Conventional Testing

Fatigue testing of crankshafts faces challenges in replicating real-world conditions due to variables such as fluctuating temperatures, dynamic loading, and complex geometry that influence stress distribution and crack initiation on the crankshaft [5]. Temperature variations introduce thermal stresses as the crankshaft heats up and cools, accelerating fatigue damage and causing thermal expansion, which then in turn changes stress distribution. Similarly, the loads acting on the crankshaft are not constant. Fluctuations in engine speed, power output, and external environmental conditions create dynamic stresses that are difficult to replicate in a controlled testing environment. Additionally, the crankshaft's intricate geometry, including bends and notches, creates stress concentrations that significantly affect crack initiation and propagation. Addressing these challenges requires a testing setup capable of precise control over test parameters while simulating both the mechanical and environmental conditions. These issues lead to our proposed idea for an innovative testing environment.

Innovation: Hybrid Testing Environment

To overcome the limitations of traditional fatigue testing and more accurately simulate the operating conditions of an engine, we plan to incorporate an innovative hybrid testing environment. This environment combines thermal cycling with mechanical loading to replicate the extreme operating temperatures encountered by the crankshaft during engine operation. In this hybrid environment, the crankshaft will undergo thermal cycling, which involves subjecting it to rapid temperature fluctuations, simulating the heating and cooling cycles experienced during real engine use. Along with thermal cycling, the crankshaft will also undergo mechanical loading in the form of bending and torsional stresses. This combination of thermal and mechanical stresses not only improves the accuracy of the fatigue testing but also allows for a fix to previously stated limitations of the traditional testing procedures. While this idea may be difficult to physically construct, our idea for a solution to temperature variation in the testing environment can shed light on the limitations of the aforementioned rotational bending fatigue test.

Conclusion

The fatigue strength testing of a crankshaft is needed to create a durable engine that performs under real-world conditions. By using methods such as rotating bending tests, S-N curve analysis, and hybrid testing, we can combat various challenges that affect performance. These include temperature fluctuations, dynamic loading, and the intricate geometries in the crankshaft. Real-time strain monitoring, crack detection, and evaluation of fatigue limits reveal potential failure points and show how the crankshaft will react. The data collected from these tests is important in making decisions about material selection, refining manufacturing processes, and suggesting design modifications. Ultimately, the testing approaches create the production of stronger, more reliable, and longer-lasting crankshafts, which leads to better engine performance, reduced maintenance needs, and improved overall vehicle durability.

Measurement Sources

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