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A STUDY OF LIGHTWEIGHT ASSEMBLED CRANKSHAFT BEHAVIOR

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Abstract. Crankshafts are fundamental components of combustion engines. Traditionally manufactured by casting and forging processes, their fatigue resistance is experimentally verified with expensive and time consuming procedures. This study aims to investigate lightweight assembled crankshafts. The assembling process eliminates important stress concentrations on regions like fillets between crankpins and crank webs. It may also eliminate the need of oil holes to lubrication and cooling, since it is possible to use roll bearings. Additionally, the crankshaft components can be made with different materials. For example, crank webs do not serve a structural function and can be manufactured with materials of lower strength than crankpins and crank journals. In that way, the final product may have reduced costs without affecting the balancing and the structural strength. The work utilized ANSYS software based on the finite element method, to simulate the non-linearity caused by interference assembling. Numerical simulations estimate the natural frequencies of the crankshaft, focusing on the crank throw design with crankpin and crank journals made of AISI 4140, and crank webs made of AISI 1045. Validation of numerical results will be future achieved through resonant fatigue test rigs, commonly used in the automotive industry, for bending and torsion. This investigation advances crankshaft design and manufacturing by providing insights into the feasibility, cost-effectiveness, and performance benefits of lightweight assembled crankshafts.

Keywords: Lightweight assembled crankshafts, ANSYS, Finite Element Method, Resonant Fatigue Test.

1. INTRODUCTION

Crankshafts are shafts with complex geometry used in combustion engines and usually manufactured of steel by casting and forging processes. The Figure 1 shows the main components of a crankshaft of a four-cylinder engine. The crankpins are connected to the connecting rods and have eccentricity in relation to the journals, which are connected to the bearings and the engine block. The crank throws are the union of a crankpin and two journal halves (Rodrigues, 2013).

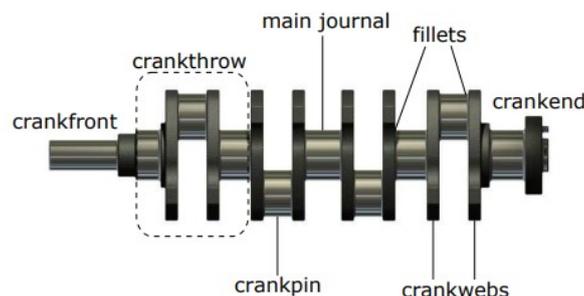


Figure 1. Representation of a four-stroke crankshaft. Adapted from Moraes (2017).

According to Ferreira (2021) crankshafts are subject to large cyclic torsion and bending loads during work. As noted by Moraes (2017), these loads induce a fatigue process in the crankshaft, potentially resulting in failure, particularly in regions with pronounced stress concentrations, such as the fillet radii. Different techniques are employed in the manufacturing process of crankshafts to increase fatigue life. For example, treatments that induce compressive residual stresses on the surface such as deep rolling and processes that increase surface hardness such as nitriding, carburizing and heat treatments.

In the automotive industry, the design of new crankshaft models uses several tools, such as pre-processing in CAD, modal analyses using CAE and the finite element method, in addition to post-processing of fatigue tests. Currently, the most applied tests are resonant fatigue tests due to their low cost.

Driven by the contemporary automotive industry's necessity to reduce emissions and material use, lightweight crankshafts

serve to achieve these goals. Considering pre-existing models of forged and cast crankshafts, this study focuses on evaluating lightweight assembled crankshafts numerically. The assessment includes the effects of operating loads using finite element analysis via ANSYS.

2. LITERATURE REVIEW

The fatigue life of crankshafts has been extensively studied, with a significant amount of research focusing on the effects of surface treatments and establishing numerical and experimental correlations for these complex components. However, there are few studies on assembled crankshafts. In the past, assembly processes were commonly employed to manufacture crankshafts, but with advances in casting and forging techniques, assembly has largely been eliminated in smaller applications. Currently, assembling processes are primarily used to manufacture large crankshafts, such as those found in marine applications.

Rodrigues (2013) conducted a study to investigate the effect of mass reduction of a crankshaft. It was observed that a mass reduction of 4.5% was possible, removing material from the crank webs. The main concern was to maintain the balancing and safety of the crankshaft, verifying with the simulations that only the crank web has balancing function and the equivalent stresses in these regions were negligible.

The analysis carried out by Ferreira (2021) verified the mass reduction of a crankshaft. Using a commercial model, the author, aiming to maintain balance and structural safety, investigated the fatigue life of the component. Using a lightweight crank throw, the fatigue life using resonant fatigue tests in both bending and torsion was studied. A comparison was made between the numerical and experimental estimated fatigue life, and the results verified that a mass reduction of 10% in the crank throw is possible, without affecting the balance and fatigue strength.

The study conducted by Prabhakar *et al.* (2021) focused on modifying the geometry of a crankshaft. Finite element analysis was performed using a commercial model of a four-cylinder engine. The study involved removing mass from the crank webs and redistributing it to the main journals while keeping the shaft mass constant. This modification resulted in improved fatigue life for one million of cycles. The modal analysis showed an increase in the bending and torsional natural frequencies.

Moraes (2017) carried out an analysis of the effect of the deep rolling process on a commercial crankshaft made of ductile cast iron. The author conducted monotonic fatigue tests and microstructural analysis of samples collected from the shafts to determine the type of manufacturing material. Subsequently, resonant bending fatigue tests were performed on samples of crank throws. The comparison between numerical and experimental results revealed an improvement in fatigue life attributed to the presence of compressive residual stresses on the surface of the crankshaft.

The fatigue life of EN GJS 700 – 2 was studied by Khameneh and Azadi (2018). Standard samples were collected from the crank webs of a commercial crankshaft, and their fatigue life was tested using a rotary bending apparatus. When comparing the experimental $S - N$ curves with the FEMFAT software database, the authors observed a difference in the average fatigue life values. This difference can be attributed to the lack of surface treatment on the evaluated parts. Analysis of the crack surface revealed the presence of non-metallic inclusions, which act as stress concentrations and accelerate the fracture process. The research highlights the importance of proper control in the casting and heat treatment processes to improve the fatigue life of crankshafts.

The deep rolling process was numerically simulated by Fonseca *et al.* (2020). Using a commercial model of a crankshaft manufactured from nodular cast iron, the authors investigated the effects of plasticity on the materials surface using finite element analysis. They established a relationship between the treatment depth and the resulting residual compressive stresses. Subsequently, a resonant fatigue test was conducted to experimentally evaluate the crankshaft fatigue life. When comparing the numerical and experimental results, the authors observed good correlations between the two methods. The study presents important insights into non-linear simulations and provides reliable numerical estimates for the fatigue life of structures still in the design process.

The effects of surface treatments on the fatigue life of crankshafts have been studied by Park *et al.* (2001). Two different commercial crankshafts were investigated, both structures were manufactured by the forging process, but one was made of micro alloyed steel and after the manufacturing process it only cooled slowly, and the other structure was manufactured in a steel alloy that after the forging was quenched and tempered. Rotary bending fatigue tests and resonant bending fatigue tests were performed on both models, original samples and samples with surface treatment. The authors noted that both treatments increase the fatigue life of the samples by more than 80%.

The bending behavior of the EN8 steel was investigated by Karthick *et al.* (2021, 2022). In the first analysis, a comparison was made between forged and cast steel, while in the second analysis, AISI 4130 was selected as material of interest. In both cases, finite element analyses were carried out in ANSYS, using a crankshaft model for a single-cylinder four-stroke engine subjected to static bending. The load applied to the model consisted of restricting the movement of the two journals, while a constant load was applied to the crankpin, simulating the effect of a rod on the crankpin. The analysis presented by Karthick *et al.* (2021, 2022) showed that EN8 steel presented smaller deflections when loaded than the other materials. Therefore, it proved to be a more suitable material to manufacture the crankshaft. The authors emphasized the advantages of using EN8 in the automobile industry, including possibilities of geometric modifications on

the shaft, such as incorporated holes in the crankpin and main journals structures, reducing the overall mass of the shaft, resulting in less use of material and fuel savings.

Investigations into catastrophic failures in crankshafts are common due to the complexity of the loads and systems acting on this component. In a study conducted by Fonte *et al.* (2015), an analysis was performed on an early failure of a crankshaft used in a diesel engine. The investigation revealed non-conformities in the hardness matrix and micro-structure of the nodular cast iron used to manufacture the shaft. Crack nucleation occurred on the fillet between the crankpin and the crank web, which was identified as the main stress concentration point under bending loads. However, the occurrence of the failure was directly attributed to the inadequate design of the main journals supports. Two of the five supports were broken during engine operation, resulting in large deflections in certain regions of the shaft, accelerating the component failure process.

Jiao *et al.* (2020) carried out a study on a crankshaft used in a four-cylinder diesel engine for trucks. The physical-chemical analysis revealed that the crankshaft was manufactured of steel 48 MnV, and the metallographic analysis indicates the existence of quenched line on the surfaces of the journals and crankpins. Using ANSYS software, the authors performed a modal analysis of the structure, identifying the natural frequencies of 911 Hz and 1097.5 Hz for bending and torsion, respectively. Fatigue simulations were performed using constant moments ranging from 2300 to 3220 Nm. Only the highest load led to shaft failure before reaching 10^6 cycles. The results suggested that the structural overload was the most probable cause of the failure, since the natural frequency values are high and can hardly be reached by the engine operation.

One of the first analyzes of assembled crankshaft effects was conducted by Davidsou (1951). In his analyses, the author used scaled crank throws of a ship engine. Electric strain gauges were employed to measure the strain on the crank webs induced by the assembly process. Finite element analysis was used to theoretically verify the results of stress and deformation in the crank webs. At the end, it was observed the occurrence of plastic deformation in the crank webs due to the heating process of the holes for assembly. According to the author, the clamping pressure in the assembly is less significant compared to the contact area between the components. That is, the plastic deformation resulting from the hole heating process has a lesser impact on the overall structural strength than the depth of the connection between the crank journals and the crank pins in the crank webs.

Król and Siemiątkowski (2019) conducted an analysis of the cooling effect on the scaled crank webs of a ship crankshaft. The authors observed that structural cooling is not uniform, leading to irregularities in the stress levels of the crank web. Through a finite element analysis of the assembly process, they observed the presence of compressive residual stress in the central portion of the journals. The authors concluded that the cooling process does not significantly affect the overall structural strength, even considering the plastic deformation resulting from the heating of the holes.

3. ARTICLE ORGANIZATION

This paper is organized as follows. Section 4 presents the numerical simulations conducted for the assembly crankshaft. We utilize ANSYS software and the finite element analysis to investigate the effects of the assembly process on the structure. We analyze the natural frequencies of the crank throw and discuss the effects of the assembly process on the fatigue life of the crankshaft. The Section 5 will summarize the main results of this work.

4. NUMERICAL ANALYSIS

To investigate the behavior of the assembly crank throw, we utilized a model based on a commercially cast crankshaft designed by a four cylinder engine. Employing finite element analysis in ANSYS Workbench, we conducted a numerical analysis considering the plasticity and the friction in all assembly regions of the crank throw. In the following sections we will present the mesh convergence analysis, examine the effects of the plasticity on the crank throw, and discuss the results for modal analysis, which are crucial to estimate the natural frequencies of the structure. These findings product a solid foundation for the subsequent fatigue tests. All analyses are conducted on the structure illustrated in Figure 2, which depicts the resonant fatigue test rig designed by Moraes (2017). The apparatus consists of two inertia plates connected by sleeves, which, using bolts, secure the crank throw between the two parts. A shaker is used to excite the crank throw samples at their natural frequencies.

4.1 MESH DEFINITIONS AND ASSEMBLY PROCESS SIMULATIONS

The crank throw assembly process was analyzed to identify the presence of plastic strain in the crank throw components. The mesh convergence analyses performed by Moraes (2017) and Ferreira (2021) was used as the basis for this investigation. The Table 1 and the Table 2 present the average element size used in the mesh, and the material properties used in the ANSYS software. In order to achieve higher precision we used quadratic elements, and a fine mesh onto the connections, following the recommendations of ANSYS, Inc. (2020).

As boundary conditions for this analysis include one of the inertial plates of the structure being fixed, with no addi-

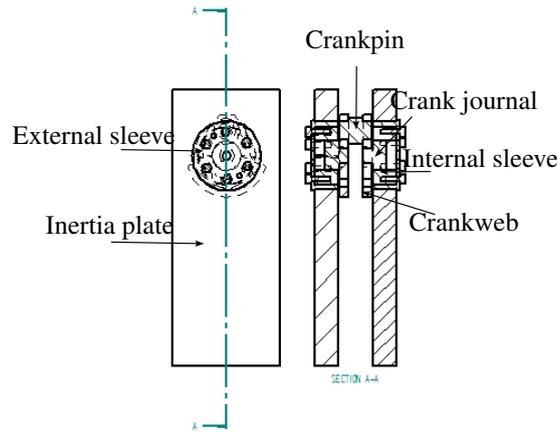


Figure 2. Structure of resonant bending test rig.

tional loads applied to the structure. The stress and strain depicted in subsequent figures result solely from the interference between the parts. In the model, the connections between the crankpins and crank journals in the crank web are characterized as frictional joints, with interference. The presence of plastic strain and frictional joints introduces non-linearities into the numerical simulation, increasing its computational cost. In order to accurately capture these non-linear effects, a specific non-linear analysis was performed, utilizing augmented Lagrangian method as the solver. This method allows for the consideration of frictional effects and provides a more accurate representation of the behavior of the assembly process.

Table 1. Mesh dimensions for numerical analysis.

Component	Element size [mm]
Inertia plates	10
Sleeves	5
Crank throw	2
Frictional joints	0.5

Table 2. Material properties for numerical analysis (Budynas and Nisbett, 2008).

Material	Density [kg/m ³]	Yield strength [MPa]	Young modulus [GPa]
AISI 1045	7850	450	200
AISI 4140	7850	600	200

To verify the mesh convergence, we used the maximum equivalent von Mises stress value on the entire crank throw as the parameter, as illustrated in Figure 3. The final mesh configuration consisted of a total of 2269878 nodes, and the maximum stress obtained was approximately 582.6 MPa, located in the crank web, indicating the presence of plastic strain in the structure. Plastic strain was also observed in the crankpin and crank journals, resulting from an interference value of 0.08 mm used in the assembly process. Figures 4 to 6 show the distribution of the equivalent plastic strain along the crankpin, crank journal and crank web, respectively.

The presence of plastic strain along the center line of the crankpin and crank journals results in the development of compressive residual stresses. This hardening process in these specific regions of the crank throw produces a similar effect to the deep rolling technique employed in cast crankshafts, increasing the fatigue strength of the overall structure.

4.2 MODAL ANALYSIS

The numerical modal analysis performed in the ANSYS workbench serves as the basis for experimental fatigue tests. In the modal analysis, we used the same mesh setup of the assembly analysis. No boundary conditions were applied to the structure during the modal analysis, as a result, the first six mode shapes represent rigid body motion with frequencies close to zero. Figure 7 shows the first bending mode shape, Figure 8 illustrate the second mode shape which represents torsion. It is important to note that ANSYS software considers all contacts as bonded (linear contact) during dynamic analysis, while in the static analysis, we can consider the non-linear connection of the crank throw parts. As a result, the outcomes represented are an approximation of the actual behavior of the structure.

The results of the natural frequencies for the assembly crank throw indicate that first bending natural frequency is

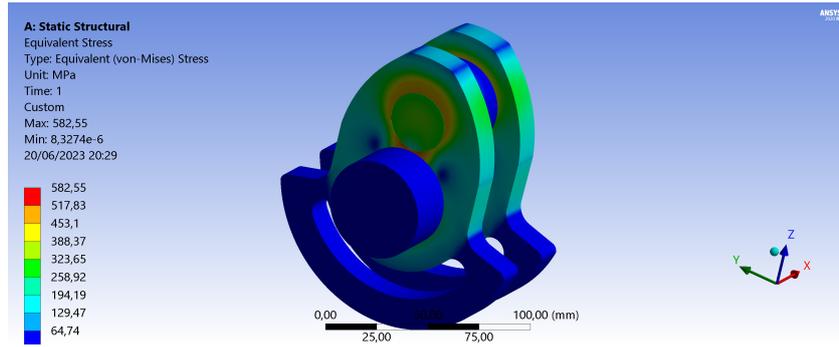


Figure 3. Equivalent stress distribution on the crankthrow.

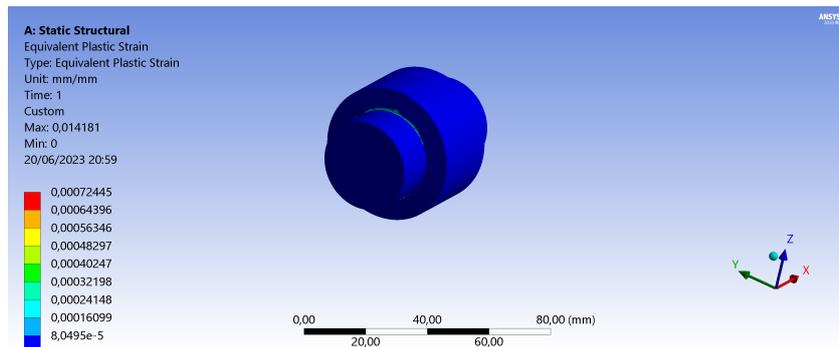


Figure 4. Equivalent plastic strain on the crankpin.

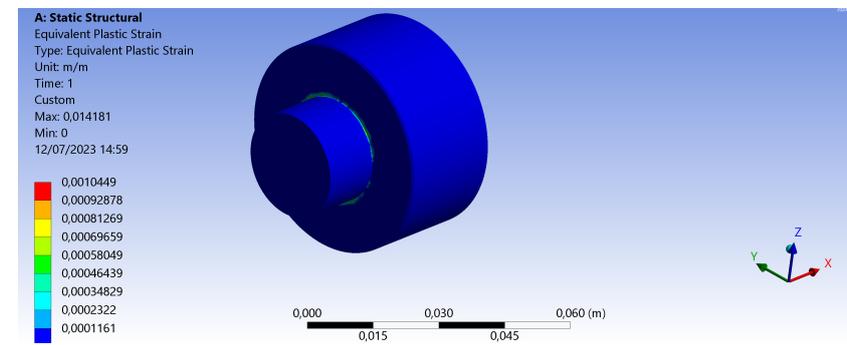


Figure 5. Equivalent plastic strain on the journal.

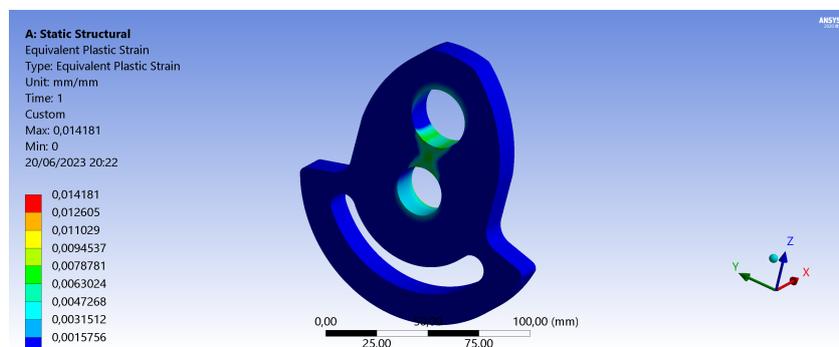


Figure 6. Equivalent plastic strain on the crank web.

40.85 Hz and first torsional natural frequency is 81.9 Hz. Therefore, similar to the cast crankshafts studied by Moraes (2017) and Ferreira (2021), the most probable failure mode case to the assembled crankshaft is bending, even in the absence of fillets radii between crankpin and the crank webs.

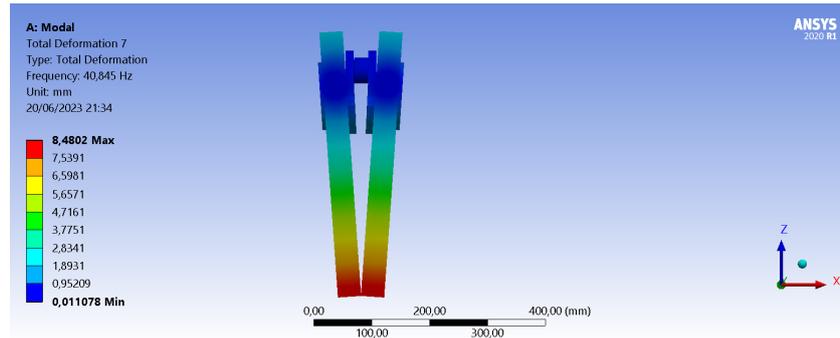


Figure 7. First mode shape, 40.85 Hz.

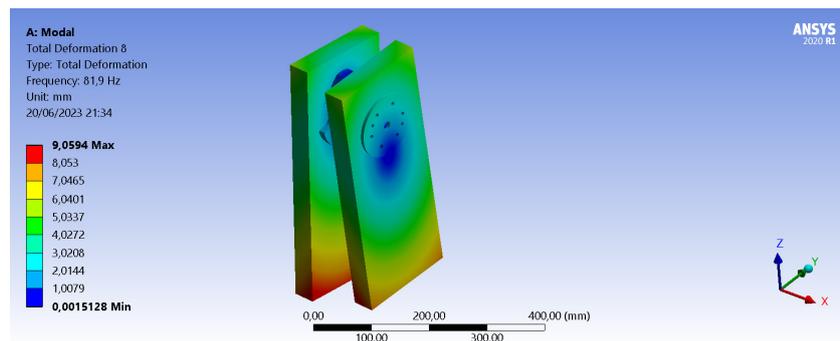


Figure 8. Second mode shape, 81.9 Hz.

5. Conclusion

The investigation and numerical simulation of the assembled crankshaft provide critical insights into the feasibility and advantages of adopting such a design. The numerical results offer some assessments about the assembled crankshaft's behavior in bending and torsion conditions. The reduction of stress concentrations, elimination of transition radii, manifest as factors for improved structural performance in overall structure.

The modal analysis provides an overview of the crankshaft's natural frequencies, establishing that bending vibrations are more critical compared to torsional vibrations. These findings are crucial for evaluating the performance of the assembled crankshaft and lay the groundwork for future experimental fatigue tests.

The utilization of an assembled crankshaft presents an opportunity for design optimization, considering diverse materials and manufacturing strategies. Reduced costs and the impact on engine efficiency and durability stand as substantial benefits associated with this crankshaft model.

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