

Circular Strategy Through Heat Treatment of Recycled Piston Rings for the Sustainability of the Automotive Economy

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Abstract: This study investigates the enhancement of mechanical performance in recycled piston rings through strategic heat treatment. The research focuses on optimizing heat treatment parameters—including austenitizing temperatures (800°C, 850°C, and 900°C), holding times (1, 2, and 3 hours), and cooling media (water, oil, and air)—to restore the hardness of used piston rings to levels comparable to new ones. Experimental methods were employed to evaluate the effects of these variables on material hardness. Results show that a holding time of three hours significantly improved hardness, with the highest achieved value reaching 38.66 HRC—nearly matching that of new piston rings (39.94 HRC). These findings demonstrate that properly controlled heat treatment can effectively rejuvenate recycled piston rings, offering a viable pathway to improve resource efficiency and reduce metal waste in the automotive industry

Keywords: Recycled Piston Rings, Heat Treatment, Microstructure, Circular Economy

Introduction

In materials science, the heat treatment process improves the mechanical properties of materials. Studies have shown that it is effective for altering microstructures, improving wear resistance, and optimizing mechanical performance. For example, heat treatment applied to alloy Al-7Si-0.6Mg containing rare earth-containing alloys showed a significant improvement in mechanical properties due to the reinforcement of precipitation produced by nano-sized deposits (Zhang et al, 2022). In addition, it is reported that optimized aging conditions can increase Rockwell's hardness, positively impact friction behavior, and improve wear resistance (Wu et al, 2023).

In addition, heat treatment achieves better mechanical properties with shorter processing times and lower temperatures than conventional treatments (Meier et al, 2022) and plays an important role in reducing anisotropy in the strength of the material (Meier et al, 2022). Studies on high chromium cast iron (HCCI) with 0.5% niobium showed that the destabilizing temperature significantly affects the microstructure and wear resistance. This makes it relevant for components such as pistons (de Faria et al, 2020). Bimetal beams made of WCI steel and AISI4140 with high Cr levels show heat treatment effects on

microstructures and mechanical properties. Hardness and bending resistance (El-Aziz & Saber, 2020) increase as a result of heat treatment.

Another important area of research is the wear behavior of piston rings during engine operation. To reduce the rate of piston wear due to frictional forces, the ideal running-in process should change the lubrication mode from boundary and mixture lubrication to hydrodynamic lubrication (Miao et al, 2022). Studies show that under the lubrication conditions of the boundary (Zhang et al, 2020), Tribofilm made of zinc dialkyl dithiophosphate (ZDDP) plays an important role in reducing friction and wear. In addition, it has been found that some of the main factors that cause piston rings to wear are dust concentration, grain hardness, and oil film thickness (Dziubak, 2022). Tribological wear behavior is also affected by the fuels used in engines, especially biodiesel (Kaplan et al, 2022). Friction, wear, and moisture are directly affected by mechanisms such as lubricant flow dynamics, which include fog lubrication. Fuel consumption and gasoline engine emissions (Dyson et al, 2023). Heat treatment, component optimization, and improved material performance contribute to the sustainability of the automotive industry. The reproduction of Automotive parts reduces waste and production costs. Studies show that material recovery through recycling reduces the consumption of key resources and significantly reduces environmental effects (Schützenhofer et al, 2022) For example, the economic gain from automotive recycling has been calculated with the current net value, the value of which ranges between 136.570 and 607.621 €/t (Cozza et al, 2023a). The process of organized dismantling and reproduction is constantly evolving. Used parts prices while keeping up with market demand for long-term service life management (Lee et al, 2023a).

The study showed that reproduction can reduce resource consumption by 21.7% to 73.5%. Based on the type of component. The mechanical properties of the piston rings are also very important for the performance and life of the engine. The quality of the cylinder liner-piston running-in process directly affects the service life, reliability, and lubrication performance (Miao et al, 2022). Intricate materials such as Cu CoBe composite gems processed with heat pressure are proven to increase the hardness of the piston rings by up to 50.5%, which greatly improves the wear resistance (Yin et al, 2017). Studies have also shown that piston ring wear reduces compression pressure, reduces engine power, and increases fuel consumption, which ultimately affects overall efficiency (Kamiński & Michalska-Požoga, 2023). Thermal analysis of the cylinder walls and pistons shows variations in temperature, thermal pressure, and deformation over various conditions (Y. Liu et al, 2022), Although additional investigation is needed to understand the impact on mechanical properties more deeply The resilience of the automotive industry depends on the efficiency of materials and data processing technologies. Indicators are used to assess the sustainability of manufacturing. economic, environmental, and social, with efficient material processing technology controlling recycling, energy consumption, and general environmental impact (Meshalkin et al, 2023). According to case studies, increasing material utilization by 20% can result in savings of £9 million annually and a reduction in CO2 emissions of 5 kilotons (Adolph, 2016), Innovative materials such as multifunctional materials and hierarchical surface nano-microstructures are essential to support the sustainability goals of the automotive industry (Anastasiadou, 2021). Sustainable material selection and efficient processing technology to offset increased energy and vehicle waste

(Pauliuk et al., 2021). Sustainable production methods such as carbon-neutral methods and circular economy models are essential to meet regulations and ensure the achievement of long-term environmental goals (Ncube et al, 2023).

Although research on recycled materials and heat treatment has grown rapidly, there are still some important aspects that have not been well understood in depth. First, how heat treatment impacts the wear resistance of recycled piston rings still requires a lot of understanding. This suggests that the a lack of studies detailing the impact of heat treatment on AlSi10Mg products (Yilmaz et al, 2021). and heat-treating recycled materials, especially on engine parts such as piston rings, which require additional investigation (Yu et al, 2022). In addition, studies on the wear of piston cylinder groups through heat treatment studies of recyclable materials or specifically addressing engine parts such as piston rings in terms of recyclable materials, are still limited (Kaplan et al, 2022). According to Zamani (2020), The potential of recyclable materials for phase-change applications rather than heat treatment has also not been optimally studied, while overarching methods that optimize multiple solution temperatures, homogenization times, and artificial aging temperatures are still uncommon.

In addition, setting the heat treatment parameters with the aim of improving the mechanical properties of the piston ring still requires additional investigation. Apart from some studies that have optimized heat treatment parameters for a wide range of applications, such as piston rings according to Aboulkhair et al. (2016), the effects of heat treatment on alloy A357 (AlSi7Mg0.6) with a focus on stress-relieving annealing, direct aging treatment, and T6 are relevant for additional investigation (Tonelli et al, 2021). Research on the impact of heat treatment on AlSi10Mg parts made by direct metal laser sintering is still ongoing. This research mainly focuses on hardness, porosity, microstructure, and minimal corrosion properties (Yilmaz et al, 2021). Even destabilization at high temperatures (980 °C), which increases wear resistance through modification of microstructures has not been thoroughly explained (Nayak et al, 2023). For now, research on the materials used for 45 steel piston rings whose mechanical properties are reinforced with heat treatment, but the consequences on recyclable materials have not been researched (Kaplan et al, 2022). The relationship between the microstructure and the performance of recycled piston rings has also not been discussed in detail. The design, manufacture, and surface testing of Cucobe-diamond composite rings to strengthen laser-textured pistons suggests a high possibility, but the relationship between microstructure and material properties Energy requires additional analysis (Ferreira et al, 2023) (G. X. Zhang et al, 2022).

Basic concept Significant microstructure design affects the performance of Aerospace applications and can be applied to recycled piston rings, but the intellectual sum data is still low (Acar & Sundararaghavan, 2019). The tribological performance of medium carbon steel (AISI) (1045) influenced by its microstructure proves that the properties of Microstructures affect abrasive friction and wear resistance, but similar studies on recyclable materials such as AA6061 aluminum chips added with B4C and ZrO₂, but the quantities available are still limited (Jiang et al, 2022).

In addition, the energy efficiency of the heat treatment process of recycled piston rings has not been thoroughly evaluated. Thermal analysis for pressure, temperature, and walls of thermal pistons and cylinders and engine heat transfer often does not take into account

the energy efficiency of the overall heat treatment process (Sharma et al, 2015). Strategies Optimization of piston ring profiles to lower friction and increase the load capacity of oil films through lubrication of mixtures and considering lubricant viscosity variables suggests possibilities, but the energy efficiency of conventional heat treatment processes, including those for piston rings, may not have been thoroughly evaluated (Zhang et al, 2016). In contrast, economic and organizational drivers of Energy efficiency in manufacturing companies show differences in the understanding of these actions (Solnørdal & Foss, 2018). Finally, the automotive industry needs to validate the results of this research. For example, for materials such as AlSi10Mg, which can be used in piston rings made from recycled materials, a wider field test is required. This material reduces porosity and increases corrosion resistance (Yılmaz et al, 2021). The addition of recycled materials, such as recycled polyvinyl butyral (RPvB), can help piston rings because they increase the wear resistance of composite materials. However, there is no evidence yet to support the use of this material on an industrial scale (Carmona-Cervantes et al, 2023). Although the process of material substitution and redesign using additive manufacturing increases attention to environmental impact and lifecycle evaluation of car components, its practical application is still far from perfect (Priarone et al, 2023). In addition, heat treatment processes such as tempering and annealing, which can be applied to recyclable materials, such as piston rings, have the potential to improve sustainability in production. However, it is necessary to conduct further research on their impact on microstructures and corrosion properties.

There is still limited research on the effect of heat treatment on the wear resistance of recycled piston rings. In addition, too few studies have studied the potential of recycled materials in phase changes during heat treatment. Its effect on materials such as alloy A357 (AlSi7Mg0.6) and the microstructure of recycled materials has not been widely studied, although several studies have attempted to optimize heat treatment parameters for specific applications. To gain a complete understanding, a thorough evaluation should be carried out regarding the relationship between the microstructure and the performance of recycled piston rings. In contrast, the energy efficiency aspect of the heat treatment process is usually overlooked in thermal analysis of the temperature of the walls and piston cylinder (Zhang et al., 2016) The results of research on the use of recycled piston rings in the automotive industry need to be further validated. In particular, reduced porosity, increased corrosion resistance, and the use of recyclable materials all require additional validation (Carmona-Cervantes et al, 2023). By optimizing heat treatment parameters such as solution temperature, setup time, and artificial aging temperature, the study offers a solution to improve the mechanical properties and wear resistance of recycled piston rings (Aboulkhair et al, 2016). The main objective of this study is to reduce porosity and improve corrosion resistance in recycled materials, specifically AlSi10Mg alloys, through proper heat treatment. In addition, the study shows that the use of recycled materials and additive manufacturing technologies can help the automobile industry become more sustainable. This research focuses on reducing environmental impacts that occur both before and during the vehicle production process, as well as on improving energy efficiency (Priarone et al, 2023).

This study aims to optimize heat treatment parameters such as solution temperature, homogenization time, and artificial aging temperature to improve the mechanical

performance of recycled piston rings. Another goal of the study was to find out how heat treatment affects the wear resistance and mechanical properties of recycled piston rings. In addition, industry validation for the use of recycled piston rings helps the advancement of environmentally friendly technologies that can reduce the impact and production costs of the automotive industry.

Methodology

This study employed a descriptive-comparative analysis as a quantitative experimental strategy. The objective was to determine the effectiveness of heat treatment strategies in restoring the mechanical properties of damaged piston rings so they can be reused in a manner consistent with circular economy principles. The study was conducted in four main, systematic stages.

Research Design

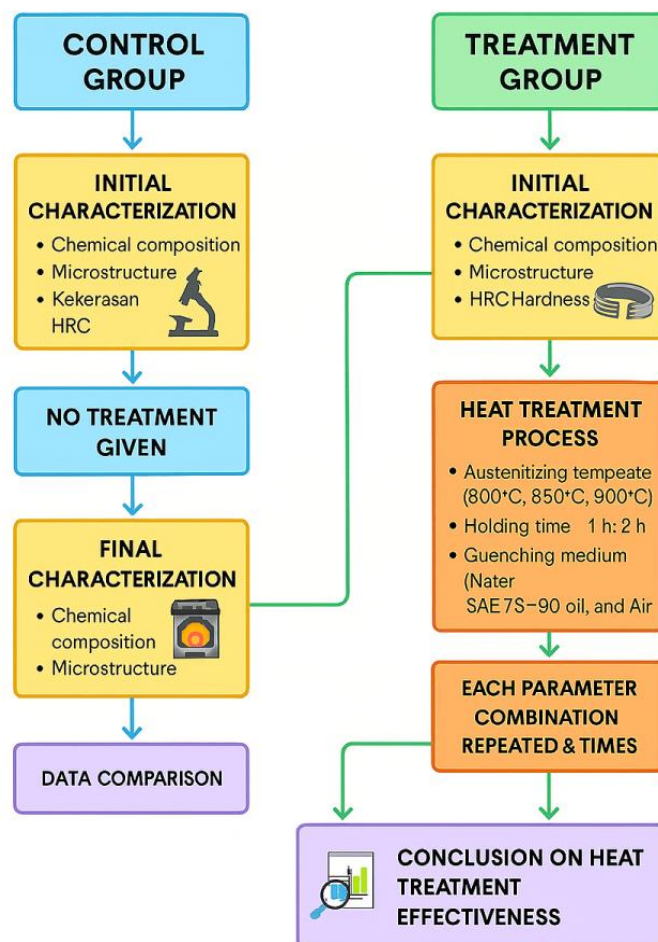


Figure 1. shows the experimental design of the this study.

Population and Sample

New piston rings from the manufacturer that have never been used and used piston rings that have been used in internal combustion engines with a minimum mileage of 50,000 km are included in this study population. Sample selection was done purposively based on several criteria. New piston rings are standard industrial products with precise technical

specifications, have never been installed, appear visually intact (no cracks or breaks), and are made of Fe-C-based cast iron material. Thirty units of old piston rings and five units of new piston rings were used as samples in this study.

Materials and equipment

Metallurgical and mechanical laboratory equipment is used to visualize materials before and after heat treatment. The information collection method is carried out in stages.

Characterization of New and Used Materials

- Chemical Composition:** Analysis was conducted using an Optical Emission Spectrometer (OES) in accordance with international standards.
- Microstructure:** Samples were cut, polished, and metallographically etched before being observed using an optical microscope or scanning electron microscope (SEM).
- Hardness:** Hardness values were calculated using a Rockwell hardness tester (C Scale), based on the ASTM E18 standard, with data taken at five random points for each sample.

Heat Treatment Process

An electric furnace is used for heat treatment, featuring automatic temperature control with a precision of $\pm 5^{\circ}\text{C}$. The process stages begin with heating (austenization), where the sample is heated to the target temperature (800°C , 850°C , or 900°C) at a heating rate of $10^{\circ}\text{C}/\text{min}$; holding, where the sample is maintained at the target temperature for 1, 2, or 3 hours; and quenching, where the sample is rapidly cooled using water, oil, or other media.

Characterization After Heat Treatment

Samples that have undergone the heat treatment process are then re-characterized using the same instruments and procedures to evaluate changes in material properties.

Data Analysis Techniques

The data obtained were analyzed descriptively and comparatively in two stages. Namely, Initial Descriptive Analysis by comparing the initial characterization data of new and used piston rings to determine the level of material degradation due to use. Comparative Analysis: Evaluating the impact of variations in heat treatment parameters on changes in hardness and microstructure, and Result Validation, namely ensuring that the experimental results are consistent and valid, involves qualitative microstructural analysis by comparing microphotos before and after treatment. Hardness and chemical composition analysis are carried out quantitatively.

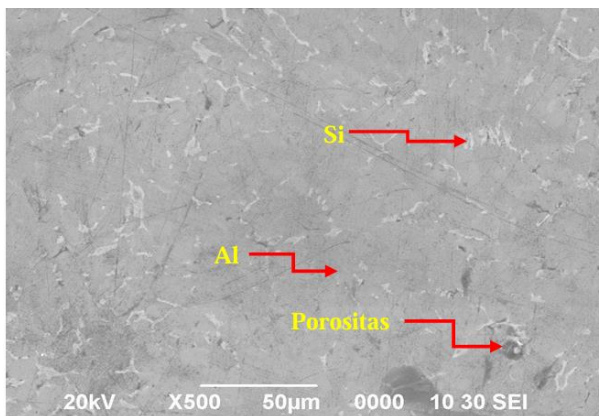
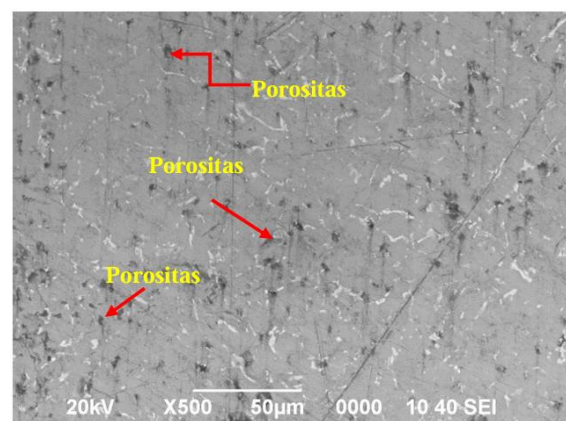
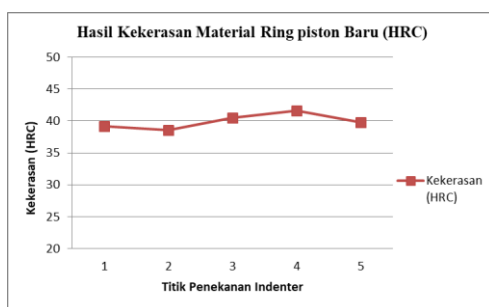
Result and Discussion

The new piston rings have a carbon content of 3.65% and an iron content of 92.45%. In comparison, the used piston rings have a carbon content of 3.11% and an iron content of 93.02%, according to OES chemical composition analysis. Table 1 shows that use has caused a decrease in carbon content, a critical element that determines the hardness and strength of cast iron materials.

Table 1. Chemical composition of the new piston ring

Alloy	Fe	C	Si	P	Mn	Mg	Cr	Ni	Mo	Cu
New piston ring	92,45	3,65	2.75	0.35	0.74	0,005	0.21	0,006	0.26	0.036
Used piston rings	93,02	3,11	2.89	0.40	0.62	0,006	0.19	0,007	0.28	0.029

Optical microscope observations (Figures 2 and 3) show that the used piston ring (before treatment) has a coarse graphite structure and uneven distribution, indicating damage due to thermal loads and friction. However, the used piston ring (after treatment, ideal heat 900°C/3 hours/oil) has a more homogeneous structure, finer graphite distribution, and rapid cooling causes the martensite and bainite phases to appear. The hypothesis that heat treatment can regenerate the internal structure of the material is supported by these visual changes.

**Figure 2.** Microstructure of the new piston ring with 500X magnification**Figure 3.** Microstructure of used 500X piston ring**Figure 4.** the hardness between the new piston rings**Figure 5.** Hardness between used piston rings

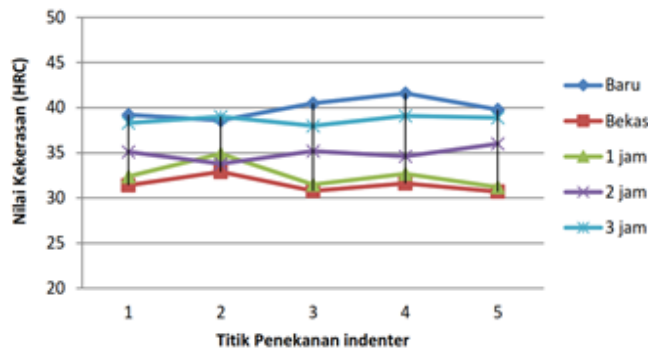


Figure 6. Material hardness

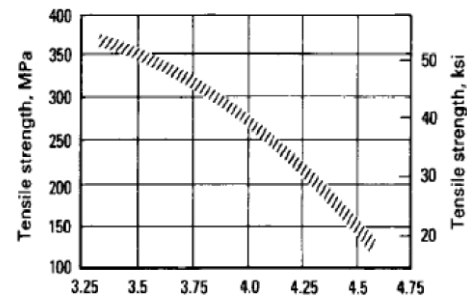


Figure 7. Effects of material carbon

A combination of parameters, based on hardness and microstructure data (Graphs 4 and 5), provides the best picture, namely at an austenitizing temperature of 900°C, a holding time of 3 hours, and a cooling medium of SAE 75-90 oil, consistently producing the highest hardness values and the most homogeneous microstructure of all variations tested.

Discussion

The hardness decrease from 39.94 HRC to 28.42 HRC directly correlates with the decrease in carbon content from 3.65% to 3.11% (Table 1). This is in line with metallurgical theory that carbon is the main component that forms carbides and martensite phases, which cause steel and cast iron to have high hardness. These results support research Liu et al. (2022), which states that control of chemical composition is very important to determine the response of materials to heat treatment.

Two main mechanisms account for the increase in hardness to 38.66 HRC after an ideal heat treatment, as shown in Figure 3. One is a rapid cold phase transformation in the oil from the austenitization temperature of 900°C, leading to the formation of the extremely strong, metastable martensite structure. This is consistent with the basic principles of heat treatment described (Nayak et al., 2023). Homogenization and Microstructural Refinement is a long-lasting, heating-required process lasting for 3 hours. This process allows for the diffusion of carbon atoms and grain recrystallization, resulting in a more uniform structure (Figure 2). This is consistent with the findings Al-Zubaydi et al. (2022). X. Liu et al. (2022) that microstructural homogenization improves overall mechanical properties.

The key finding of this research is that old piston rings can be regenerated to 96.8% the hardness of new material. This means that a single reconditioned component is not discarded. In other words, resource reconditioning saves more energy and raw materials than new production (Cozza et al, 2023b) (Schützenhofer et al, 2022) (Lee et al, 2023b).

The Microstructure-Performance Relationship in Recycled Materials shows a strong correlation between microstructural homogenization and material performance (Yu et al, 2022) (Kaplan et al, 2022). The Effect of Heat Treatment on Recycled Materials shows that heat treatment is effective not only on new materials but also on used materials that have undergone degradation (Ferreira et al, 2023) (Jiang et al, 2022). The Parameter Optimization

Method for Specific Applications successfully found the ideal parameters for used piston rings (900°C/3 hours/oil), which has not been widely studied before (Aboukhair et al, 2016) (Tonelli et al, 2021)

This study has several limitations. One is the lack of tribological testing, which is important because high hardness does not necessarily mean good wear resistance. For full validation, friction and cyclic wear testing are required (Shah et al, 2022). Energy Aspects Have Not Been Measured: No research has been conducted on the energy efficiency of the heat treatment process; this is crucial for sustainability (Neves et al, 2022) (Solnørdal & Foss, 2018). Results may be influenced by differences in the used materials and chemical composition between samples. In the future, materials should be tested before treatment. Therefore, the study findings clearly demonstrate that heat treatment strategies have the ability to restore the mechanical properties of aged piston rings. Furthermore, the discussion highlights the relevance of these findings to metallurgical theory, recent research, and the significant circular economy goals in the automotive industry.

Conclusion

The results of this study indicate that through recrystallization of a more homogeneous microstructure, heat treatment can significantly improve the hardness and wear resistance of used piston rings. In addition, the use of recycled materials supported by advanced manufacturing technology can help the automotive industry reduce its negative impact on the environment and production costs. Although the findings of this study provide new knowledge, there are several limitations. The consistency of the response to heat treatment can be affected by differences in the chemical composition of used piston ring materials, especially for carbon and silicon elements. During the heat treatment process, temperature and duration control are also very important because errors can lead to the formation of undesirable microstructures. There has not been a comprehensive evaluation of the energy efficiency of the heat treatment process in this study. Therefore, recommendations for future research are needed to additionally include elements of thermal analysis followed by tribology testing to determine the wear resistance, especially for recycled materials.

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