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FAILURES/BREAKDOWNS DUE TO RESIDUAL STRESSES IN THE VEHICLE INDUSTRY

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Abstract: The evaluation of residual stress is crucial since it has a significant impact on the component's lifetime and can cause breakdown or failure during manufacture, which may affect the economics, lives, and the environment. Residual stress analysis has now become a mandatory requirement in the automobile industry. Because each manufacturing process like machining, casting, heat treatment, and coating impacts the residual stress state, it can be pretty complicated and varied within the components. If the effects of these processes are well studied, it is possible to achieve a stress state in the part that will increase its lifetime and performance while lowering costs with an optimized method. This paper discusses the effect of residual stress on the automotive industry and illustrates how is residual stress participates in every manufacturing process of vehicles.

Keywords: residual stress, automotive industry, manufacturing process, failure.

Introduction

The residual stress can be defined as the remaining stresses persisting inside the material's structure or component without any external loading or thermal gradients following a manufacturing process or can be defined as the remaining stresses created within a structural material or component after releasing the load (Coules *et al.,* 2018). Residual stresses can be caused by various factors, including temperature gradients, heterogeneous plastic deformation, and phase transitions, which may act in a complex way (Coules *et al.,* 2018; Kwak & Hwang, 2018; McAndrew *et al.,* 2018). Scientists, researchers and engineers should pay close attention to residual stress because of its impact on the mechanical behavior of materials and structures. In (Withers & Bhadeshia, 2001a, 2001b), Withers and Bhadeshia provide a complete discussion of residual stress measurement, nature, and origins. The ASM book (American Society for Metals), edited by (Totten *et al.,* 2002), is an essential reference regarding residual stress in steel. McClung's review (McClung, 2007), which the FAA (Federal Aviation Administration) supported, emphasizes the stability and relevance of residual stresses during fatigue and includes over 230 references. Many conference volumes on the topic are significant, including the ECRS (European Conference on Residual Stresses) and the ICRS (International Conference on Residual Stresses). The Advances in Surface Treatments series promoted by (Niku-Lari, 1987) are among them.

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Positive tensile residual stresses increase fracture propagation, whereas compressive residual stresses often slow it down. The impact of residual stress on the fatigue behavior of structures is the subject of studies such as (Häusler *et al.,* 2011; Lanciotti *et al.,* 2011; Moreira *et al.,* 2012; Richter-Trummer *et al.,* 2011; Tavares *et al.,* 2011).

The stress under which an element is subjected determines its mechanical behavior. The conventional stress state computations utilizing standard Strength of Materials analysis (torsion, bending of beams, etc.) assume that the studied body is stress-free before the loads are applied. If that material is already subjected to persistent stress independent of external loads—so-called residual stresses—then the original stress system will likely affect its mechanical behavior (Ficzere *et al.,* 2017; Tavares & de Castro, 2019). The residual stress system is the starting point for adding the stress from external loads. Residual stress is overlaid on the stress conditions that take place during the component's service life; therefore, its volumetric extent, nature, and magnitude have a significant impact on the component's lifetime. In some instances, the existence of nature and magnitude of residual stress (tensile or compressive) at definite areas of the element - is the same as that has to fulfill the suppliers' requirements, such as strength, elongation, or hardness. Compressive stress near the surface region should be achieved by employing common surface compression or heat treatment options like (carburizing, rolling, burnishing, shot peening) to extend the part's lifespan against fatigue (Davis, 2002). The overall stress state could be well controlled using those strategies. There is another significant feature of residual stress. The distribution and nature of residual stress generated during production might vary significantly. Because external loads like torsion or forces do not form residual stresses, they must be balanced. Balance is attained inside the deformed part. Some macroscopic deformations happen due to the relaxation of the stress if this balance is disturbed by any later technological process like machining or welding. In this case, the heat effect may change the stress condition. This form of distortion is permanent and lasts until the end of the production process, increasing the waste product ratio. Therefore, the monitoring and evaluation of the residual stress should be done during the whole production process, not only at the end of the production line. A large number of studies and researches have been conducted to investigate the residual stress phenomena and its impact on component mechanical characteristics. However, the number of control reports for the entire production line is relatively low (García Navas *et al.,* 2011; Sepsi *et al.,* 2017).

Failure due to Industrial Manufacturing Processes

Many industries are interested in mechanical failures containing residual stress because they can exist in a wide range of metallic materials (Hosford, 2005). Many case histories, like the Silver Bridge collapse (Czyzewski, 1975) and the collapse of a high-strength steel frame in a US army jet fighter (White and Kantimathi, 1992) led to an essential step in investigating residual stress. (Fairfax & Steinzig, 2016) used the ASM Failure Analysis Database™ to find the mechanical failure articles connected to the residual stress, and they found 147 articles in which the residual stress is a part of the mechanical failure reasons. They found that 118 out of 147 failures occurred in steel material. They also found that 111 of the failures involved SCC, and Fig.1 shows the most common failure mechanisms involved in the 147 cases.

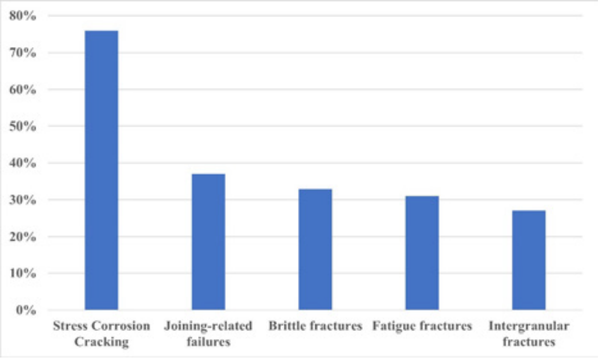

Fig. 1.
Common Failure Mechanisms
Source: (Fairfax & Steinzig, 2016)

To sum up, steel is the most commonly stated material that fails because of residual stress. Steel is widely employed in many manufacturing and industrial applications (Zhang *et al.,* 2021); therefore, this is most certainly associated, if not caused, by this. All such failures are induced mainly by stress corrosion cracking (SCC), a process of failure that includes three factors: a vulnerable ductile material (like steel), tensile stresses, and the appearance of a particular corrosive factor (such as chlorides, even in small quantity). Tensile stresses are frequently residual stresses from the phase transformation that is not entirely alleviated by tempering or other surface treatments. The level of residual stress is affected by many factors. It depends on both the technology and the process parameters.

2.1. Machining

The tensile and compressive stress can influence the nature and magnitude of the residual stress during machining. Tensile stress is increased by increasing the feed rate and cutting speed, while a favorable choice of edge angles can enhance the compressive stress. In grinding, the grain material quality determines the stress character. The typical distribution of residual stress as a function of layer depth is shown in Fig. 2 (forgacsolaskutatas.hu. 2022). The layer below the surface is subjected to compressive stress, while the layer near the surface is subjected to tensile stress. The subsequent stage contains tons of compressive stress depending on the heat treatment of the component. For example, compressive stress indicates a hardened structure.

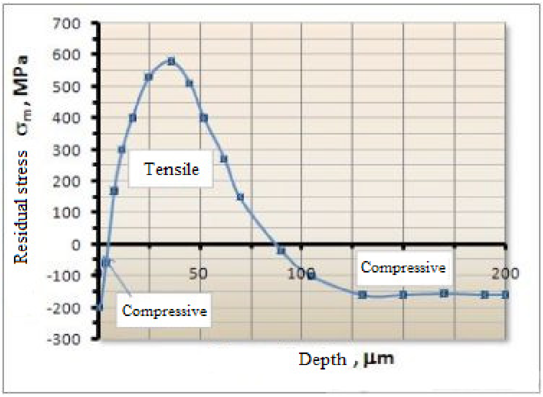

Fig. 2.
The Distribution of Residual Stress as a Function of Layer Depth
Source: (forgacsolaskutatas.hu. 2022)

2.2. Casting

Casting technique is still the most popular way to improve mechanical characteristics (Dahunsi *et al.,* 2020). After casting, tensile stress remains in the top layer below the product's surface. Compressive stresses are present in the lower layers. The residual stresses depend on the condition of the mold. Higher residual stress is measured if the product is cooled quickly (Podgornik *et al.,* 2010). The presence of undesirably distributed tensile residual stresses is linked to the potential for fracture formation in elements produced by centrifugal casting, according to (Zelenova *et al.,* 1982). Moreover, tensile stresses enhance the likelihood of creep failure in components that operate at high temperatures, such as those used in hot-rolling. To accomplish the needs in terms of wear and temperature resistance, toughness and hardness rolls for hot-rolling are generally formed as double-layer manufacturing by casting in two phases, first by the centrifugal casting of the outer layer from harder heat and wear-resistant material, second by the traditional casting of more ductile inside material.

2.3. Heat Treatment

In the various mechanical systems manufacturing industries, two primary manufacturing areas can be distinguished according to the purpose of the production: component manufacturing and final product manufacturing. Component manufacturing produces components with a specific geometry, surface quality, and material properties. Forming can be carried out using built-up (casting, welding) or deposition (machining) processes. Specific material and manufacturing properties are demanded because of the stresses during the work of the part. Therefore, it is needed to change the material properties of metal and alloyed parts. This is the reason we apply heat treatment. A general task is to choose the appropriate treatment process and regulate the material quality. That is why heat treatment is used. The general task is to find the proper heat treatment for the purpose process and the specification of the material quality.

During the various heat treatments, internal stresses are generated in the components (Podgornik *et al.,* 2010). The magnitude of these stresses influences the subsequent machining and, in many cases, can lead to product failure. We need to know the way internal stresses are generated to avoid component failure. It is also necessary to understand the external and internal influencing factors, the heat treatment dimensional variations, and their effect on the cracking.

Significant temperature differences can occur during cooling between the core and the component's surface. This significant temperature difference can be further reduced by increasing the cooling rate or increasing the size of the workpiece. Due to the temperature gradient, the time course of the volume changes inside the part and in the layers closer to the surface are different, creating thermal stress. When this thermal stress exceeds the yield stress, the part undergoes plastic deformation. During the cooling process, the austenite is subjected to different fabric structures. This transformation leads to a change in the bulk density, which affects the stresses inside the component. Basically, two types of stress (thermal and transformation stress) determine the magnitude of the residual stresses in the element and the distribution of the residual stresses in parts.

2.4. Coating

The effects of residual stresses during coating on fatigue life are described in (McGrann *et al.,* 1998). That is done by applying WC-Co coatings on both aluminum and steel structures to bending tests under constant deflection, and they found that by increasing the compressive residual stress in the WC–Co coating, the number of cycles to failure will increase vs. the log of the number of cycles to failure in the 6061 aluminum substrate specimens. The chrome-plated specimens had about the same number of cycles to failure as the WC–Co-coated 4130 steel substrate specimens with a low compressive residual stress. Increasing the compressive residual stress in the WC–Co coating will increase the number of cycles to failure in the specimens with steel substrate. The number of cycles that WC-Co coated 4130 steel substrate specimens, which have a tremendous compressive residual stress, reached failure was the same in the case of bare shot-peened steel.

2.5. Welding

Recently, there has also been a significant transformation in welding technologies (Agarwal *et al.,* 2021). One such new technology is remote laser welding (Watson, 1999). Despite its short development period, it offers a wide range of applications. The ideal applications for laser beam welding are tight tolerance parts, very well welded parts, and welding of materials or material pairs that cause welding difficulties or welded joints. Some application examples:

- Automotive halogen bulbs;
- Car windscreen frames;

- Gears in gearboxes;
- Torsion dampers;
- Passenger car floor frames and body panels;
- Plate welding for large deep-drawn automotive body panels.

Residual stresses and distortions might occur in areas near the weld bead because of heating localization by the welding process followed by a fast cooling rate. Brittle cracks, SCC, and fatigue can all be caused by high residual stresses near the weld. In the meantime, residual stress in the base plate might lower the structure components' buckling strength. As a result, welding residual stresses should be kept to a minimum to meet the standards. Many researchers have improved different techniques, such as vibration stress releasing, hammering, weld sequencing, pre-heating, and thermal treatment, to minimize the residual stress referred to welding. Choosing an accessible welding sequence is more straightforward and efficient in these ways for reducing welding residual stresses (Koch *et al.,* 1985; Rybicki & McGuire, 1982).

3. Failures in the Automotive Field

The main aspect of vehicle parts is the operating lifetime, which could be significantly associated with residual stress in parts. Residual stress can arise in many vehicles manufacturing processes such as welding structures, additive manufacturing, different rotating shafts like gears and crankshafts, machining operations (grinding, cutting), heat treatment processes, casting, and intentionally utilizing a variety of methods (flow turning, burnishing, shot peening) (Alzyod & Ficzere, 2021; Totten *et al.,* 2002). If the impacts of these manufacturing processes are understood, it is easy to reach a stress state in the part that will increase its lifespan and performance while lowering costs with an optimized method. Many types of research were done to investigate the residual stress in cars parts. (Sepsi *et al.,* 2017) studied the residual stress into two countershafts during the manufacturing steps (machining in the annealed state, heat treatments (carburizing), shot peening, and machining in the hard state). In the heat treatment step, they put one in the pusher furnace while the other in the chamber furnace. They found that the residual stress state changed in a range that exceeded 1 GPa during the process. At the end of the process, the tensile stress was more than 500 MPa. (Sediako *et al.,* 2021) studied the residual stress in an as-cast and T4 I6 Engines Block, and they figured out there is a complex relationship between heat treatment and the development of residual stress during quenching part of T4 process.

(Keste *et al.,* 2016) succeeded in determining and minimizing the residual stress in a shifter during the casting process using ANSYS finite element analysis software and verified the results experimentally.

More than half of the vehicle's weight is in the chassis, body, and suspension elements, as shown in Fig. 3. The main component in the chassis is the steel with different grades, and Fig. 4 illustrates that. While steel, aluminum, and Carbon-fiber-reinforced polymers (CFRP) are generally used in Body-in-White (BiW) manufacturing.

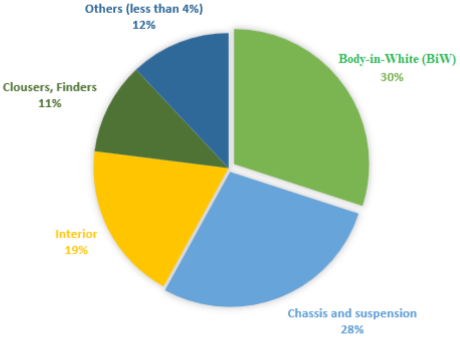

Fig. 3.
The Weight Ratio of Various Vehicles Components (excluding the Powertrain)
Source: (Tisza & Czinege, 2018)

Fig. 4.
Steel Distribution in a Vehicle
Source: (Bachman, 2018)

4. Samples of Manufacturing Processes used in the Automotive Industry

4.1. Shot Blasting

Shot blasting is the process of shooting a large number of solid particles, up to a few millimeters in diameter, at a target at high speed. This technology aimed to clean mechanically adhering contaminants on the surface of semi-finished products awaiting further processing in a given manufacturing process. Its task was to remove the crumb layer formed on their surface during heat treatment from iron-based alloys, typically cast or hot-plastic-formed. Another important industrial application of the method is when the target is sprayed primarily with steel balls to create a sub-microscopic residual compressive stress in layers close to the piece's surface at a depth of a few microns. Small craters form on the surface as a result of the impacting particles. Shotguns work in the tight surroundings of impact sites. The kinetic energy of the impacting particles, on the one hand, causes plastic deformation of the material and, on the other hand, releases the stresses remaining in the material. This method primarily increases the fatigue resistance of parts subjected to fatigue. Tensile stress is created on the surface of the piece, which is compensated by the residual compressive stress caused by the shotgun. Some residual stress problems appear with shot blasting, such as:

- Residual stress in lower strength materials is more challenging to create, causes fewer property changes, and relaxes more easily;
- The residual stress decreases during fatigue;
- The accompanying blasting phenomenon may be that the surface roughness deteriorates if the grain sizes are inappropriate (Mertinger *et al.,* 2010).

Shot blasting is used in car parts such as valve springs for engines, suspension springs, crankshaft, connecting rods, and transmission parts. Moreover, the combination of residual compressive stress and surface hardening increases spring life against fatigue stresses (Podgornik *et al.,* 2010).

4.2. Rolling

The rolling process makes the structure more resistant to corrosion fatigue and stress corrosion fracture, and it is used in many vehicles components like engine block, rim, parts of the gearbox system, and cylinder sleeve. This technology also increases the fatigue life of the material, as does shot blasting. Fig. 5 compares the different types of rolling, and the machined surface shows that rolling has the best surface quality, but ball rolling achieves higher hardness (Mertinger *et al.,* 2010).

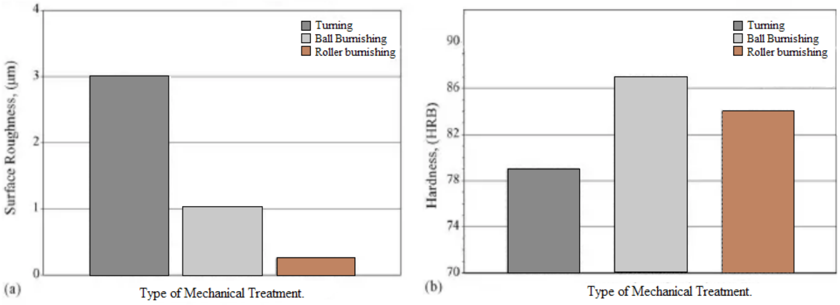

Fig. 5.
Effect of Mechanical Treatment on (a) Roughness and (b) Hardness
Source: (Mertinger et al., 2010)

5. Conclusion

Our ability to prevent, anticipate, or delay the breakdown of components and structures based on fundamental physical principles is critical to our safety. While external loadings acting on a component or structure are clearly crucial, additional factors such as undesirable material microstructure, previously existing defects and residual stresses can also play a role. As residual stresses are produced at practically every stage of the manufacturing process, the impact of processing applied to failure-critical areas must be adequately studied, controlled, and optimized. Once fully grasped, fabrication techniques can be optimized and enhanced to produce high-quality components at a competitive price.

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