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SHOT TEMPERING

RFCS-2023-02-RPJ

Deliverable D3.1: Surface states for optimized warm peening conditions

ShotTempering

Shot Peening Integration in Tempering Processes of Steels
for Enhanced Fatigue Performance

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Deliverable Type	Report
Dissemination Level	Public
Due Date (Annex I)	31.12.2025 (Month 18)
Pages	23
Document Version	Final
GA Number	101156779
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Version Log			
Rev #	**Date**	**Author**	**Description**
0.1	19.01.2026	Benjamin Dollhofer (KIT)	Draft
0.2	19.01.2026	Philipp Reeh (STRESSTECH)	Update Methods
1	21.01.2026	Philipp Reeh (STRESSTECH)	First Revision
2	21.01.2026	Valentina Dellaca (CRF)	First Revision
3	03.02.2026	Stefan Dietrich (KIT)	Second Revision
Final	04.02.2026	Marcel Egger (I2M)	Coordinators Review

Project Abstract

In response to pressing challenges, such as climate change and the increasing need for enhanced energy efficiency in the transport sector, the ShotTempering project addresses the imperative for advancements in the production process chain. The project introduces an innovative hybrid technique known as ShotTempering. In contrast to established shot peening at elevated temperatures, commonly referred to as warm peening, ShotTempering operates at temperatures high enough to integrate shot peening directly into the tempering treatment of components. This approach is particularly relevant for high-demand applications such as electric vehicles, where components are subjected to significantly higher loads, requiring further optimization of manufacturing processes to enhance performance and prevent premature failure. This novel ShotTempering process offers dual advantages. Firstly, it promises to boost the overall efficiency of the process chain in terms of energy consumption, resource utilization, and time savings. Secondly, it holds the potential to significantly enhance the mechanical properties of manufactured parts, particularly their fatigue resistance, through shot peening at elevated temperatures. This technique is recognized for its capacity to augment cyclic residual stress stability, fatigue strength, and, consequently, the longevity of critical components. The ShotTempering project represents a pioneering endeavour poised to revolutionize the manufacturing landscape, catering to the evolving demands of the transport sector while contributing to sustainability and energy efficiency goals.

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Public Summary

This deliverable presents the methodology and results related to the characterization of ShotTempered surface conditions, the evaluation of relevant process parameters, and their influence on local fatigue strength. Process temperature and process time were varied in test series corresponding to three different process routes for 27MnCr5 (carburized), 42CrMo4 (hardened in a furnace), and C55 (induction surface hardened).

To characterize the material response, hardness profiles and residual stress depth profiles were determined. These data enable the estimation of fatigue strength in the high-cycle fatigue regime for a given load and allow assessment of the influence of different process parameters. The effects of selected parameters on surface hardness, residual stresses, surface roughness, and, in the case of the carburized samples, retained austenite content were analyzed and compared across the different process routes.

Compared with the respective reference processes, ShotTempered samples generally exhibit higher compressive residual stresses extending to greater depths below the surface. The results further provide valuable input for the design of subsequent process chains and potential applications.

1 Introduction

1.1 Rational of this deliverable

This deliverable (D3.1) focuses on defining the surface states required for optimized ShotTempering, which form the basis for all subsequent actions in WP4 & 5. The primary goal of this deliverable is to improve the fatigue strength of components across the specified process routes.

WP3 addresses the optimization of ShotTempering for different materials and hardening routes. Consequently, this document presents the methodology and results related to the characterization of surface conditions, the evaluation of relevant process parameters, and the evaluation of their influence on local fatigue strength. The document is structured to first outline the applied measurement techniques, followed by a description of the individual processes and the final results used for the optimization of the ShotTempering process.

The optimization approach is based on the concept of local fatigue strength. To define this material parameter, the hardness profiles and the residual stress depth profiles are determined. These data enable estimating the fatigue strength in the high cycle fatigue region for a given load and allow evaluating the influence of different process parameters. The results also provide the basis for defining the boundary conditions for fatigue testing in subsequent work packages.

The different processes for the investigated materials were first studied separately. The influence of selected parameters on surface roughness, hardness, and residual stress, and therefore on local fatigue strength, was analyzed and later compared across the processes. In addition, the mechanically induced transformation of retained austenite during shot peening was examined, since it leads to an additional increase in hardness. This effect is particularly relevant for carburized 27MnCr5 components, where the retained austenite content can be significant.

This deliverable integrates contributions from several project partners. The material was supplied by Sidenor I+D (WP2), while the samples and all ShotTempering processes were prepared and performed by KIT (T3.1). The conventional hardening of the 42CrMo4 samples (T3.3) and the inductive surface hardening of the C55 samples (T3.4) were also performed by KIT. The case hardening of the 27MnCr5 material was carried out by an external partner of CRF (T3.2). Surface roughness and hardness measurements were conducted by KIT, while residual stress and retained austenite measurements were provided by STRESSTECH (T3.5).

The main results of this work include the identification of optimized process parameters and a consolidated overview of their effects on surface integrity and local fatigue strength. These findings form the basis for the selection of the final set of parameters (T3.6), which will be used in the upcoming investigations of the lifetime of the components at the laboratory scale (T3.7, WP4) and at the component scale (WP5).

<u>Objectives (Extention):</u>

The objectives cover the majority of the objectives of WP3:

- Determination of the effect of different shot peening parameters, temperatures (200 °C – 500 °C), hold times and process sequence on residual stress profiles, roughness and hardness evolution.
- Investigation of effects on carburized parts, conventionally hardened parts and surface induction hardened parts.

- Optimization of the ShotTempering process with regard to desired hardness, residual stresses, roughness and if applicable, retained austenite contents of specimens and demonstrator components.

Furthermore, to be able to separate the influence of the sample preparation, the initial state of the samples was investigated in the same way as the further processed samples. Additionally, samples were peened at room temperature (RT) to analyse the effect of shot peening without tempering.

<u>Deviations (Extension):</u>

Selecting optimal parameters is essential for the project's success. Therefore, the partners decided to draw this choice on a more comprehensive data set. The risk associated with schedule delays is regarded as lower than the risk of implementing suboptimal parameters.

Therefore, the outcomes of the novel ShotTempering process must be examined in more detail than originally planned. Additional data for the carburizing route remain necessary, as tempered martensite embrittlement must be prevented. The detailed examination of the process conditions has already taken substantially more time than anticipated. Moreover, the process stability of ShotTempering had to be revalidated after one sample group showed deviating results, leading to extended preparation and calibration efforts. Enhanced process monitoring has since mitigated this risk. The high air flow temperatures of 400–500 °C also cause very slow temperature regulation, requiring a prolonged period to reach stable operating conditions.

Due to capacity constraints, T3.2 and T4.5 were carburized in the same run, leading to a minor delay for T3.2. All other samples, except those of T3.7, are completed and ready for subsequent processing, which is expected to compensate for delays in WP4 and the overall project.

2 Methods

2.1 ShotTempering

ShotTempering was carried out on a Baiker shot peening machine SKUK-1 system. The sample was fixed at the center of a rotating table. Cut-wire shot with a diameter of 0.9 mm was employed. The peening distance was 100 mm, and the nozzle diameter was 4 mm. In this configuration, the impact angle is 90°. The peening pressure was adjusted to 1.2 bar with a shot mass flow rate of 1 kg/min. Furthermore, a stream of hot air was directed onto the component during treatment to offset the cooling effect of the carrier air stream. Additional heating was provided by resistance heating via two copper clamps attached to the sample holder.

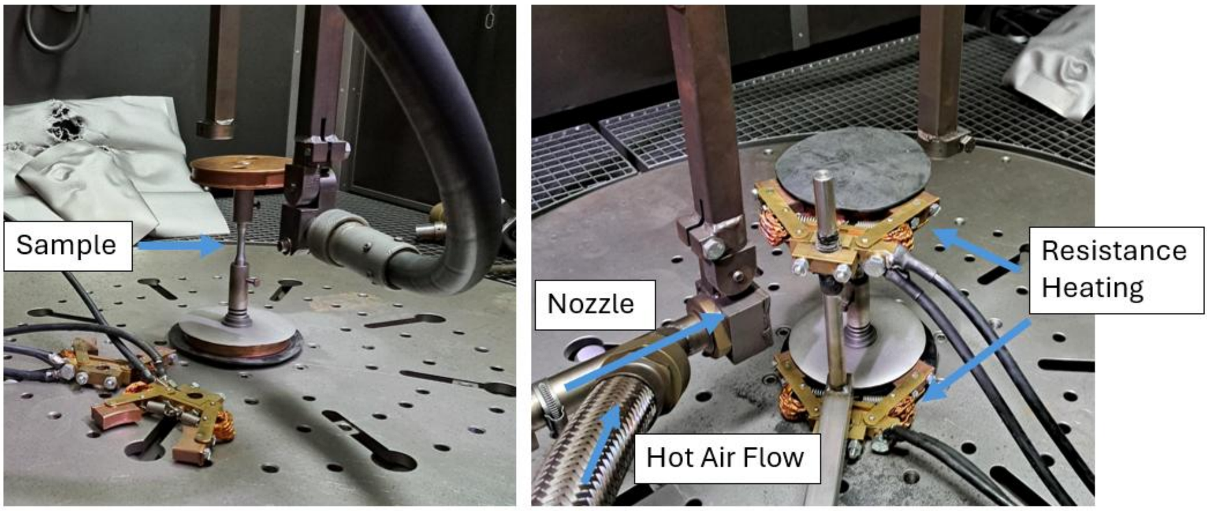

Figure 1: ShotTempering setup

2.2 Surface Roughness

The surface roughness (Rz) was measured with a KEYENCE 3D Profilometer. The measurement was taken at the middle of the surface at several points around the circumference.

2.3 Hardness Depth Profiles

The hardness measurement was performed with a Qness Q10A micro hardness tester using the Vickers method with a test weight of 0.1 kg (HV0.1) according to DIN EN ISO 6507-1. For statistic evaluation, three measurement points per distance to the surface were made for each sample.

2.4 Residual Stress Depth Profile (Stresstech)

The evaluation of residual stresses in the axial and tangential directions was performed according EN 15305:2009 standard, using the X-ray difraction method $\sin^2(\psi)$, utilizing material parameters as outlined of experimental XEC ½ S2 = $5{,}84 \cdot 10^{-6}$ MPA^{-1}[1]. Therefore, the Xstress DR45 difractometer at STRESSTECH was used with Cr-Kα radiation (30 kV and 9mA) to assess the {211} α-Fe difraction line at distinct Ψ angles ranging from −45° to 45° in modified χ mode with number of 9 tilts.. In all experimental procedures, an exposure duration of 5 s was maintained and a collimator with a beam diameter of 1 mm was used. Raw data analysis was performed using the Xstress Studio software from STRESSTECH. The residual stress measurements were performed with the following (nominal) depth steps:

C55: 0, 10, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1.000, 1.100, 1.200, 1.300, 1.400, 1.500µm

42CrMo4/27MnCr5: 0, 10, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500µm

The individual depth steps were generated by electrolytic polishing of the surface and the true depths were meaured with a dial indicator.

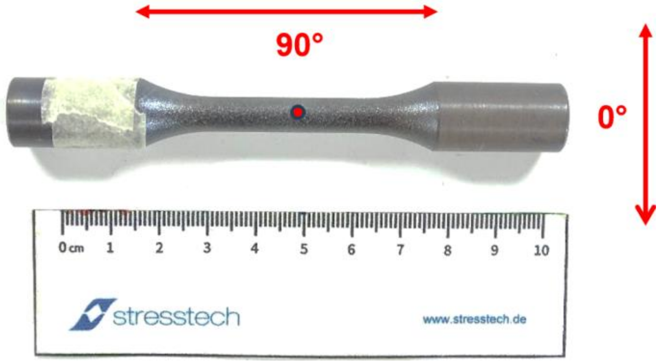

Figure 2: Measurement directions; 0° tangential and 90 ° axial residual stresses

2.5 Retained Austenite Measurement (Stresstech)

The retained austenite measurement was made only on the carburized samples. The retained austenite content was measured according to ASTM E975-22 with the four-peak-method by using a Cr-radiation. Here the measurements was taken at the surface and at a depth of 500 µm.

2.6 Concept of Local Fatigue Strength

The concept of local fatigue strength was introduced by Winderlich [2] and used in the following form:

$$R_F = \omega(r=0) * n(HV(r), \sigma_V(r)) * R_{F,0}\big(HV(r)\big) * \left(1 - \frac{\sigma^{RS}(r)}{R_m\big(HV(r)\big)}\right)$$

R_F	– local fatigue strength
ω	– factor dependend on surface roughness (Rz)
$HV(r)$	– hardness depth profile
$\sigma_V(r)$	– external applied local von Mises stress
$n(r)$	– local support ratio dependend on $HV(r)$ and $\sigma_V(r)$
$R_{F,0}$	– local fatigue strength without residual stresses; dependend on $HV(z)$
$\sigma^{RS}(r)$	– residual stress depth profile
$R_m\big(HV(r)\big)$	– local tensile strength; dependend on $HV(z)$

Since suitable post-treatments can significantly improve surface roughness, its influence on the local fatigue strength ω was neglected as a first approximation in the evaluation of the process routes. Regarding the parameters depending on the hardness depth profile, the following fits are used:

$$R_{F,0} = \frac{1.98 * HV(r) - 0{,}0011 * HV(r)^2}{1 + \frac{20.7}{HV(r)}}$$

$$R_m = 3.3 * HV(r)$$

$$n = 1 + \sqrt{\frac{1600}{HV(r)} * \frac{d\sigma_v}{\sigma_v dr}}$$

As the state is evaluated without applied loading $n = 1$. In conclusion, local fatigue strength can be characterized from hardness and residual stress depth profiles. The concept of local fatigue strength plays a key role in determining which parameter sets are to be selected for further analysis.

3 Characterization of the surface states

3.1 Route 1: 27MnCr5

In this process route, samples of 27MnCr5 were first carburized and then further shot peened or ShotTempered. Table 1 shows the parameters used for the different processes.

Table 1: Parameters investigated for process route 1 (27MnCr5)

Nr.	Temperature [°C]	Time [min]	Description
Initial	-	-	Initial state after carburizing without shot or ShotTempering
Ref.	250	5	Reference process; first tempered at corresponding temperature, then shot peened at room temperature
1	RT	5	Shot peened at room temperature (RT)
2	200	10	ShotTempered
3	250	5	ShotTempered
4	250	10	ShotTempered
5	350	5	ShotTempered

3.1.1 Hardness Depth Profiles

Figure 3 shows the hardness depth profiles for the different process parameters. The tempering effect during the ShotTempering process can be clearly seen as increasing process temperature is reducing the hardness of the sample. Higher hardness values than the initial state indicade strain hardening due to the shotpeening process. This effect decreases again as the ShotTempering temperature is increased. The reference process shows no significant deviation from the corresponding ShotTempering process on the surface.

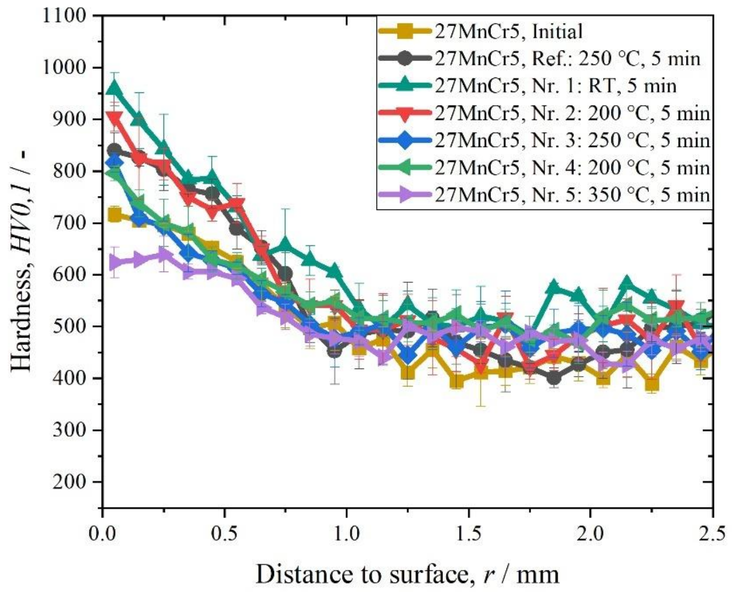

Figure 3: Hardness depth profiles of 27MnCr5 samples

3.1.2 Residual Stress Depth Profile

The results in Figure 4 show that the maximum compressive stress decreases as the process temperature increases. The influence of process time is not significant and does not noticeably affect the outcome. Compared with the reference process, the ShotTempered samples under the same conditions exhibits higher compressive stresses at greater depths from the surface. Overall, the reference process behaves comparably to the RT experiments.

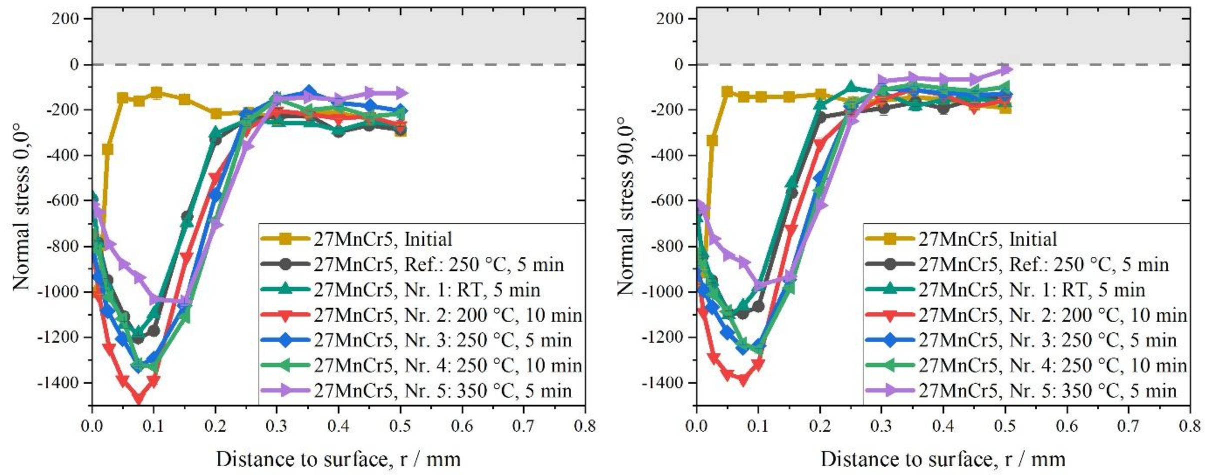

Figure 4: Residual stress depth profile for the 27MnCr5 samples in 0° and 90° direction

3.1.3 Retained Austenite Measurement

The amount of retained austenite diminishes with longer process times or elevated temperatures. This behavior may indicate tempered martensite embrittlement (TME), which is associated with the nucleation of coarse cementite during the decomposition of austenite between martensite laths [3]. As this leads to a reduction in fatigue strength, this parameter process parameters should be avoided (Nr. 4 and 5).

Table 2: Retained austenite in 27MnCr5 samples

Nr.	Temperature [°C]	Time [min]	0 µm	500 µm

Initial	-	-	4.4 ± 0.7 %	5.4 ± 0.7 %
Ref.	250	5	3.2 ± 0.9 %	6.2 ± 0.8 %
1	RT	5	3.1 ± 0.6 %	5.7 ± 0.6 %
2	200	10	4.2 ± 0.5 %	6.2 ± 0.3 %
3	250	5	2.8 ± 0.8 %	3.1 ± 0.2 %
4	250	10	< 2 %	< 2 %
5	350	5	< 2 %	< 2 %

3.1.4 Local Fatigue Strength

Figure 5 presents the computed local fatigue strength for the 27MnCr5 samples. Based on the most promising case, which exhibits the highest maximum local fatigue strength close to the surface, a large penetration depth, and low gradients in the subsequent progression, the following parameter sets were selected for more detailed analysis in the interrupted cycle tests (T4.2):

- 27MnCr5, Ref: 250 °C, 5 min
- 27MnCr5, Nr. 3: 250 °C, 5 min
- 27MnCr5, Nr. 2: 200 °C, 10 min

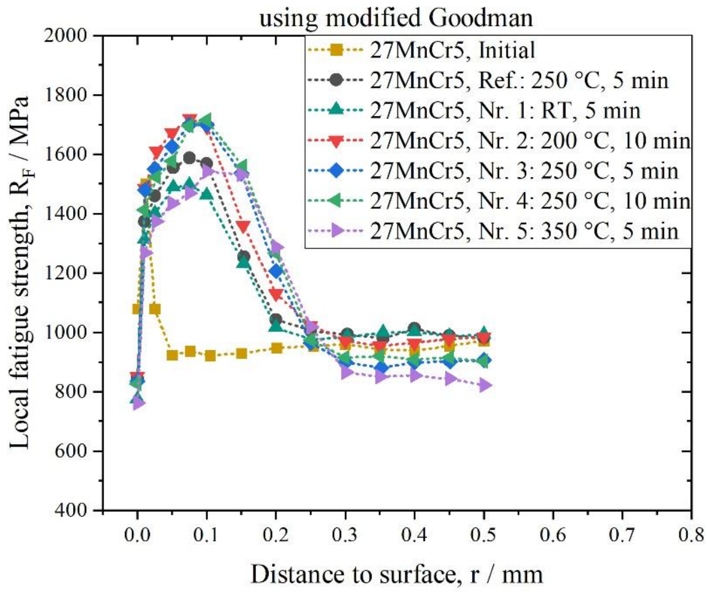

Figure 5: Local fatigue strength as function of distance to the surface of 27MnCr5 samples

3.2 Route 2: 42CrMo4

In this processing route, 42CrMo4 specimens were austenitized at 850 °C for 1 h in a vacuum furnace and subsequently oil-quenched within the same furnace. The parameters used for the individual processes routes are listed in Table 3.

Table 3: Parameters investigated for process route 2 (42CrMo4)

Nr.	Temperature [°C]	Time [min]	Description
Initial	-	-	Initial state after quenching without shot or ShotTempering

Ref.	500	10	Reference process; first tempered at corresponding temperature, then shot peened at room temperature
1	RT	5	Shot peened at room temperature (RT)
2	350	5	ShotTempered
3	350	10	ShotTempered
4	500	10	ShotTempered

3.2.1 Hardness Depth Profiles

Figure 6 presents the hardness depth profiles for the various process parameters. The tempering effect of ShotTempering is evident, as higher process temperatures lead to reduced sample hardness. The reference process does not differ significantly from the corresponding ShotTempering condition, and the process time likewise shows no notable influence.

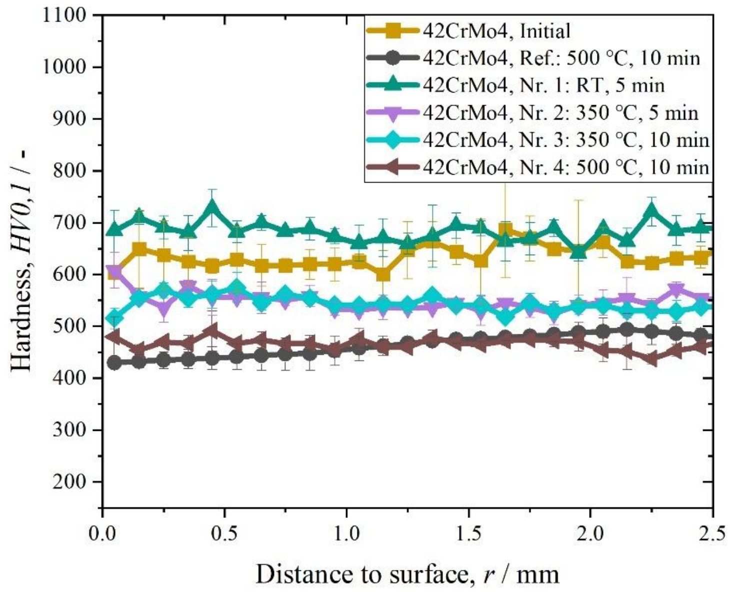

Figure 6: Hardness depth profiles of 42CrMo4 samples

3.2.2 Residual Stress Depth Profile

As shown in Figure 7, the maximum compressive stress decreases as the process temperature increases. The influence of process time is not significant and does not noticeably affect the results. Under identical conditions, the ShotTempered samples exhibits lower compressive stresses than the reference.

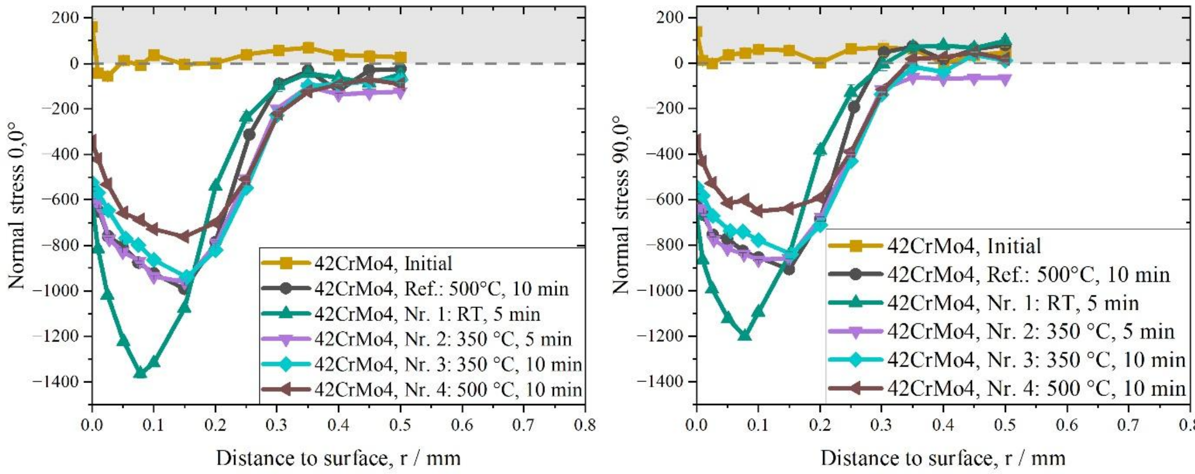

Figure 7: Residual stress depth profile for the 42CrMo4 samples in 0° and 90° direction

3.2.3 Local Fatigue Strength

Figure 7 presents the computed local fatigue strength of the 42CrMo4 samples. Considering the most promising evolution of the maximum local fatigue strength close to the surface, together with a high penetration depth and low gradients in its subsequent progression, the following parameter sets were selected for more detailed examination in the interrupted cycle tests (T4.2):

- 42CrMo4, Ref: 500 °C, 10 min
- 42CrMo4, Nr. 2: 350 °C, 5 min
- 42CrMo4, Nr. 4: 500 °C, 10 min

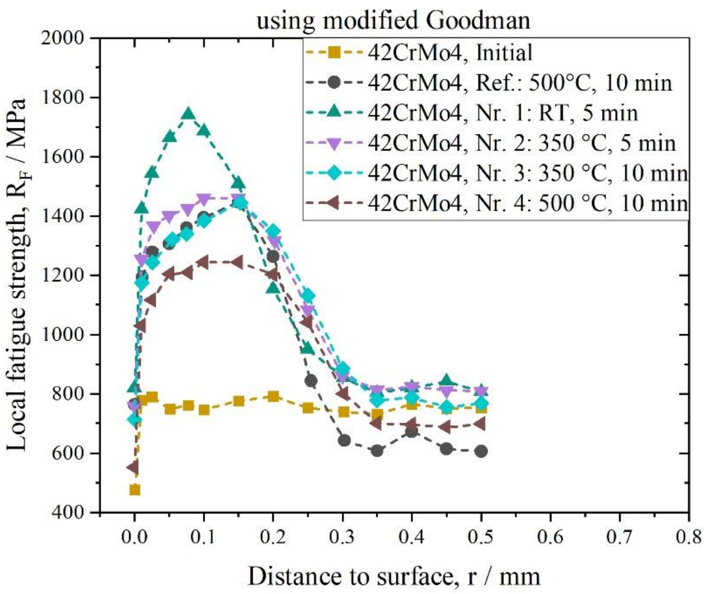

Figure 8: Local fatigue strength as function of distance to the surface of 42CrMo4 samples

3.3 Route 3: C55

In this process route samples of C55 were initially induction hardened and subsequently subjected to further treatments. The parameters applied in the various processes are listed in Table 4.

Table 4: Parameters investigated for process route 3 (C55)

Nr.	Temperature [°C]	Time [min]	Description
Initial	-	-	Initial state after induction hardening without shot or ShotTempering
Ref.	250	5	Reference process; first tempered at
1	RT	5	Shot peened at room temperature (RT)
2	250	5	ShotTempered
3	350	5	ShotTempered
4	350	10	ShotTempered
5	500	10	ShotTempered

3.3.1 Hardness Depth Profiles

Figure 9 shows the hardness depth profiles for the different process parameters. The tempering effect of ShotTempering is evident, as increasing process temperature lowers the hardness. Although the reference process yields substantially higher hardness than the respective ShotTempering condition, it still lies within the scatter of the RT and initial samples. The process time has no significant effect.

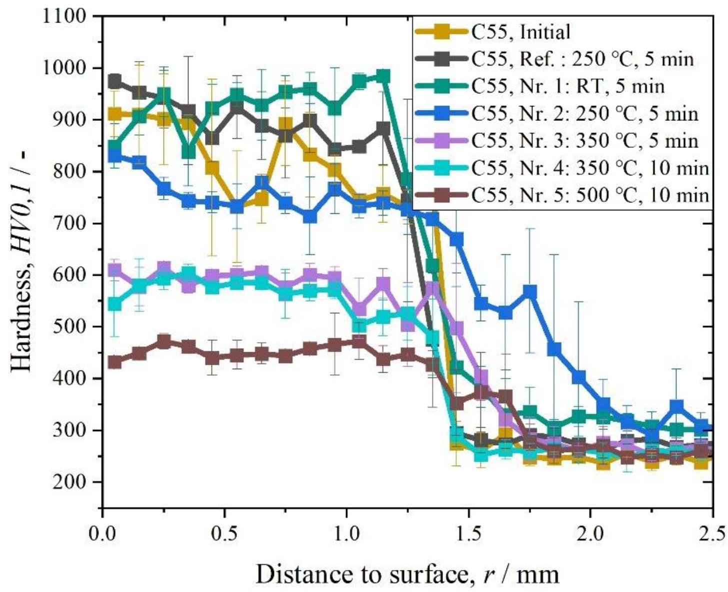

Figure 9: Hardness depth profiles of induction hardened C55 samples

3.3.2 Residual Stress Depth Profile

As shown in Figure 10, higher process temperatures lead to a reduction in the maximum compressive stress. Increasing the process time further decreases the maximum compressive stress while simultaneously increasing the penetration depth. In comparison with the reference process, the ShotTempered sample exhibits higher compressive stresses at greater depths than the reference.

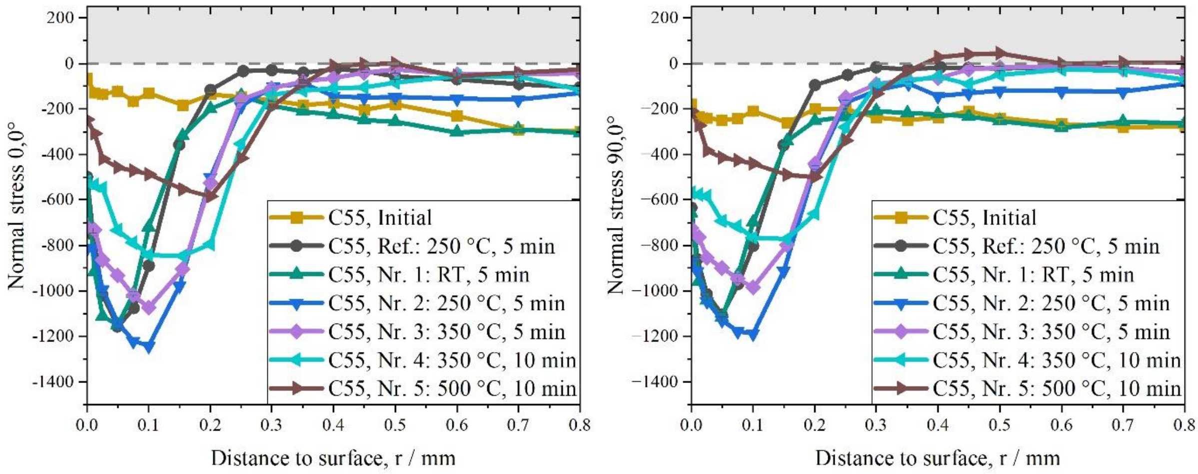

Figure 10: Residual stress depth profile for the C55 samples in 0° and 90° direction

3.3.3 Local Fatigue Strength

Figure 7 presents the computed local fatigue strength for the C55 samples. Based on the most promising development in maximum local fatigue strength near the surface, combined with a large penetration depth and low gradients in its further development, the following parameter sets were selected for a more detailed examination in the interrupted cycle tests:

- C55, Ref: 250 °C, 5 min
- C55, Nr. 2: 250 °C, 5 min
- C55, Nr. 3: 350 °C, 10 min

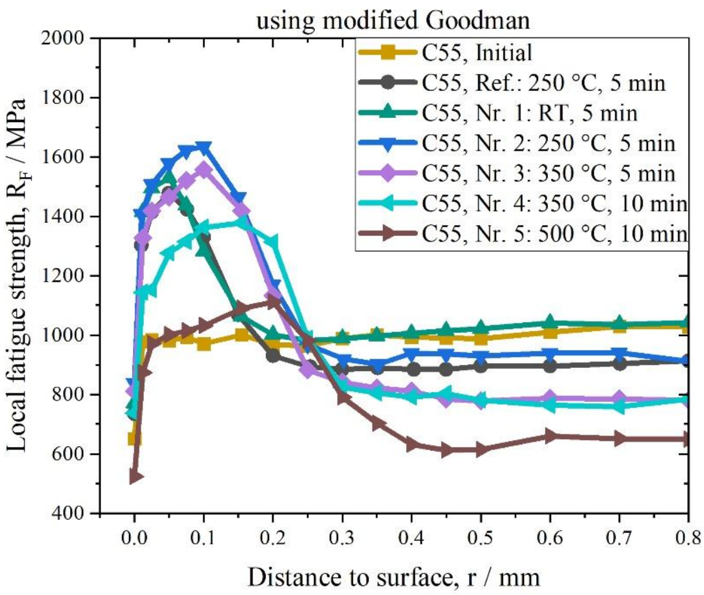

Figure 11: Local fatigue strength as function of distance to the surface of C55 samples

3.4 Surface roughness of the different process routes

Figure 12 shows the R_z values for the different sample groups. There is a general increase in Rz as the process temperature increases. Regarding the process time, only the 42CrMo4 samples showed a difference when comparing the experiments at 350 °C. The reference sample generally has smaller R_z values as their equivalent ShotTempering process. The results can be related to the decreasing yield stress with increasing process temperature.

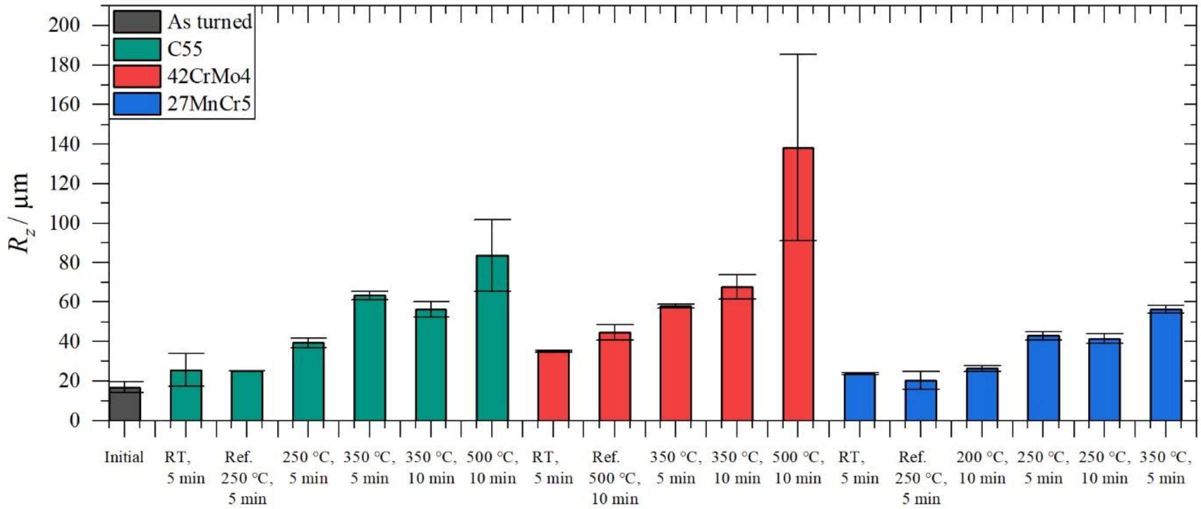

Figure 12: Surface roughness R_z values of all sample groups

4 Conclusions

The parameter optimization carried out in the deliverable will serve as baseline for all following work packages and is starting point for the experiments point WP4.

It also provides valuable insights for subsequent process chains or applications, as it showed that the ShotTempering process enables independent adjustment of hardness and residual stress profiles. Moreover, in future projects, altering the parameters of the previously applied process routes (carburizing, oven quenching, and inductive hardening) could allow additional tailoring of both hardness and residual stress profiles, thereby further enhancing the fatigue strength of the samples.

5 References

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6 Acknowledgements and disclaimer

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

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LEGAL DISCLAIMER

Funded by the European Union

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 101156779.

Abbreviations and Definitions

Term	Definition
RT	room temperature
RZ	surface roughness

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