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Identification of Influencing Factors in Machine Hammer Peening with Consideration of Lubricant Influences

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Abstract. Lightweight construction and performance requirements in the automotive industry have resulted in increased power density. At the same time, this increases the load on the workpieces. To counteract the resulting wear, either a more wear-resistant material may be applied or the functional surface may be specifically modified against wear. Machine hammer peening (MHP) is a process for such a targeted adjustment of the functional surface and the surface area properties. MHP is a mechanical surface treatment, which increases the wear resistance of the workpieces by introducing residual compressive stresses and work hardening as well as by smoothing or structuring the surface. To ensure an accurate adjustment of the surface properties, the influencing factors (material, process parameters and lubricant) and their interactions must be sufficiently well studied and understood. In particular, the influence of the lubricant on the surface area properties has not yet been adequately investigated. The objective of the work presented in this paper was to provide a deeper insight into the influence of the type of lubricant on the resulting surface properties in terms of roughness, residual stresses and hardness. The lubricant's influence was investigated using a partial factorial experimental design. Additional factors investigated, besides the choice of lubricant, were stroke, distance of indentation and step over distance. The results show a strong influence of the lubricant selection, especially on the resulting surface roughness. For the same process parameters, a deviation of 540 % in the resulting surface roughness was measured between two surfaces machined with different lubricants.

Introduction

According to the Climate Protection Act of 2019, a greenhouse gas emission reduction of at least 55 % is aimed for by the year 2030 compared to the emissions of the year 1990 [1] . This results in a need for transition for almost all industrial sectors in Germany for their own production as well as their products. In order to reduce the greenhouse gas emissions of automobile, ships and airplanes, lightweight construction is used with the aim of saving weight and increasing resource efficiency. This puts the workpieces under higher load which in return results in a decrease in their service life. To counteract this, more wear-resistant materials are used [2] or the wear resistance is improved by means of coating [3] or surface treatments [4]. Among the surface treatments is machine hammer peening (MHP), in which a plunger strikes the surface of a workpiece in a defined manner [5]. In this process, the surface area is plastically deformed, causing the surface area to work-harden [6] and introducing residual compressive stresses [7]. In addition, smoothing or structuring of the surface is possible due to the defined plunger movement [8]. Previous work showed that by means of the MHP, the service life of MHP machined workpieces is increased compared to non-MHP machined reference workpieces [9]. The subject of research related to MHP has been predominantly the study of the interactions between the process parameters, the machined material and the resulting surface integrity in terms of hardness, residual stresses and roughness. *Lechner et al.* showed that an increase in hammer head diameter leads to reduced roughness [10]. *Groche et al.* used EN-GJS-HB265 to demonstrate that with an increasing angle of impact the resulting higher hardness is less pronounced orthogonally to the surface [11]. *Mannens et al.* investigated, among other things, the influence of the lubricant quantity on the resulting roughness during MHP processing of stainless steel X3CrNiMo13-4 [12]. It was shown that an insufficient amount of lubricant has a negative influence on the roughness. In addition to the lubricant quantity, other lubricant properties such as the state of aggregation, the additivation or the viscosity are decisive for the application behavior of the lubricants. Still, the influence of the different lubricant properties on the resulting surface integrity has so far been insufficiently investigated. The aim of this work was to increase the understanding regarding the influence of the lubricant during MHP on the surface integrity in form of residual stresses, roughness and hardness. For this purpose, a lubricant selection was conducted in a first step and the liquid lubricants were then characterized by means of drop shape analysis. Subsequently, MHP tests were carried out with varying lubricant as well as process parameters (stroke, distance of indentation and step over distance). After the experimental tests, the hardness, roughness and residual stresses were determined and compared with each other and with reference tests in which no lubricant was used.

Lubricant Selection

Lubricants with different properties (viscosity, additivation and aggregate state at room temperature) were selected to investigate the influence of lubricant properties on surface integrity. The complete lubricant selection is shown in table 1. First, *Castrol*'s Viskogen KL3 with a kinematic viscosity of ν=32 mm² · s^{-1} was selected. This is a universally applicable, temperature-stable synthetic lubricating oil. In previous work at WZL, this was commonly used for lubrication during MHP [12]. The lubricating oils Wisura LS710 and Wisura LS711 from *Fuchs Wisura GmbH* were selected to investigate the influence of kinematic viscosity on surface integrity. The aim was to compare two lubricants with similar or equal additives but with varying kinematic viscosities. Wisura LS710 has a kinematic viscosity of $\nu = 73$ mm² · s^{-1} and Wisura LS711 of $\nu = 294$ mm² · s^{-1}. Furthermore, Graphitex WF7 AL, a lubricant concentrate with pressure-resistant additives, was selected and diluted with water in a mixing ratio of 1:24. In addition, the solid lubricants Gardomer L6261 and Gardolube L6301/1 were selected from *Chemetall GmbH*. Gardomer L6261 is a polymer dispersion and Gardolube L6301/1 a molybdenum disulfide dispersion.

Table 1: Lubricant selection

Lubricant	Producer	Description
Viskogen KL3	Castrol Limited	Lubricant used so far
Wisura LS710	Fuchs Wisura GmbH	Lubricating oil with low kinematic viscosity
Wisura LS711	Fuchs Wisura GmbH	Lubricating oil with high kinematic viscosity
Graphitex WF7 AL	Chemetall GmbH	Lubricant with extreme pressure (EP) additives
Gardolube L6301/1	Chemetall GmbH	Molybdenum disulfide dispersion (solid lubricant)
Gardomer L6261	Chemetall GmbH	Polymer dispersion (solid lubricant)

For further characterization of the undiluted lubricating oils, the interaction of the lubricants (Viskogen KL3, Wisura LS710 and Wisura 711) with the workpiece surface of the unmachined samples of 34CrMo4 was investigated by drop shape analysis. For this purpose, a Drop Shape Analyzer-DSA100 from *Krüss* was used. The result of this analysis was the determination of the work of adhesion, which is a measure of the adhesion of the lubricant to the workpiece surface. In the course of this, the surface tensions as well as their polar and disperse fractions were determined for the lubricants and the workpiece surface as well as the interfacial tension using the method according to *Owens, Wendt, Rabel* and *Kaelble* [13]. The resulting values of the drop shape analysis are given in Table 2.

Table 2: Surface tension of the lubricants

Lubricant/ Surface	Surface tension σ [MPa]	Polar surface tension fraction σ_P [MPa]	Disperse surface tension fraction σ_D [MPa]
Castrol Viscogen KL3	31.57	0.97	30.6
Wisura LS710	29.86	3.45	26.41
Wisura LS711	30.21	3.72	26.49
34CrMo4	42.95	25.54	17.41

The work of adhesion for Castrol Viscogen KL3, Wisura LS710 and Wisura LS711 lubricants on the workpiece surface correspond to $W_{\mathrm{KL3}} = 63.91\ \mathrm{mN \cdot m^{-1}}$, $W_{\mathrm{LS710}} = 67.44\ \mathrm{mN \cdot m^{-1}}$ and $W_{\mathrm{LS711}} = 68.12\ \mathrm{mN \cdot m^{-1}}$. Due to the comparable additivation of the lubricants Wisura LS710 and Wisura LS711, the surface tension as well as the work of adhesion differ only within the measurement inaccuracies. Thus, the influence of the viscosity of the lubricant on the modification of the surface integrity during MHP is separated for these lubricants. The results of the drop shape analysis offer another approach to identify interactions between the lubricant used during MHP and the resulting surface integrity.

Experimental Setup and Design

The test setup for carrying out the MHP tests with different lubricants is shown in Fig. 1. The MHP system type 2002 from *accurapuls* is moved by an industrial robot type IRB6660-205/1.9 from *ABB*. A Kistler 9257 force measurement platform from *Kistler Group* was used to record the impact force. The plunger movement was measured by means of a distance sensor RC20 of *Philtec, Inc.* installed in the MHP system.

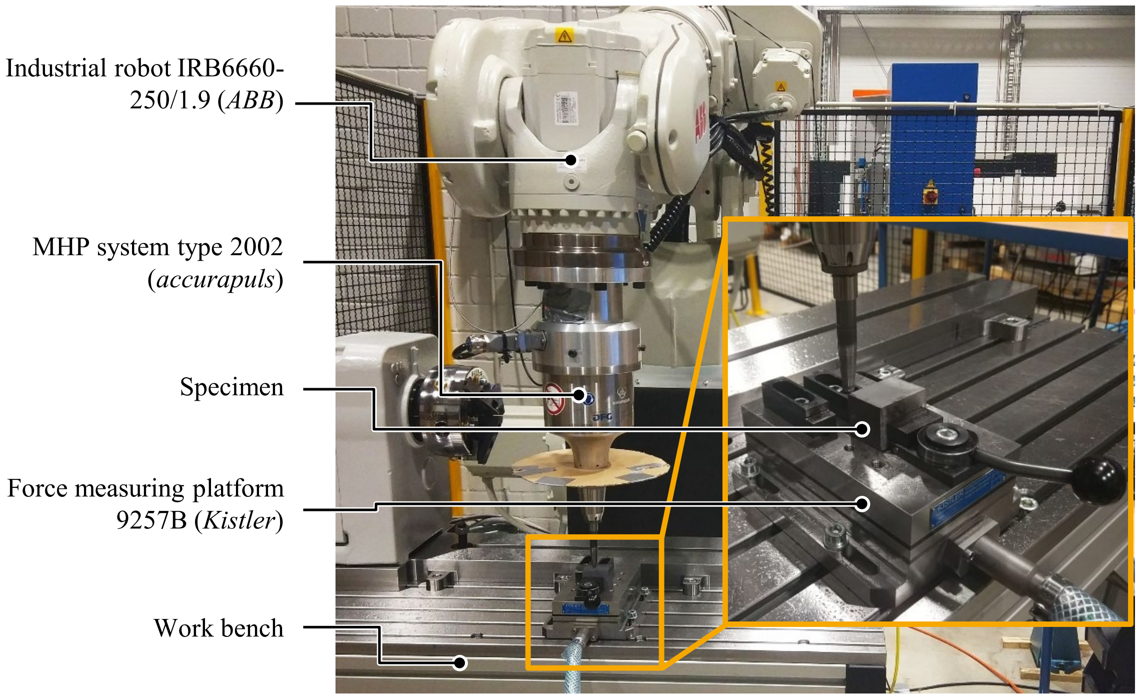

Figure 1: Experimental setup for MHP of cuboid specimen

The specimens investigated in this work were cuboids with dimensions 95 x 40 x 30 mm³ made of 34CrMo4, which were fixed on the force measurement platform with the aid of clamping elements. The specimens were initially characterized by means of the residual stresses, roughness and hardness. These investigations were repeated again after machining to determine the interactions between the lubricants and the resulting surface integrity after the MHP. In addition to the variation of the lubricant, the process parameters in the form of the stroke, the distance of indentations as well as step over distance were varied in order to consider the influences of the lubricant at different process parameters on the surface integrity due to the MHP (compare table 3). The lubricant was applied to the workpiece surface in a completely wetting manner in accordance with industrial practice. When varying the stroke, the energy introduced per stroke is changed. When varying the distance of indentations and step over distance, the overlap of the individual strokes is changed, thereby adjusting the energy density. Table 3 shows the three parameter variations investigated for each lubricant.

Table 3: Process Setups

Parameter variation	Stroke *h* [mm]	Step over distance *s* [mm]	Distance of indentation *a* [mm]
1	0.9	0.15	0.15
2	0.9	0.35	0.35
3	0.3	0.15	0.15

Results and Discussion

The results of the tests are divided into force and stroke profiles recorded during the tests and the evaluation of the surface integrity of the hammered specimens compared with the initial condition. In the evaluation of the force and stroke curves, the extent to which the lubricant has an influence on these curves was determined. First, the average impact velocity was determined on the basis of the curves in order to determine the kinetic energy of each impact. In a first step, the stroke curve was differentiated over time and then filtered using a Savitzky-Golay filter to extract the measurement noise. The maximum velocity of the plunger was then determined for each stroke and the kinetic energy was calculated on the basis of the moving mass. In addition, the area-related kinetic energy was determined based on the indentation and path distances of each parameter variation. The results of this evaluation are listed in Table 4. Due to the short contact time between tool and workpiece during MHP, the contact is only represented by six data points per cycle, even though a sampling rate of 50 kHz was applied. Consequently, the gathered data is not suitable to identify influences of the lubricant on the plunger's kinematics.

Table 4: Kinetic energy of MHP machining

Parameter variation	1	2	3
Stroke *h* [mm]	0.9	0.9	0.3
Step over distance *s* [mm]	0.15	0.35	0.15
Distance of indentations a [mm]	0.15	0.35	0.15
Number of strokes evaluated *N* [-]	5427	2068	5582
Averaged energy per stroke *E* [mJ] (Standard deviation s_E [mJ])	43.9 (3.0)	42.1 (1.6)	18.7 (1.5)
Number of strokes per mm² [-]	44.44	8.16	44.44
Area-related energy [$\mathrm{mJ} \cdot \mathrm{mm}^{-2}$]	1951.7	343.3	832.5

Surface roughness, residual stresses and hardness define the surface integrity and serve as description values for assessing the influence of the different lubricants on the MHP process. These were examined both before and after machining.

Surface roughness. Topography measurements to determine surface roughness were performed tactilely using a MarSurf LD260 from *Mahr*. A 2 x 2 mm² field was measured in each case. The measurement resolution was 0.5 µm x 10 µm. Both the mean arithmetic height *Sa* and the maximum height *Sz* were taken into account as evaluation variables. The results of the roughness measurements are shown in Fig. 2. Thereby, a correlation between the roughness and the process parameter, as it has also been described in previous work [14], has been identified. Furthermore, the lubricant selection has a significant influence on the roughness. The experimental results show that the roughness of the surface after peening is lowest when no lubricant is used. This is in contrast to the results shown by *Mannens et al* [12]. A possible reason for this difference given by *Mannens et al*. is an unscrewed plunger during MHP resulting in a swaying movement and therefore in an undefined processing of the surface. Furthermore the different material may be the reason. When the two solid lubricants were used, the highest roughness of all the investigated lubricants were measured. For process parameter 3, the mean arithmetic height *Sa* after machining with the solid lubricant Gardolube L6261 is higher by a factor of 5.4 than using no lubricant. One possible explanation lies in the low energies transferred to the workpiece per impact. The influence of inhomogeneities in the lubricant film on the plastic deformation of the workpiece surface is correspondingly strong. This results in a more inhomogeneous machining of the surface, which results in poorer roughness.

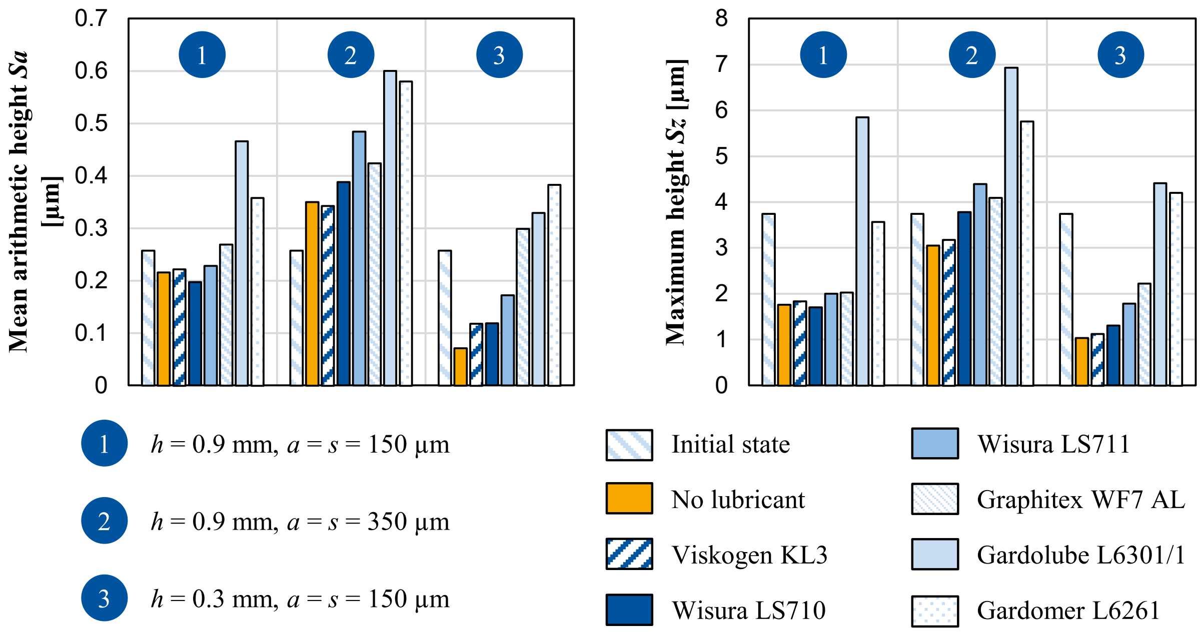

Figure 2: Results of the roughness measurements for the three process setups with different types of lubrications

For the lubricants Viskogen KL3, Wisura LS710, Wisura LS711 and Graphitex WF7 AL, the process parameters of the MHP effect the influence of the lubricants on the roughness. For process setup 1, the lubricants have a small effect on roughness compared to the reference test without lubricant. In process setups 2 and 3, on the other hand, a strong dependence between the lubricant used and the roughness is seen. The mean arithmetic height *Sa* differs by a factor of up to 4.2. The contact model described by *Baillet et al.* gives a possible explanation [15]. According to this, there are four characteristic phases in the loading of closed lubricant pockets. In the first phase, the volume of the lubricant pocket decreases due to deformation of the roughness peaks until the complete lubricant pocket is filled with lubricant. In the second phase, the volume is further reduced, causing hydrostatic pressure to build up. When a leakage pressure is reached, the lubricant is forced out of the lubricant pocket, causing the surface of the workpiece to separate from the surface of the tool around the lubricant pocket in the third phase. In the fourth phase, there is complete material contact because there is no more lubricant in the lubricant pocket. In his work, *Hauer* showed the applicability of this model for the simulation of smoothing-in tests [16]. As a result of the model, the more closed lubricant pockets reach the fourth phase of the model, the stronger the smoothing-in becomes. For the tests, this means that the higher the energy introduced by means of MHP, the more closed lubricant pockets should reach the fourth phase resulting in a lower roughness. Accordingly, when the fourth phase is reached in all closed lubricant pockets, a comparable roughness should be achieved as in the tests without lubricant. This is confirmed by the test results. At a stroke of $h = 0.9$ mm, more energy per impact is introduced into the surface compared with a stroke of $h = 0.3$ mm, according to the evaluation of the plunger movement and the force profile. As a result, more closed lubricant pockets reach the fourth phase of the model or are more advanced in the third phase. The path distance or indentation distance results in a larger or smaller overlap of the individual impacts. Since some closed lubricant pockets have reached the fourth phase in the overlapped area, the energy applied in each impact is distributed to fewer lubricant pockets, thus more closed lubricant pockets reach the fourth phase of the model with a small indentation and path spacing compared to a machining strategy with a larger distance of indentation and step over distance. Accordingly, the lubricant influence on roughness is lowest at a stroke of h = 0.9 mm and a distance of indentation and step over distance of $a = s$ = 150 µm. The results suggest that the influence of single impact energy on roughness is more significant than that of overlap, since the energy per area in this case is higher for process setup 3 than for process setup 2 (see Table 4). This correlation has to be confirmed in further investigations.

The influence of viscosity on roughness was investigated using the lubricants Wisura LS710 ($v = 73$ mm² · s^{-1}) and Wisura LS711 ($v = 294$ mm² · s^{-1}). These are characterized by comparable additivation at different viscosities. It is noticeable that the roughness resulting from using the lubricant Wisura LS710 is always lower than with the higher viscosity Wisura LS711. The contact model described above offers a possible explanation. Due to the lower viscosity, the leakage pressure is lower than with the lubricant with a higher viscosity, thus less energy is required for the closed lubricant pockets to reach the fourth phase of the contact model or to be further advanced in the third phase.

Hardness. The hardness was measured using a ZHU 250 hardness testing machine from *Zwickroell*. HV5 measurements were performed in accordance with DIN EN ISO 6507. The low test load was selected because a change in hardness compared to the initial state was to be expected, especially in the near-surface area. The lower test load results in a lower indentation depth, which emphasizes the influence of the hardening of the near-surface area. For statistical validation, five measurements were performed in each case and then averaged. The hardness results are shown in Fig. 3. Compared to the initial state, all process setups investigated and lubricants used resulted in an increase in hardness. In particular, when using the lubricants Viskogen KL3 and in the reference tests without lubricants, the hardness increased. With the solid lubricants, the behavior is comparable with individual exceptions. These are due to the inhomogeneous lubrication condition during MHP. Overall, the individual hardness measurements are very close.

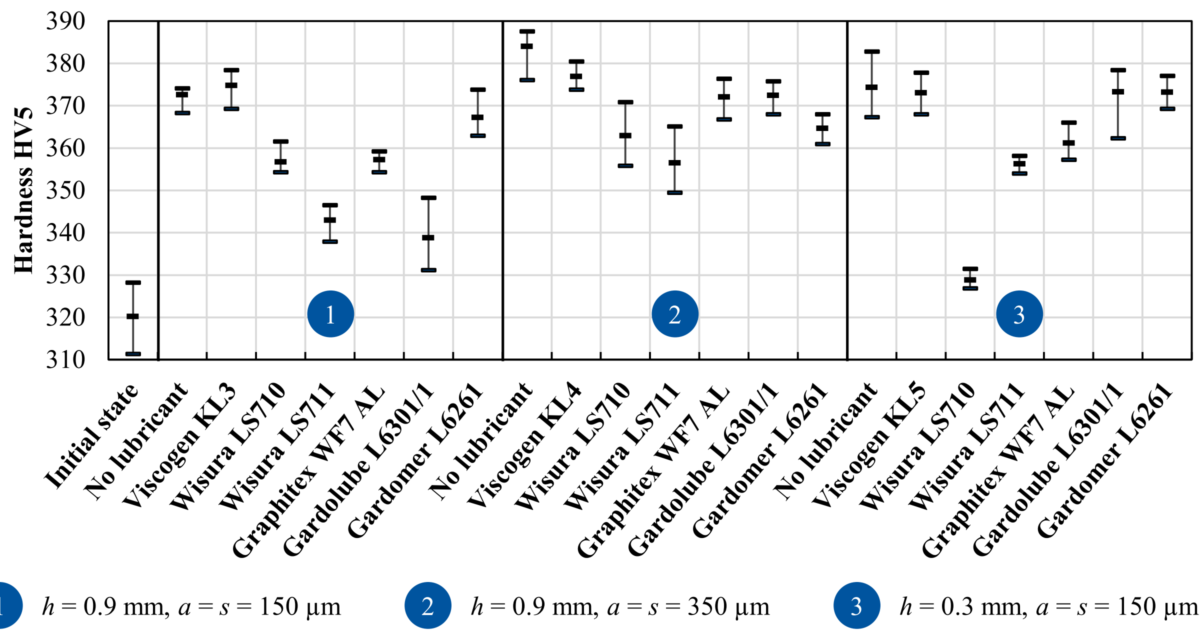

Figure 3: Resulting hardness when using different lubricants

Residual stresses. The residual stresses after and before machining the specimens were determined using the borehole method. The Prism system from *Stresstech GmbH* was used. The drill used had a diameter of d_B = 0.8 mm and measurements were taken to a depth of z = 0.25 mm. The results of the residual stress measurements are shown in Fig. 4. The diagram on the top left shows the residual stresses depth curves for the first process setup (h = 0.9 mm, a = s = 0.15 mm) of all lubricants compared with the initial state. Under processing with different lubricants, compressive residual stresses were induced in the surface area compared to the initial condition. The maximum induced compressive residual stress varied between σ_{max} = -680 MPa and σ_{max} = -825 MPa. It is noticeable that the residual stresses of the machined specimens without the use of lubricant are among the lowest in all tests. In addition, the variance of the residual stress curves without the use of lubricant is significantly lower than for the hammered specimens with lubricant. Fig. 4 shows the residual stress depth curves of the different process setups peened without lubricant (bottom left), with Wisura LS710 (top right) and with Wisura LS711 (bottom right). The curves for peening without lubricant for the three parameter setups are almost identical to each other. Only the residual stress curves hammered with process setup 3 (h = 0.3 mm, a = s = 0.15 mm) with the lubricants Wisura LS710 and Wisura LS711 have a comparable curve compared to the hammered specimens without lubricant. Peened with process setup 1 and 2, the surface area shows higher residual stresses when using the lubricants. From the results, it is reasonable to conclude that the lubricant has a positive influence on the induced compressive residual stresses, provided that the impact energy exceeds a limit value.

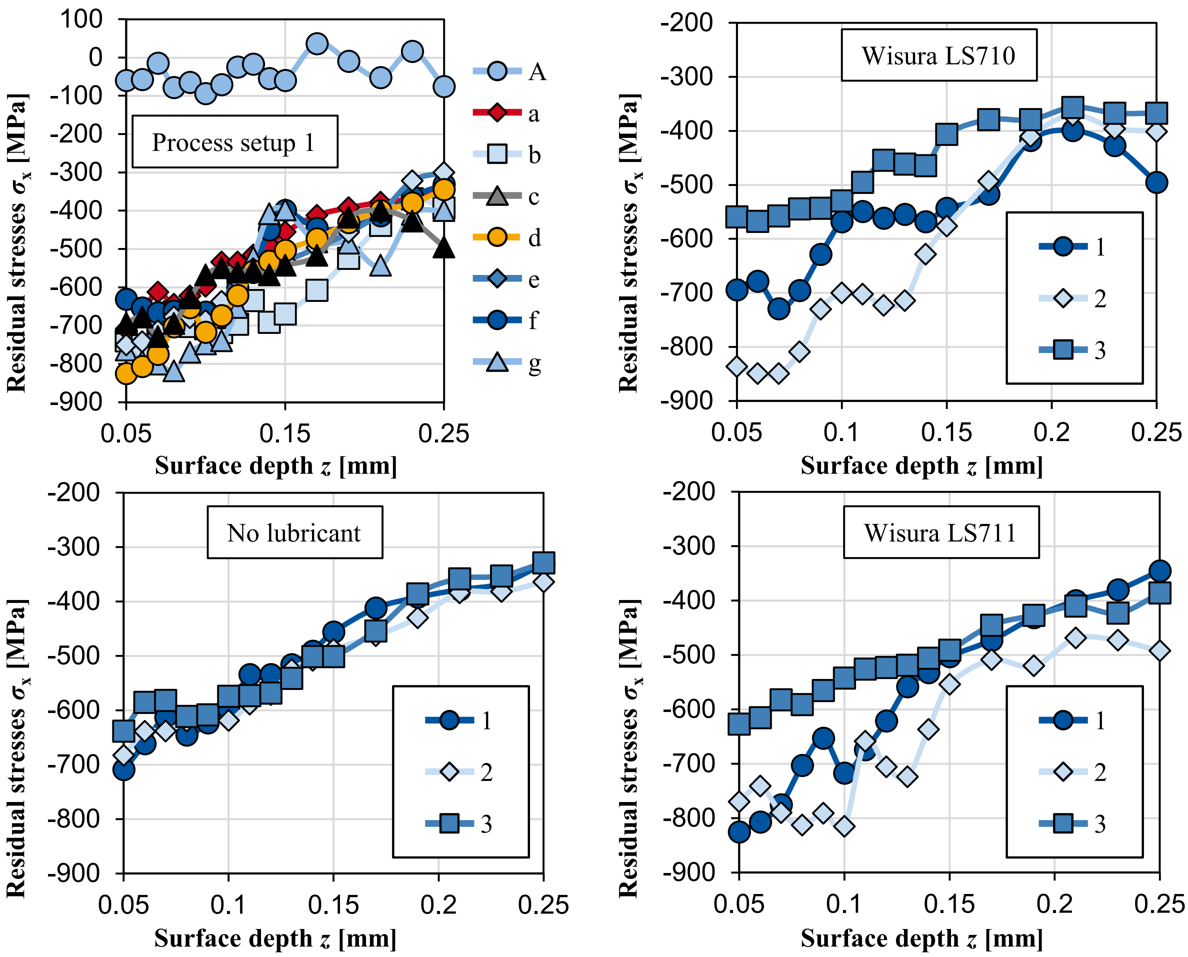

Figure 4: Resulting residual stresses when using different lubricants. Legend: A-initial state, a-no lubricant, b-Viscogen KL3, c-Wisura LS710, d-Wisura LS711, e-Graphitex WF7 AL, f-Gardolube L6301/1, g-Gardomer L6261, 1-process setup 1, 2-process setup 2, 3-process setup 3.

Summary and Outlook

In the context of this work, the influence of lubricants in machine hammer peening on the resulting surface integrity in the form of roughness, hardness and residual stresses was investigated. The lubricants investigated differed in viscosity, aggregate state and additivation. In addition, the process parameters stroke and indentation/step over distance were varied. The results showed a strong influence of the lubricant selection on the resulting roughness. It was observed that the resulting roughness increases with higher viscosity. This effect is dependent on the process parameters. At higher applied energies, the effect is less pronounced. In addition, the workpieces machined with the solid lubricants exhibit higher roughness compared to those machined with the liquid lubricants. The influence of the process parameters on the introduced residual stresses depends on the lubricant used. Without lubricant, hardly any influence of the investigated process parameters on the residual stresses can be detected. In contrast, the measured residual stresses of the different process parameters vary when lubricant is used. Thus, higher compressive residual stresses are introduced in the process setups with higher individual impact energies than in the specimens processed without lubricant. Initially, the hardness results do not allow a clear correlation between the lubricant used and the resulting hardness. The results presented show an impact of the lubricant used during MHP onto the surface integrity. Nevertheless the lubricants used are quite complex which leads to the conclusion that several effects are responsible for the measured differences of the surface integrity. Therefore in future work these effects need to be separated to understand the underlying cause effect relationships. Furthermore, in order to investigate the influence of the lubricants on the resulting hardness in more detail, micro hardness measurements will be carried out in a depth profile in future investigations. In addition, it will be investigated whether there is a limit value of the introduced energy above which the lubricant has a positive influence on the compressive residual stresses.

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