Sustainable approach of heat treatment-free surface hardening by deep rolling

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Abstract: Cold surface hardening is a sustainable approach to generate surface hardened steel components without a time- and energy-consuming heat treatment. The mechanical energy induced by a deep rolling process enables martensitic surface-hardening of metastable austenitic steels and thereby the combination of hardening and finishing in one single step. Using spray formed special alloys, a specific adjustment of the stability of the microstructure is possible by the alloy composition. In this paper spray formed alloys (X120CrMn5-2 and X150CrMn9-3) are investigated with respect to the potential of mechanically induced martensitic hardening compared to results of conventional AISI D3 (X210Cr12). The resulting surface integrity is analysed concerning the hardness penetration depth and the content of martensite.

Keywords: surface hardening; deep rolling; metastable austenite; spray formed special alloy.

Reference to this paper should be made as follows: Meyer, D. and Kämmler, J. (2018) 'Sustainable approach of heat treatment-free surface hardening by deep rolling', *Int. J. Sustainable Manufacturing*, Vol. 4, No. 1, pp.64–78.

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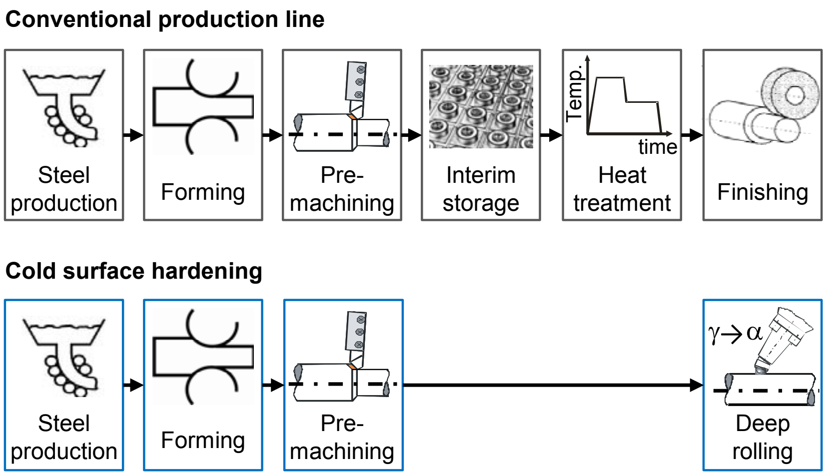
1 Introduction

In industrial practice, surface hardened steel components are conventionally produced by thermal, thermo-chemical and thermo-mechanical processes. These heat treatments are often time- and cost-intensive due to the high consumption of energy. For sustainable and efficient manufacturing of surface hardened steel components, an integration of the heat treatment in the production line is difficult. A replacement of the conventional heat treatment is necessary by processes inducing a surface hardening without thermal energy input.

Cold surface hardening (Brinksmeier et al., 2008a) is an approach to integrate a surface hardening without a separate thermal heat treatment in the manufacturing process. The use of high-alloyed austenitic steels with a metastable microstructure at room temperature enables a transformation of the microstructure due to the plastic deformation by the deep rolling process. Subsequent to pre-machining, a deep rolling process induces mechanical energy in the workpiece leading to a conventional strain hardening as well as a martensitic transformation in surface and subsurface material layers.

Brinksmeier et al. (2008b) succeed in shortening of process chains by the combination of hardening and finishing in one single process step (Figure 1). Besides the reduction of process time, the combination of processes is leading to reduced energy consumption in production of hardened steel components. By the elimination of energy-consuming heat-treatment, a new sustainable design for production of surface hardened steel components is developed.

Figure 1 Sustainable design of process chain by process elimination due to mechanical induced surface hardening (see online version for colours)



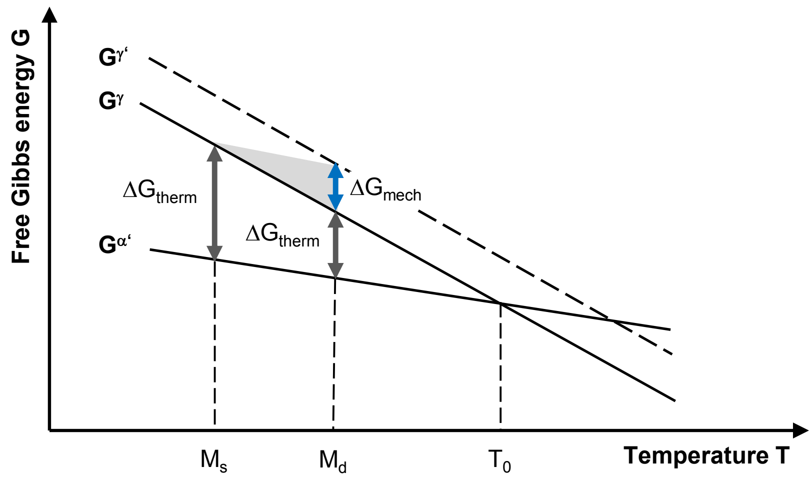
Source: According to Brinksmeier et al. (2008b)

1.1 Mechanically induced martensitic transformation

In 1924, Saveur (Nishiyama, 1978) recognised the formation of martensite under high plastic deformation of austenitic steels. The transformation is strongly dependent on the stability of the microstructure at room temperature which is influenced by the alloy composition. As a result of quenching, these materials provide a microstructure which is in a non-equilibrium state. This state is known as metastable. Vöhringer and Macherauch (1977) discussed this topic by illustrating the free Gibbs energy of martensite and austenite as a function of temperature (Figure 2). At a temperature of T_0 martensite $G^{\alpha'}$ and austenite G^{γ} are thermodynamically balanced. By cooling the system, the martensite is in a more thermodynamically favourable state to austenite. To start the martensitic transformation due to purely thermal effects (martensite start – M_s), a thermal energy of ΔG_{therm} is required as activation force. For iron based steel, an undercooling of $M_s \approx 200°C$ below T_0 is necessary in order to achieve the driving force.

In consequence of plastic deformation (cold forming), the free Gibbs energy of the martensite is elevated to $G^{\gamma'}$ by the induced mechanical energy. The amount of energy to start the martensitic transformation in deformed material (M_d) is a combination of thermal and mechanical energy resulting in an increase of the martensitic start temperature from M_s to M_d. While Cohen et al. (1950) describes a mechanically induced martensitic transformation starting at T_0, Angel (1954) introduces a temperature $M_{d30} < T_0$, where a martensitic transformation can be induced by mechanical load.

Figure 2 Effect of free Gibbs energy on austenitic and martensitic microstructure (see online version for colours)



Source: Vöhringer and Macherauch (1977) and Tamura (1982)

The stability of the austenite as well as the martensitic start temperature is dependent on the material's microstructure. The material characteristics are influenced by the chemical composition of the alloys. Maurer (Schumann, 1991) found that the microstructure of austenitic steels depends on the amount of chromium and nickel as described in the Maurer diagrams. This influences the content of austenite and martensite at room temperature in the material. For this reason, Hull (1973) evaluated the nickel and chromium equivalents of alloying elements to describe the influence on the stability of the austenitic structure of the material.

Folkhard (1984) and Eckstein (1969) as well as Roberts and Cary (1980) provide approaches for the determination of the martensitic start temperature on basis of the alloying elements. Thereby, carbon decreases the M_s-temperature as well as the martensite finish (M_f) temperature by its function as interstitial element (Eckstein, 1969).

Manganese as an austenite former extends the area of stable austenite up to room temperature (Schumann, 1991). In addition, the diffusion rate can be decreased by the alloying element chromium. This enables the reduction of quenching rates to secure a thermodynamically metastable microstructure. Llewellyn (1997) summarises the influence of different elements on austenite stability.

The stability of the microstructure can also be affected by the heat treatment influencing the phase composition of the material. The percentage of dissolved chromium and carbon atoms in austenite influences the M_s-temperature. By varying the austenitising temperature T_A, Dong et al. (2010) investigate the influence of heat treatment on M_s-temperature of austenitic steels aiming at adjusting a metastable microstructure at room temperature. Thereby the mechanically induced surface hardening should be allowed without an undesired martensitic transformation during preliminary machining.

1.2 *Mechanically induced transformation in production*

Multiple manufacturing processes deal with the approach of mechanical induced martensitic transformation. The best known representatives are the *transformation-induced plasticity* (TRIP) steels. Aiming at an increase in strength, Dan et al. (2008) simultaneously raise the high ductility of these steels. Avishan et al. (2009) emphasise the need to improve the machinability of TRIP steels.

The potential of forming processes to generate structured fields with local adapted material properties in metastable austenite is investigated by Behrens et al. (2008) and Bach et al. (2008). Brinksmeier et al. (2008a) achieve a heat treatment free surface hardening of metastable austenitic steel by the mechanical energy induced by a deep rolling process and therefore fulfil the requirements of highly stressed components of a hardened surface layer combined with ductile bulk material. However, the stability of microstructure is important for application of the material. In investigations of Meyer (Meyer, 2012b; Meyer and Kämmler, 2015) undesired microstructural transformation was determined in endurance tests, resulting in loss of shape accuracy of the workpieces.

By the combination of mechanical impact of deep rolling process and process-integrated cooling, the effect of structural transformation can be increased. Jawahir et al. (2016) summarise the effect of cryogenic processing on surface integrity. As a result of varied cooling conditions, Aurich et al. (2014) and Mayer et al. (2014) affect a martensitic transformation in a turning process. Pusavec et al. (2010a, 2010b) emphasise the sustainable alternative to change material behaviour by cryogenic machining in contrast to conventional machining with lubricants. An increase in tool life as well as a reduction of production time can be reached in machining Inconel 718. The combination of thermal and mechanical energy induced by a deep rolling process under cryogenic conditions enables an increase in hardness and in the penetration depth as well as microstructural transformation in more stable materials (Meyer et al., 2011).

However, the use of austenitic steels, e.g. X210Cr12, enables a heat treatment-free hardening of steels components. By the combination of hardening and finishing in one single step by cold surface hardening according to Brinksmeier et al. (2008b), an elimination of high energy-consuming process enables a sustainable design of process chains for generating surface hardened steel components. This stability of austenite of conventional X210Cr12 can be varied in a limited range only. This leads to undesired martensitic transformation and thereby loss in shape accuracy in practice. Although the use of cryogenic cooling enables a mechanically induced surface hardening of more stable austenite (Meyer, 2012a, 2012b), the additional demand of coolant such as CO_2-snow or liquid nitrogen needs a further energy source to start martensitic transformation compared to deep rolling at room temperature. To reduce the required energy input, it is necessary to adapt the workpiece materials on cold surface hardening. Austenitic materials with a thermodynamically higher stability are aspired, which could withstand the pre-machining with a soft austenitic microstructure, but start martensitic transformation in finishing by deep rolling at room-temperature under dry conditions to suite sustainable criteria.

For this reason, in the presented approach, new steel alloys were developed to perform the mechanically induced martensitic transformation at room temperature. The material properties of the austenitic steels are to be configured as they correspond to the requirements of the mechanically induced surface hardening. The pre-machining is described with respect to the sufficient stability of the materials by analysis of the cutting forces. Afterwards, the potential of the special alloys for martensitic transformation in deep rolling processes are investigated. The analysis of change in hardness after deep rolling should allow correlations with the amount of the generated martensite.

2 Experimental setup

2.1 Material properties

For the investigations, special alloys were prepared to adjust the material properties specifically to the requirements of the mechanically induced hardening. The special alloys are intended to have a lower carbon and chromium content compared to X210Cr12 (AISI D3). This leads to a reduction in the amount of carbides in the microstructure to improve the machinability as well as a reduction of costs caused by the reduced amount of expensive chromium. In Table 1 the chemical composition of the investigated special alloy (SA) in comparison to the conventional X210Cr12 is shown.

Table 1 Chemical composition of the investigated materials

	Carbon [%]	*Manganese [%]*	*Chromium [%]*
X210Cr12 (AISI D3)	2.1	0.2–0.6	12.0
X150CrMn9-3 (SA 1)	1.5	9.0	3.0
X120CrMn5-2 (SA 2)	1.2	5.0	2.0

The workpieces of the special alloys were produced by spray forming. This method allows the production of small batches with highly defined composition. This offers the advantage of a fine-grained and homogeneous dispersed microstructure of the material after subsequent hot rolling of the workpieces. A subsequent heat treatment of the workpieces with an initial diameter of d_{wp} = 33 mm allows the conservation of an austenitic microstructure with varied stability. By variation of the austenitising temperature (T_A), a metastable austenitic microstructure at room temperature can be achieved. Dong et al. (2012) analysed T_A = 1,125°C for X210Cr12, T_A = 950°C for X150CrMn9-3 and T_A = 1,060°C for X120MnCr5-2 as adapted temperatures. In industrial use the special alloys were manufactured by casting processes with a combined heat treatment. Besides conventional heat treatment in the steel mill, no further energy input is necessary to create a microstructure for cold surface hardening. However, for the experiments presented here, a preliminary heat treatment under highly defined conditions in special ovens were applied to allow for specific adjustment of the microstructures' stability.

2.2 Workpiece preparation

For generating the geometry with a diameter of d_{wp} = 60 mm for the X210Cr12 and d_{wp} = 30 mm for the special alloys X150CrMn9-3 and X120CrMn5-2, the workpieces were pre-machined by a longitudinal turning process at a CNC lathe. Using constant process parameters a comparison of the workpiece materials is possible regarding the machinability in cutting process. The chosen turning parameters are shown in Table 2.

Table 2 Cutting parameters for pre-machining

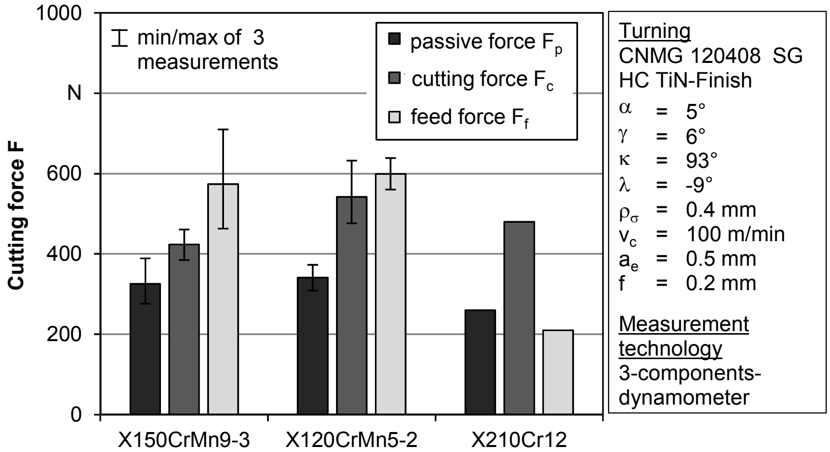
Parameters	*Values*
Turning tool	CNMG 120408 SG
Cutting speed	v_c = 80 m/min
Depth of cut	a_p = 0.2 mm
Feed	f = 0.2 mm
Metal working fluid	5%–emulsion

The turning process induces thermal and mechanical loads in the surface and subsurface layers of the workpiece. In order to avoid undesired microstructural transformation during the pre-machining for generating geometry, the material's microstructure has to withstand these loads, while simultaneously ensuring a good machinability in the previous turning process. To evaluate the potential occurrence of undesired martensitic transformation during cutting process, the machining forces (cutting force F_c, feed force F_f and passive force F_p) were measured by a 3-component piezo-electric cutting force dynamometer on the tool-side (Kistler type 9121). High-alloyed steels are susceptible to a high strain hardening, a low thermal conductivity and high ductility. Additionally, these steels tend to show adhesion between chips and tool. This leads to high machining forces and the formation of unfavourable chip formations such as ribbon and thread chips. To guarantee a sustainable process chain, a conventional generation of geometry e.g. by turning has to be possible. Undesired martensitic transformation during pre-machining can be indicated by an increase in cutting forces leading to an increase in energy consumption. For this analysis, a cutting force measurement during turning process for generating geometry was assessed.

The forces in turning are composed of the cutting force F_c, the feed force F_f and the passive force F_p, see Figure 3. The cutting force determines the chip formation whereas passive and feed forces are crucial for workpiece accuracy. Extensive investigations on the development of machining force when turning X210Cr12 under varied stability conditions were carried out by Garbrecht (2006). In comparison to these results, the special alloys were evaluated regarding the cutting forces (Figure 3). The selected special alloys lead to significantly higher passive and feed forces compared to X210Cr12. The X150CrMn9-3 shows low cutting forces, whereas the X120CrMn5-2 has a higher cutting force compared to the conventional X210Cr12. The stability of all microstructures shows a comparable machinability in pre-machining process.

However, the further investigations aim for identification of a microstructure with an adapted stability, which allows mechanically induced martensitic transformation in a subsequent deep rolling process.

Figure 3 Cutting forces in turning of special alloys and X210Cr12



2.3 Deep rolling

The deep rolling experiments were performed on a conventional CNC lathe, which is also used for the pre-machining. The experimental setup for the deep rolling of cylindrical workpieces is shown in Figure 4. For the investigations, a hydrostatically guided deep rolling tool (Ecoroll HGx-5) with ceramic deep rolling ball was used. The tool is guided by a 5%-emulsion which enables a free rotation of the spherical tool tip as well as an almost frictionless contact by the negligible leakage of the lubricant. Furthermore, the hydrostatic tool realises a constant rolling force F_r along the workpiece.

The deep rolling process induces elasto-plastic deformation of the surface and subsurface layers of the workpiece, depending on chosen process parameters. To induce a maximum influence on the martensitic transformation, maximum deep rolling pressures of p_r = 400 bar are chosen (see Table 3). The resulting calculated deep rolling forces are around F_r = 1,130 N for a tool diameter d_b of 6 mm compared to a theoretical deep rolling force of F_r = 5,310 N for d_b = 13 mm. Due to the leakage in a hydrodynamic system, a deviation between theoretical and real deep rolling force F_r results. With rising volume flow rate by increase of deep rolling force, an increase of deviation between the theoretical and concrete measured process forces can be recorded. Analogical experiments by Meyer (2012) dealing with deep rolling of prismatic workpieces allow the integration of workpiece-sided force measurement. The resulting measured deep rolling force deviates about 13.4% to a $F_{r,meas}$ = 978 N from theoretical force for a deep rolling tool of d_b = 6 mm, while the 13 mm-tool effects a measured deep rolling force $F_{r,meas}$ of 4,050 N with a deviation of 23.7%.

Figure 4 Experimental setup for deep rolling (see online version for colours)

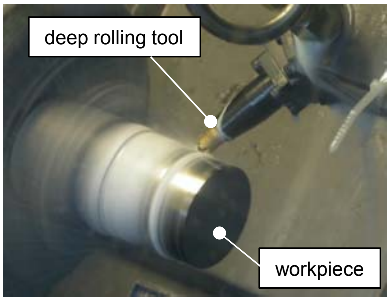


Table 3 Process parameters for deep rolling

Parameters	*Values*
Deep rolling tool	Ecoroll HG6-5 / HG 13-5
Ball diameter	d_b = 6 mm / 13 mm
Deep rolling pressure	p_r = 400 bar
Feed	f = 0.02 mm
Circumferential speed of the workpiece	v_{cw} = 100 m/min

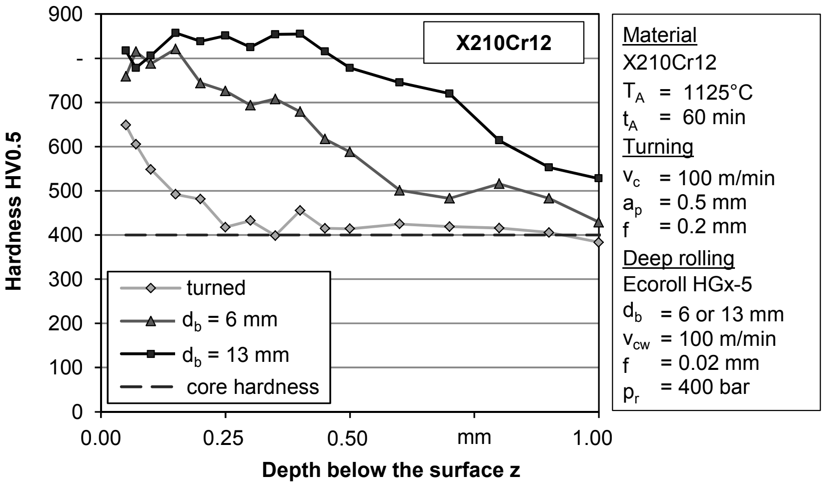
3 Results

3.1 Martensitic transformation of X210Cr12

The aim of the investigation is a heat treatment free surface hardening induced by the mechanical energy of a deep rolling process. This requires a workpiece material with a high amount of metastable austenite at room temperature, which transfers to martensite under the mechanical process load. In addition to strain hardening, the induced plastic deformation also causes microstructural changes in the subsurface area (Schulze, 2016).

The deep rolling investigations were performed with a ball-shaped hydrostatically supported tool with a diameter of d_b = 6 or 13 mm and a maximum deep rolling pressure of p_r = 400 bars. Hardness depth profiles were examined by using the Vickers method on the samples. Figure 5 shows the hardness depth profiles of conventional metastable X210Cr12 with an initial hardness of 400 HV over the components cross section. To illustrate the surface and subsurface modification induced by the mechanical load, the depth profiles of the deep rolled surface are compared to exclusively pre-machined surfaces, machined by turning process. A significant increase in hardness of up to 250 HV at the surface is determined in pre-machined samples caused by the thermo-mechanically impact of the turning process. In contrast, the deep rolled workpieces show a higher penetration depth of z = 1.00 mm for the 6 mm-tool, while the tool of d_b = 13 mm shows still an 30% increase compared to initial hardness at a depth of z = 1.00 mm. The profiles show a characteristic alteration in hardness corresponding to the hertzian contact pressure. These contact conditions are characterised by a maximum of hardness below the surface. The surface hardness for both tools is comparable at a hardness of 800 HV. A tool diameter of 6 mm leads to a maximum of hardness of 820 HV in a depth of z = 0.15 mm, whereas the 13 mm-tool results in a hardness of 850 HV and a depth of maximum of z = 0.40 mm.

Figure 5 Hardness depth profiles of turned and afterwards deep rolled surface of conventional X210Cr12



The higher transformation rates caused by the 13 mm-tool diameter can be explained by the higher process forces, which also manifests in an increasing stress field in the material. Meyer and Kämmler (2016) describe an analytic approach to assess internal material loads in terms of mechanically induced stress fields during deep rolling process based on hertzian contact. By this, an assessment of material modification as well as depth effects of deep rolling under consideration of varied process parameters is possible in spite of the restrictions of the model, e.g., a solely normal force for elastic material behaviour. To model the deep rolling process of cylindrical workpieces, the hertzian contact of two spherical bodies is used which offers the best approximation to the real contact conditions in process, described by Röttger (2003). The used equations for hertzian contact are summarised by Johnson (1985). Material properties like the elastic modulus and the poisons ratio, summarised in Figure 6, allow the calculation of the resulting stress field. For a comparison of varied process parameters, the equivalent stress can be calculated according to von Mises. Figure 6 shows the equivalent stress depth profiles for the varied tool diameters db and the measured deep rolling forces. Similar to the tendency of the hardness depth profile shown in Figure 5, the equivalent stress for the 6 mm-tool shows a lower maximum and a reduced penetration depth compared to the larger tool with a diameter of d_b = 13mm. This leads to a more significant increase in hardness in the sub-surface layers due to the induced martensitic transformation. Especially in the near-surface layer, the accuracy of the model approach is limited. The tangential force, induced by the feed motion in the deep rolling process, shifts the maximum of the equivalent stress closer to the surface. Due to the high plastic deformation and the resulting stresses in the near-surface layers, the martensitic transformation is increased compared to the modelled approach of hertzian contact.

Figure 6 Equivalent stress depth profile of conventional X210Cr12 for varied process parameters

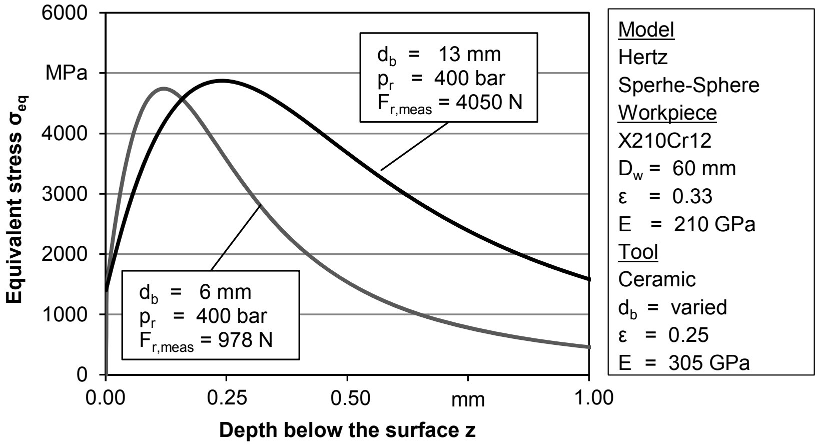
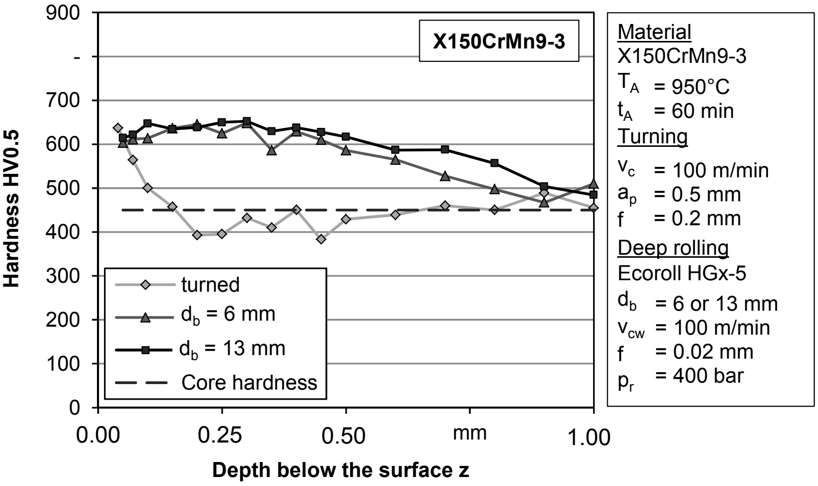


Figure 7 Hardness depth profiles of turned and afterwards deep rolled surface of special alloy X150CrMn9-3



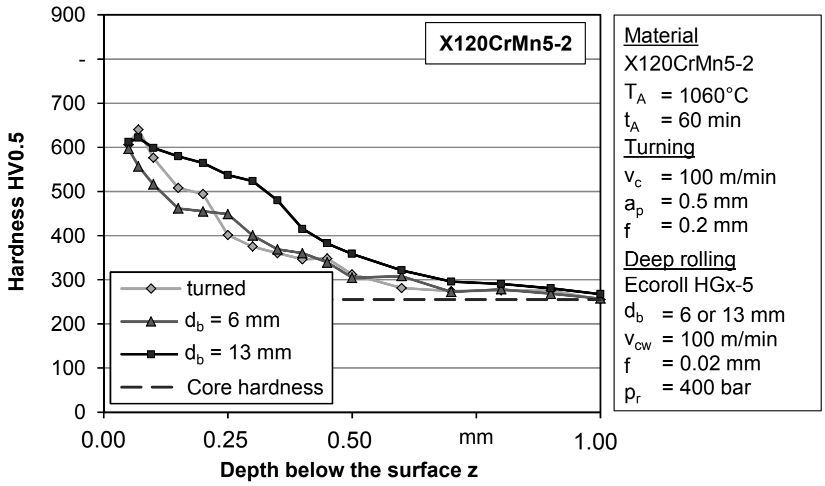
3.2 Martensitic transformation of special alloy X150CrMn9-3

Figure 7 shows the hardness depth profiles of a turned and the deep rolled (sub-) surface of the special alloy X150CrMn9-3. The material has a core hardness of 420 HV. Similar to the results of the conventional X210Cr12, martensitic transformation is already induced by the mechanical energy of the turning process, but only a penetration depth of z = 0.20 mm is observed. Deep rolling of the material is leading to an increase of hardness up to 250 HV in a depth of z = 0.25 mm. The hardness of the deep rolled workpieces slowly decreases below the surface until the core hardness is achieved in depth of z = 1.00 mm. In contrast to hardness depth profiles in Figure 5, deep rolling of X150CrMn9-3 indicates no significant difference between different tool diameters. This effect can be explained by the stability of material's microstructure. Due to transformation of austenite to martensite, the microstructure reaches an energetically more stable state. To overcome the stabilising effect of martensitic structure to induce further martensitic transformation of retained austenite, a significant increase of energy input is necessary, which cannot be achieved by the mechanical process. Although the machining with both tool diameters indicates a comparable hardness depth profile, deep rolling with small tool diameters (d_b = 6 mm) offers the possibility of reduced energy input by lower cutting forces.

3.3 Martensitic transformation of special alloy X120CrMn5-2

The hardness depth profile of the special alloy X120CrMn5-2 shows a similar trend as the special alloy X150CrMn9-3 and the conventional X210Cr12. However, core hardness is about 280 HV. As shown in Figure 8, there is no significant increase in maximum hardness compared to the turned surface, but in the penetration depth of hardness in deep rolled surface with a diameter of 13 mm compared to the turned surface. The 6 mm-tool does almost not affect the surface. The surface is affected up to a depth of z = 0.70 mm. In conclusion, the special alloy indicates a more stable microstructure compared to other considered materials suggesting a prevention of undesired martensitic transformation in use of workpieces. However, for industrial use, an increase in penetration depth is desired.

Figure 8 Hardness depth profiles of turned and afterwards deep rolled surface of special alloy X120CrMn5-2



In order to improve the transformation behaviour of the special alloy X120CrMn5-2, an adaption of the preliminary heat treatment was carried out by varying the austenitising temperature T_A. Thereby, the microstructure of the material was adjusted to ensure a change in the stability of the austenite and also modified transformation behaviour.

For this reason, the influence of the austenitising temperature on the change of hardness is examined for the austenitising temperature T_A of 975°C and 1,000°C compared to T_A = 1,060°C. Core hardness is also influenced by the heat treatment. This leads to a core hardness of 470 HV for T_A = 975°C and a hardness of 380 HV for T_A = 1,000°C.

Figure 9 shows the effect of the deep rolling with a ball diameter of d_b = 13 mm as a change of hardness in comparison to the turned surface. Compared to the previously considered heat treatment condition (T_A = 1,060°C) a significant increase in hardness as well as an enhanced penetration depth for both microstructures can be achieved. The microstructure with T_A = 1,000°C leads to an increase in hardness of 180 HV, whereas the less stable microstructure (T_A = 975°C) shows a maximum growth of about 250 HV compared to the hardness of the turned surface. In addition, a significantly higher penetration depth of z = 1.30 mm is achieved for both microstructures.

Figure 9 Effect of deep rolling on change of hardness for varied microstructural stabilities

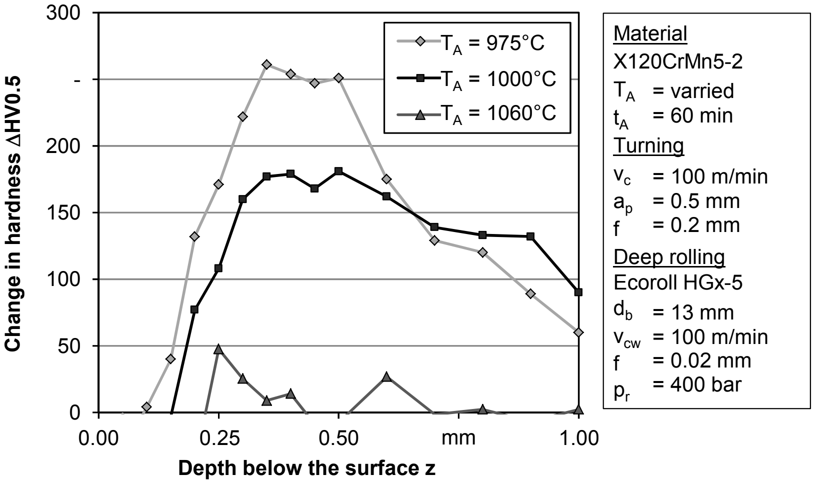
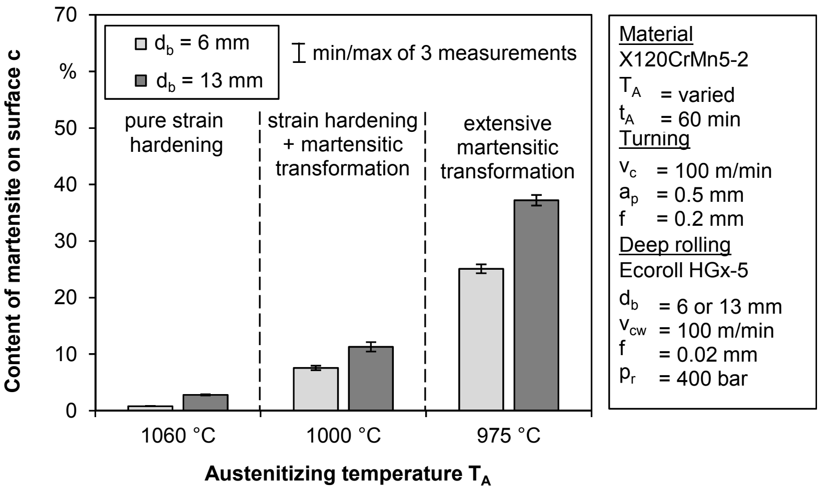


Figure 10 Content of martensite on surface after deep rolling with varied tool diameter on X120CrMn5-2



These results are also confirmed by the magnets-inductive measurement of the content of martensite at the surface of the special alloy under the varied microstructural stability (Figure 10). By lowering the austenitising temperature, the microstructure of the material becomes more instable, so that an increased martensitic transformation is recorded.

While an austenitising temperature of T_A = 1,060°C only shows little rise in content of martensite, the more instable microstructures achieve proportions up to 11% or 37% for a tool diameter of d_b = 13 mm. In addition, the adapted heat treatment enables the processing with smaller ball diameter to induce martensitic transformation as well as a hardening of the surface. This enables a reduction of the machining forces leading to reduced energy consumption.

4 Conclusions

The presented results show the possibility of a time- und energy-efficient manufacturing of surface hardened steel components by the use of mechanically induced surface hardening of metastable austenitic steels. By the combination of hardening and finishing in one single step, cost- and resource-intensive thermal heat treatment can be avoided, while at the same time, a shortening of process chains is possible. For the first time, special alloys were developed, adapted in their compositions optimised for the use in cold surface hardening. Compared to X210Cr12, both materials, X150CrMn9-3 and X120CrMn5-2, contain a reduced content of chromium of 9% or 5%, which reduces material cost for this high alloying component.

The high microstructural stability of the material shows a high stability of microstructure in pre-machining by turning. Reduction of cutting forces cannot be detected despite reduced content chromium carbides, which can be attributed to increased core hardness of the special alloys. Furthermore, the special alloys show a significant increase of hardness on surface and subsurface layers after deep rolling indicating the martensitic transformation. The special alloy X150CrMn9-3 (T_A = 950°C) shows a high stability of microstructure, which is required for this sustainable alternative way of producing surface hardened steel components. Further investigation on practice-related workpieces can secure a high stability without undesired martensitic transformation in use. The special alloy X120CrMn5-2 showed high microstructural stability. Adaption of the austenitising temperature enables variation of the microstructural stability, whereby an increase in temperature T_A responses in high stability of residual austenite. Consequently, the stability of the microstructure affects the process boundaries for mechanically induced hardening. On the one hand, low microstructural stability leads to undesired martensitic transformation in practice, on the other hand high initial load for transformation is limited by machining parameters in deep rolling. On the basis of these experiments, the special alloy X120CrMn5-2 with an austenitising temperature T_A of 975°C realises a microstructural stability suitable for mechanical induced surface hardening.

The development of materials, regarding their alloying composition as well as an adapted heat treatment, enables an adaption of workpieces on their functional performance. This requires adjustment of conventional process chains to heat treatment-free manufacturing of steel components. A combined heat-treatment during hot rolling in steel production enables a sustainable supply of materials with suitable microstructure for mechanical induced martensitic hardening without an additional microstructural adjustment. By this, the application of alternative energy- and resource-efficient manufacturing processes will be possible.

Acknowledgements

The authors wish to thank the German Research Foundation (DFG) for funding the transregional Collaborative Research Center SFB/TRR 136 'Process Signatures', subproject F01 and the Collaborative Research Center SFB 1232 'Farbige Zustände', subproject U04.

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