Shot peening of TWIP steel – influence on mechanical properties

C. Teichmann and L. Wagner

Institute for Materials Science and Engineering, Clausthal University of Technology, Germany

Abstract

TWIP-steel with high manganese content of 15 % was shot peened using an injector type facility. The peening media was spherically conditioned cut wire (SCCW14) and the peening pressure was changed resulting in various Almen intensities ranging from 0.15 mmA to 0.30 mmA. The influence on hardness, residual stresses and fatigue performance was studied. A marked enhancement in hardness could be achieved by shot peening. While peening with 0,15 mmA already results in an increase of surface hardness from about 250 to about 470 HV0.1, peening at 0.22 mmA achieved an even higher hardness of up to 520 HV0.1. Highest hardness of about 550 HV0.1 was found after peening with 0.30 mmA. The residual stress measurements were carried out using the incremental hole drilling technique. The amount of residual compressive stresses can be increased by rising the Almen intensity. While the maximum values of the residual compressive stresses in specimens peened at 0.15mmA and 0.22mmA Almen intensities were about the same, the penetration depths differed. Whereas increasing the Almen intensity from 0,22mmA to 0,30mmA does not further increase the penetration depth the maximum compressive stresses significantly increase. Shot peening was found to increase the fatigue strength in rotating beam loading from 400 to 610 MPa. Presumably, the extraordinary high enhancement of surface hardness and fatigue performance due to shot peening results not only from the pronounced twinning induced plasticity but also from a phase transformation observed by optical microscopy.

Keywords twinning-induced plasticity (TWIP), transformation-induced plasticity (TRIP), manganese steel, fatigue performance

Introduction

Steels with a high manganese content of 13-30 wt.-% and additions of silicon and aluminum of up to 4 wt.-% show an exceptional good combination of high strength and high ductility [1]. Therefore, these materials are considered as a new class of steels. The manganese content has to be adequate high to stabilize the austenite. Therefore, a higher carbon content of up to 0.8 wt.-% is mostly used for stabilization if the manganese content is lower than 18 wt.-%. The reduction of the manganese content is desired because of the higher cost level of manganese. The higher carbon content increases the strength by solution hardening and in addition, it affects the transformation behavior [3]. Multiple martensitic transformations of such alloys are reported [1, 2, 3]. They were observed mostly at high strain levels or high strain rates, comparable to those taking place locally in mechanical surface treatments such as shot peening.

The high ductility of this class of steels results from a multi-stage strain hardening effect [4]. Because of a low stacking fault energy of only about 40 mJm^{-2}, deformation is accommodated not only by glide of dislocations, but also by mechanical twinning at low and intermediate strain levels [3]. In addition, TRIP (transformation induced plasticity) effect was found in alloys with a carbon content in the range of 0,6 to 0,8 wt.-% [1]. These deformation mechanisms can compete during deformation because all of them increase the shear stress, although the resulting dislocation structures differ from case to case. For true tensile strains below 0.3, dislocation substructures without twinning are reported in [3] for a 22 wt.-% manganese TWIP steel with a carbon content of 0.6 wt..-%. Presently, this class of steels is in use for parts that require high wear resistance, e.g. in applications in mining and railway junctions. Historically, the use for combat helmets, so called Brodie helmets, has to be mentioned. If the technical problems of a continuous production of sheet material are solved, there is a high potential in automotive and transport applications, especially for safety related parts protecting passenger compartments [5]. A demonstration plant, using BCT©(belt casting technology) was already built under authority of the Salzgitter AG in Peine, Germany. The next step in the value-added chain is the integration of the new material into the existing production processes. Welding studies were already carried out and the welding additive was patented by Salzgitter Flachstahl GmbH in 2013 [6]. In order to estimate the lifetime of construction components a good understanding of the deformation mechanisms and statistical data for fatigue life are both necessary. Since there is actually little knowledge about the fatigue behavior of austenitic high manganese steels, this work contributes to a better set of data as well. The stress and surface dependent lifetimes are discussed with regard to residual stresses, microstructural changes and surface roughness which are affected by the shot peening process.

Experimental Methods

Material Preparation

A high manganese alloy with contents of 15.5 wt.-% manganese, 0.6 wt.-% carbon, 1.5 wt.-% silicon and 3.0 wt.-% aluminum was rolled to a thickness of 2.5 mm resulting in flat samples for residual stress measurements. Round samples for tensile and rotating bending tests were produced by rotary swaging at 900°C. This was an incremental process with a starting diameter of 23mm and a final diameter of 8.5 mm. The swaging process is given in more detail in [7].

Material Characterization

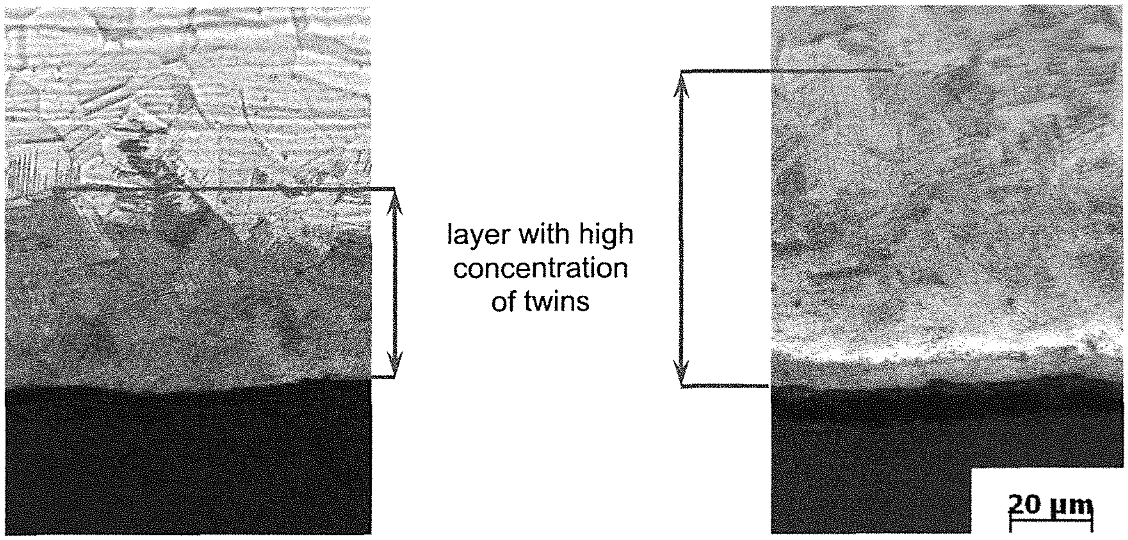
Microhardness measurements, tensile tests, residual stress measurements and rotating beam fatigue tests were used to characterize the material properties. Samples for tensile testing with 6 mm test diameter and 30 mm test length, as well as hourglass shaped samples for fatigue testing were machined out of the round profiles. Flat samples of 19x80mm were cut from the flat material for the residual stress measurements. The incremental hole drilling method was used for residual stress measurements using an increment of 20µm. The used clip gage was a delta-type rosette. Further information about the theoretical model to derive the residual stress from the measured strain is given in [8].

Tensile tests were carried out with a universal testing machine (Zwick/Roell Ulm, UTS, 100 kN). Tensile test results were determined using standard DIN EN ISO 6892-1.

Shot peening was carried out with a universal peening machine, (OSK) in injection mode. The shot peening media was spherically conditioned cut wire (SCCW14) with a diameter of about 0.35 mm. The air pressure varied from 1bar over 3bar to 5 bar, resulting in Almen intensities of 0.15, 0.22 and 0.3 mmA, respectively. Peening time was chosen in order to guarantee full coverage. This was realized in 45 s for the hour-glass samples and 60 s for the residual stress samples. For the rotating beam tests, four-point-bending machines (Sincotec, Clausthal) were used. The tests were intercepted in case of failure or after 10^7 cycles.

Experimental Results and Discussion

The near-surface microstructures of the peened samples were characterized by cross sections after etching with Nital etching solution using optical microscopy and ZEISS AxioVison software (Fig. 1). The microstructure showed smaller effects of shot peening regarding penetration depth than residual stress and hardness measurements. A possible explanation is that visible twinning is demanding relatively high dislocation densities while invisible dislocation substructures are capable of enhancing hardness about 100HV0.1. Twinning was observed up to depths of 60 µm after peening at 0.15 mmA, while peening with 0.30 mmA peening intensity results in twinning even in depths of about 100µm.



a) 0.15 mmA; high concentration of twins in up to 60µm depth

b) 0.30 mmA; high concentration of twins in up to 100µm depth

Figure 1: Near-surface cross sections after shot peening

The curves in Figure 2 illustrate the depth distribution of the residual stresses. The measurements were repeated after 7 to 9 days to get an idea whether the stresses are stable and in order to qualify the results of the first measurement.

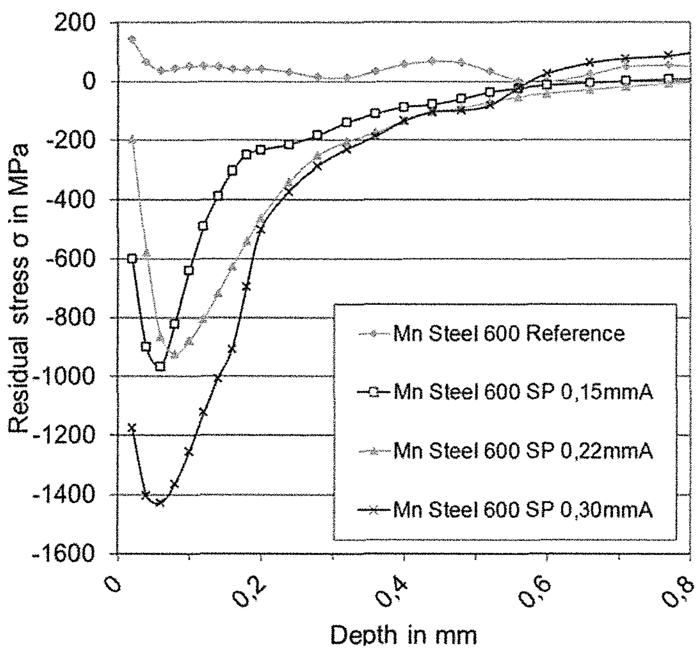


Fig. 2 Influence of shot peening intensity on residual stress-depth distributions

It can be seen from the figure that peening induces high compressive stresses even with only 0,15mmA peening intensity. An increase to 0,22mmA results only in higher penetration depth of the compressive stresses, but the minimum value of about 950MPa compressive stress equals to the value with lower peening intensity. A further increase has little effect on penetration depth, but now the measured compressive stresses reach 1400MPa.

These results show that shot peening with SCCW14 has been highly effective and it can be assumed, that the compressive stresses are capable of increasing fatigue life as well as fatigue strength.

It is estimated that mainly two mechanisms, work hardening by dislocations and Hall-Petch hardening by small grains increase the Yield Strength (YS) to a level at which residual stresses of -1400MPa are stable. These values correspond quite well to the results of the tensile test shown in Tab.1. The tests were performed on a Zwick/Roell Ulm Universal Testing System, capable of a maximum force of 100 kN. It has to be considered, that the flat samples used for residual stress measurements had already an increased YS of about 600 MPa due to the cold rolling process. Therefore, the swaged samples are referred to as "Mn600". Microhardness-Depth profiles were measured using a Struers Duramin-10 micro-Vickers testing machine. The curves can be seen in Fig. 3

YS	UTS	El	σ_F
295 MPa	1005 MPa	56,6 %	2480 MPa

Tab. 1 Mechanical properties of austenitic manganese steel after swaging

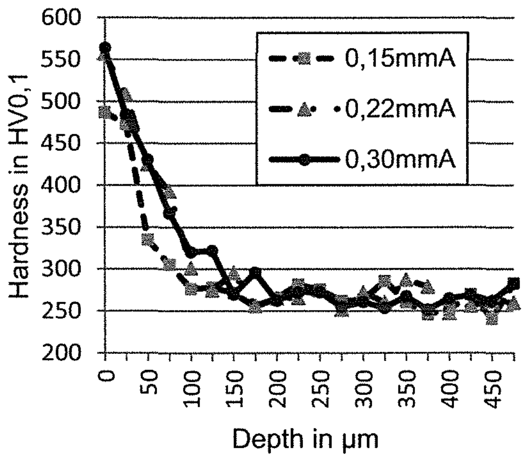


Fig. 3 Hardness-Depth profiles of Mn600 after shot peening with different intensities

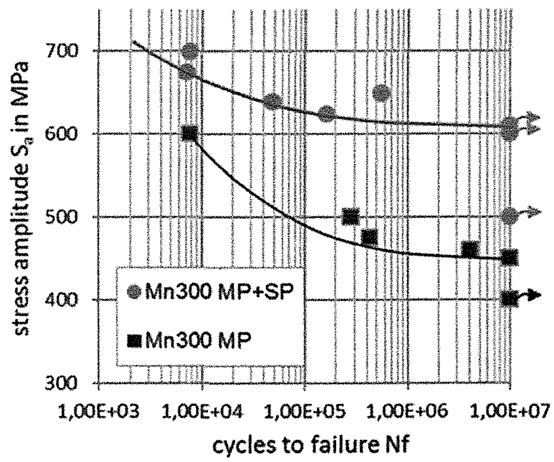


Fig. 4 S-N-curves of Mn300 before and after shot peening with an intensity of 0.30 mmA

Increases of hardness in subsurface regions were observed. In a depth of about 275 µm the values comply to the hardness of the bulk material, which is 255 HV0,1. Shot peening with the lowest applied intensity of 0,15 mmA already results in a marked increase in hardness reaching 490 HV0,1 at the surface. Increasing peening intensity can enhance surface hardness up to 550 HV0,1 but seems to reach saturation with an intensity of about 0,22 mmA. In correspondence to the residual stress measurements a higher penetration depth for 0,3 mmA peened samples was found as well by hardness testing. The difference can only be estimated to 50µm due to the step width of 25µm used for the measurements.

The fatigue strength of the mechanically polished surface conditioned samples is 450 MPa, which is quite high in comparison to the YS of only 300 MPa. This behavior can be explained by small plastic deformations due to the alternating stresses, which result in increases of hardness and strength. This effect is also called training. After shot peening at 0.30 mmA, the fatigue strength is drastically increased from 450 to 625 MPa.

Conclusions

Austenitic manganese steels show an extraordinary good relation between Yield and fatigue strength, caused by training. The fatigue strength of this material can be considerably improved by shot peening. The high work hardening capability of the material and a multi-stage hardening behavior demand high shot peening intensities if a high penetration of mechanical surface treatments is necessary.

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