Machine hammer peening of austempered ductile iron: Microstructural investigation, surface roughness and mechanical properties

J. Scheil, C. Müller, L. Ahmels

Fachgebiet Physikalische Metallkunde, TU Darmstadt, Petersenstraße 23, 64287 Darmstadt

Abstract

Austempered ductile iron (ADI) has become a serious competitive material to conventional steels. In addition to its favorable price the main reason is that its mechanical properties can be adjusted over a wide range by different heat treatments. The unique microstructure of ADI consists of ferrite, graphite and metastable austenite. Adjusting the microstructure (phase fractions, stability) with regard to the application is one important challenge. The key phase hereby is the metastable austenite because it can be transformed into hard martensite under external forces. EN-JS2070 is a cast iron widely used for forming dies. Part of this study is to investigate whether a suitable heat treatment leading to ADI microstructures can be found for this material. Therefore the cast iron was austempered choosing austenitizing temperature of 950 °C and different austempering conditions. Additionally the effect of a mechanical surface treatment, machine hammer peening (MHP), on the microstructural changes in this ADI was examined. Before and after MHP the sample surfaces were characterized using optical microscopy, XRD, hardness measurement and laser microscopy. It could be shown that by a suitable heat treatment an ADI microstructure in EN-JS2070 can be produced. MHP of the heat treated samples results in hard martensitic surfaces. This is accompanied by a significant smoothing of the surfaces. By combining MHP with the ADI heat treatment of EN-JS2070 a further qualification of this tool material becomes feasible.

Keywords Machine Hammer Peening, Mechanical Surface Treatment, Austempered Ductile Iron, Stress / Strain Induced Martensite, Surface Roughness Reduction

Introduction

During the last years Machine Hammer Peening (MHP) has gained a large interest in the forming dies industry. The process, in which a spherical tungsten carbide tool is repeatedly accelerated onto the tool piece, results in smooth surfaces accompanied by the formation of a cold worked surface layer containing compressive residual stresses [1]. These effects can have a positive influence on the fatigue performance, surface hardness and wear resistance of the tool pieces [2]. Moreover the tool pieces can be hammered automatically using a computer numerical controlled (CNC) robot or milling machine. Thereby hand polishing of tool pieces can be omitted [3]. However the hardness gain by MHP, due to cold working of the surface, is at least for cast iron, rather small. A cost intensive laser hardening of the tools cannot be omitted. Enhancing the mechanical properties of tool materials has been part of intensive research in the last years. One outcome is a temperature treatment of grey cast iron resulting in austempered ductile iron (ADI) with an austenitic-ferritic (ausferritic) microstructure. ADI shows promising mechanical properties like higher fracture toughness and yield strength compared to conventional grey cast irons [4]. The heat treatment consists of austenitizing followed by austempering in a salt bath at approximately 350°C resulting in an ausferritic microstructure. The resulting microstructure contains an austenitic matrix with featherlike ferrite and spherulitic carbide precipitations. The ADI microstructure evolves during austempering in the salt bath. Hereby the carbon precipitations serve as carbon sinks in the austenite matrix and their surrounding areas become favorable nucleation sites for ferrite precipitations. As the soluability of carbon in ferrite is significantly lower than in austenite, the austenite enriches with carbon while the ferrite grows. This enrichment causes the austenite to become stable even at room temperature. If the austempering time is too short, the diffusion of carbon from the ferrite to the austenite is not sufficient and the austenite cannot be stabilized and transforms into martensite during quenching. If the austempering is too long the matrix starts decomposing into the stable perlitic structure [5]. One interesting feature of the microstructure is the remaining metastable austenite which can be transformed into martensite by deformation process. It has been reported that in austenitic steels metastable austenite transforms into martensite during deep rolling [6] and thus leads to a significant hardness increase of the surface due to the rolling process. Whether MHP on ADI leads to the same result is not clear up to this point. Scope of this paper is to investigate if the ADI microstructure for the widely used tool material EN-JS 2070 is possible. Therefore different heat treatments of EN-JS2070 leading to an ADI microstructure have been investigated. The samples are machine hammer peened and the microstructural changes of EN-JS2070 are studied. Furthermore the command variables after MHP consisting of hardness increase and reduction of surface roughness are examined.

Experimental Methods

Samples were cut out of a casted block of EN-JS 2070. The samples were austenitized in a furnace at 900 °C for 120 min using hardening foil and argon atmosphere to avoid oxidation. The samples were quenched to an austempering temperature of 300 °C and 350 °C respectively in a salt bath and held at that temperature for 30 min and 120 min respectively. Then they were water quenched to room temperature. The different heat treatments are presented in Table 1.

Table 1. Heat treatment parameters

Sample	300/30	300/120	350/120
Austempering temperature [°C]	300	300	350
Time [min]	30	120	120

The microstructure was examined preparing a cross section of each sample. The cut surfaces were grinded, polished and then etched using a 2% nitric acid, also referred as Nital and an etching called Beraha I . The cross sections were examined using a light microscope. For MHP a sample made of EN-JS2070 as cast and three samples heat treated according to Table 1 were used. Before MHP all samples were milled with a 16 mm ball nose mill at a path distance of 0.5 mm and an infeed of 15 µm. On each sample three areas were machine hammer peened perpendicular to the milling direction using different parameters as can be seen in Table 2. Hereby the hammer head diameter *d* and the stroke *h*, initial offset from the sphere to the surface, were changed.

Table 2. MHP parameters

Field	*d* [mm]	*h* [mm]
MHP1	12	0.15
MHP2	6	0.3

The frequency of the hammer head was kept constant at 300 Hz and the impact angle was 0° (vertical impact). Line pitch (0.11 mm) and the feed rate of 2.0 m/min were kept constant. The average surface roughness R_a and the average peak-to-valley height R_z were measured perpendicular to the milling traces before and after MHP using a confocal laser microscope (Olympus LEXT OLS4000). Additionally the surface hardness HB 2.5/187.5 was measured on each area before and after MHP. Ten indentations per area were measured and averaged. In addition XRD measurements were carried out before and after MHP in order to investigate whether the austenite could be transformed into martensite by MHP.

Experimental Results

The microstructure of EN-JS 2070 consists of spherulitic graphite precipitations in a perlitic matrix and exhibits a hardness of 249 HB. The microstructure of sample 300/30 after heat treatment consists of spherulites in a matrix of ferrite needles and martensite, as can be seen in Figure 2. The hardness of this sample amounts to 448 HB. The cross-sections of the samples 300/120 and 350/120 reveal a microstructure consisting of graphite spherulites and ferrite needles in a mostly austenitic matrix (small amounts of martensite at the phosphide eutectic) that can be seen in Figure 1.

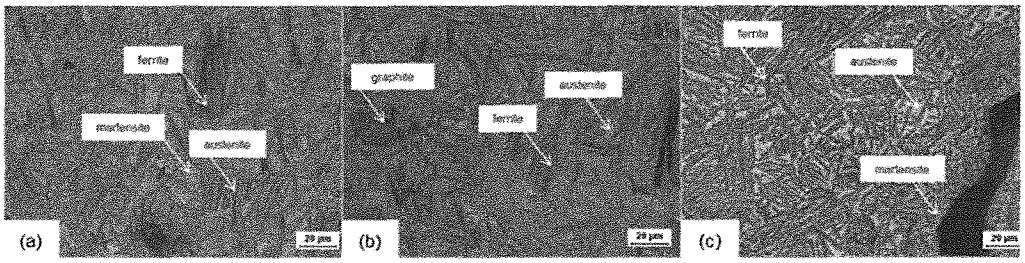

Figure 1: Microstructure of samples (a) 300/30 (b) 300/120 (c) 350/120 before MHP, colour-etched with Beraha I

The difference between the two machine hammer peening combinations is the use of a smaller head diameter and larger stroke in MHP2. In contact mechanics smaller sphere diameters lead to larger Hertzian pressure in the contact zone. Additionally a stroke of 0.3 mm in combination with a hammering frequency of 300 Hz correlates to impact velocities of 0.42 m/s (MHP2) compared to 0.34 m/s (MHP1) with a stroke of 0.15 mm. Therefore the input energy as well as the Hertzian pressure in MHP2 is larger compared to MHP1. The examination of the machine hammer peened EN-JS2070 revealed that the highest hardness increase can be observed at MHP2, where the hardness increases from 249 HB to 298 HB as can be seen in table 3. The highest smoothing from R_z 18.59 µm to 4.61µm respectively from R_a 3.85 µm to 0.45 µm however is obtained at MHP1. This means that for EN-JS 2070 smaller head diameter and a higher stroke cause higher hardening but also a lower smoothening.

At the martensitic sample 300/30 the highest hardening from 448 HBW to 567 HBW and highest smoothening from 15.12 µm to 10,09 µm respectively 1.08 µm to 0.89 µm can be found at MHP2. For this sample smaller hammer head diameter and higher stroke cause a higher hardening and also smoothening. Looking at samples 300/120 and 350/120 that show a similar microstructure, the highest hardening from 341 HBW to 468 HBW respectively from 329 HBW to 434 HBW is found at MHP2. The highest smoothing of 45.19 µm to 7.23 µm (6.4 µm to 0.7 µm) respectively from 14.54 µm to 5.68 (2.47 µm to 0.63 µm) is also observed at MHP2 in these samples. Here a larger stroke and a smaller head diameter increase both the hardness and the smoothening of the MHP treated surface. In difference to the as cast material ADI samples show the highest hardening and smoothening if the energy input is high (MHP2). Under this MHP condition surface failure, i.e. cracks and spalling, in 300/120 and EN-JS2070 were observed (fig. 2c/d).

XRD measurement of sample 300/120 MHP1 before and after MHP can be seen in figure 3.

Before MHP, the measurement exhibits peaks referring to graphite, ferrite and austenite. After MHP the XRD measurements reveal a decrease in the intensity of the austenite reflexes while the ferrite reflexes increase and the graphite reflex vanishes. This means that austenite could be transformed to martensite by MHP.

Table 3: Hardness and roughness values after MHP

EN-JS2070	**Reference**	**MHP1**	**MHP2**
Hardness [HBW]	249	283	298
R_z [μm]	18.59	4.61	8.76
R_a [μm]	3.85	0.45	1.28
Sample 300/30			
Hardness [HBW]	448	515	567
R_z [μm]	15.12	10.80	10.09
R_a [μm]	1.80	1.38	1.06
Sample 300/120			
Hardness [HBW]	341	418	468
R_z [μm]	45.19	21.62	7.23
R_a [μm]	6.40	1.05	0.70
Sample 350/120			
Hardness [HBW]	329	397	434
R_z [μm]	14.54	10.87	5.68
R_a [μm]	2.47	1.64	0.63

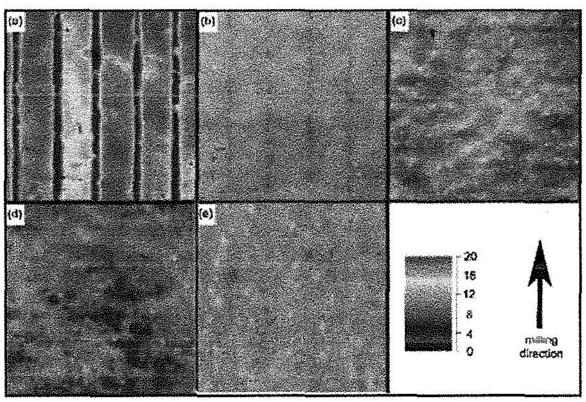

Figure 2: Topography of samples (a) EN-JS2070 after milling (b) EN-JS2070 MHP1 (c) EN-JS2070 MHP2 (d) 300/30 MHP2 (e) sample 350/120 MHP2

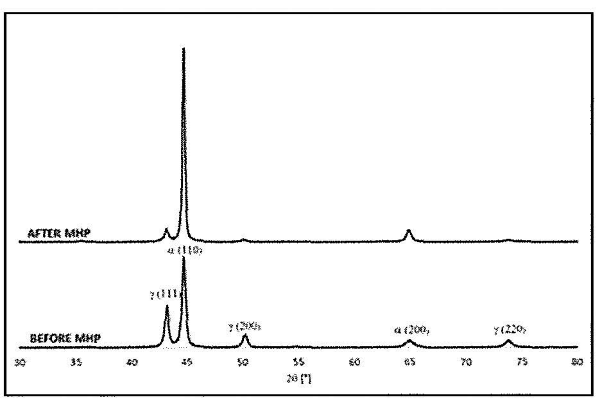

Figure 3: XRD pattern of sample 300/120 MHP1 before and after MHP

Discussion

Due to the short time in the salt bath sample 300/30 shows a martensitic matrix. The time was not long enough for the ferrite needles to interfuse the austenitic matrix. Therefore the enrichment of the austenite grains with carbon is not high enough. The austenite is not metastable at room temperature. After quenching in water the austenite completely transforms to martensite resulting in a high hardness of 448 HBW. In samples 300/120 and 350/120 the time in the salt bath is long enough and metastable austenite can still be observed after quenching in water. *Daber* [7] reported a higher austenite content and a lower carbon content in austenite for samples with a higher salt bath temperature. Meaning sample 350/120 contains slightly more metastable austenite which is less stable than the austenite in 300/120. The higher hardness with 341 HBW compared to 329 HBW is a first indicator for the difference in material behavior. This difference is due to the higher carbon content in austenite which results in larger distortion and therefore higher hardness of the martensite. After MHP the differences become even more visible. In all ADI samples (300/120 and 350/120) deformation induced martensite could be observed after MHP, even at low energy input (fig. 4). The intensity of the (111) reflex shows a decrease as the intensity of (110) increases due to the formation of martensite. Compared to sample 300/120 sample 350/120 contains a larger amount of metastable austenite before MHP. This means that more austenite can be transformed to martensite. Regarding the hardness the effect of larger distortion by a higher carbon content seems to be dominating. The combination of cold working and martensitic transformation leads to surface hardness up to 468 HBW (300/120 MHP2). With increase of the contact pressure and input energy the deformation induced martensite becomes more feasible. Therefore a higher hardness can be found on MHP2 peened with a small head diameter of 6 mm and a larger stroke. For EN-J2070 as cast a maximum hardness increase from 249 HBW to 298 HBW could be achieved by MHP. *Scheil* [8] reported a maximum hardness after MHP up to 312 HBW due to work hardening of the surface. Hereby the head diameter showed a significant influence on the resulting surface hardness. The smaller the head diameter the larger is the resulting Hertzian pressure. Comparing a head diameter d = 6 mm (MHP2) with d = 12 mm (MHP1) the resulting surface hardness on MHP1 is significantly smaller than in MHP2.

The largest initial as well as resulting hardness can be found in sample 300/30 (fig. 4 left) because this sample has a martensitic structure. In addition to the hardness increase a smoothing of the milled surface is the second goal of MHP. Smoothing was calculated using eq. 1.

$$Smoothing\ of\ R_a = \frac{R_{before} - R_{after}}{R_{before}} \cdot 100 \qquad (1)$$

Where R_{before} and R_{after} is the mean surface roughness R_a before respectively after MHP process.

However sample 300/30 shows only a smoothing of the mean surface roughness R_a of 41 % in difference to the other samples (fig. 4 right). As the martensite is hard and brittle, MHP can cause material failure when high energy input is used (MHP2; fig. 2). Therefore the smoothening of this field is not so high compared to the other samples. MHP2 in samples 300/120 and 350/120 shows a smoothing of 84 % respectively 61 %. Here, too, sample 300/120, with a higher amount of carbon in austenite, shows a larger smoothing compared to 350/120. In EN-JS2070 as casted the MHP parameters for the smoothest surfaces are precisely the opposite than that for the hardest surfaces with regard to the head diameter. MHP with the 12 mm sphere shows a high decrease in R_a of 88% and R_z of 75% compared to the milled surface because every single impact produces a pile-up around the impact area. This pile-up height is directly correlated to the sphere diameter. Smaller sphere diameters create larger pile-ups [9]. So a sphere diameter has to be chosen accurately to create hertzian pressures high enough to flatten the asperities from the milling process although high contact pressures can cause spalling as reported by *Steitz* [10]. The combination of high surface hardening and smoothing can be found in the sample 300/120 with the highest amount of carbon in metastable austenite. This underlines its suitability for MHP of ADI deep drawing tools where a hard surface accompanied by a significantly smoothing of the milling asperities is needed.

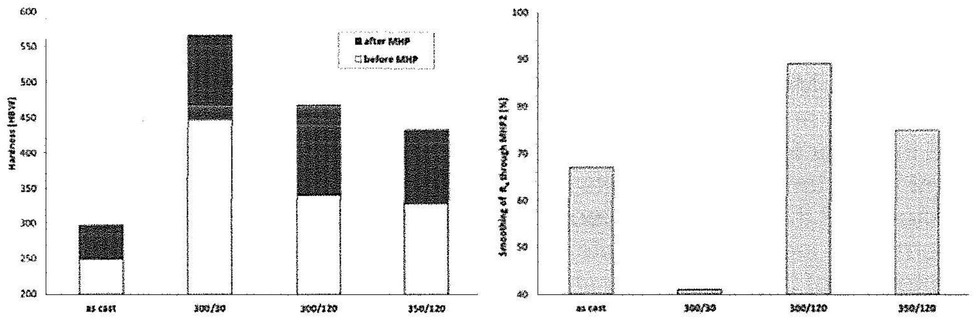

Figure 4: Comparison of hardness and hardness increase through MHP2 (left and comparison of the smoothing through MHP2 (right)

Conclusion

It could be shown that heat treatment on EN-JS2070 can lead to an ADI microstructure. ADI shows a higher hardness than the material without heat treatment. If the austempering time is too short the austenite cannot be stabilized and transforms to martensite during cooling. It had been demonstrated that MHP performed on ADI results in a higher hardening and smoothening of the surface than on EN-JS2070 without heat treatment. Hardness values of 468 HBW accompanied with a mean surface roughness R_a of 0.7 µm could be achieved. Hereby a heat treatment resulting in a high amount of carbon in austenite shows the best properties regarding smoothing and hardening. Via XRD measurements the deformation induced transformation of austenite into martensite could be identified as the mechanism responsible for the higher hardening. Material properties of EN-JS2070 with ADI microstructure can be tailored over a wide range, i.e. hardness, hardness increase through MHP, toughness. Because of its good hardening and smoothing ADI is a suitable material for deep drawing tools smoothened by MHP. Due to its higher hardening it may replace the usage of a separate hardening step on heavy loaded parts of the tool. Further investigations should be made to examine to which extend the higher hardness of the surface leads to a better tribological behavior of the surface.

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