DEFORMATION ZONE SIZE AROUND DRILLED HOLE IN DP STEELS

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Resume

In the present study, there are given results of the experimental tests primarily focused on determination of dimension of plastic strained layer near drilled hole surface. Three hot rolled low carbon steels with strength ranging from 416 to 967 MPa (a conventional mild steel and two microalloyed steels) were examined in the state after annealing to eliminate residual stress and after intercritical quenching. It was found that the size of deformation zones (determined by differential interference contrast light microscopy) as well as thickness of hardened layer (determined by micro-hardness tests) can be correlated with the macro-hardness of the steels, however, they are also dependent on their microstructure.

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1. Introduction

Drilling is one of the most important material removal processes that have been widely used in the aerospace, aircraft and automotive industries. It has been reported that drilling accounts for nearly 40% of all metal removal operations in the aerospace and automobile industries [1]. Although, modern metal cutting methods, including electron-beam machining, electrolytic machining, abrasive jet machining, ultrasonic machining have improved in the manufacturing industry, conventional drilling still remains one of the most common machining processes [2, 3]. The drilling operation in comparison with other methods has relatively very little effect on surrounding material. On the other hand, it is known that the drilling process produces burrs on both entrance and exit surfaces of the work-piece and more often than not an additional operation to remove the burrs is usually required [4, 5]. An economic evaluation of the impact of burrs related toproduction costs has been provided by Aurich [6] (cited in [7]) and has been estimated up to 500 million Euro expense per year only in Germany. Therefore, also aspects of surface integrity of the drilled hole are very important. Surface integrity is generally defined by the mechanical, metallurgical, chemical and topological states of surface properties such as surface roughness, hardness variation, structural changes and residual stress, etc. [8]. This involved also the investigation of microstructural and microhardness changes in the subsurface of the drilled hole, which may influence fatigue, creep and stress corrosion cracking resistance [1, 4, 8 - 12].

This work was initiated by our previous experimental results of the fatigue tests (unpublished results), which in accordance with the previous studies [10 - 12] showed that the fatigue limit of notch specimens can differ by more than 50% in dependence on notch preparation.

The consumption of dual phase steels is constantly rising in many industries [13, 14], however, in the literature there are not studies focused on behavior of these steels during drilling a hole. Main goal of this work is to determine the thickness of hardened layer formed during drilling the hole in the steel with ferritic as well as ferrite-martensitic microstructure (dual phase steels) and strength ranging from 416 to 967 MPa.

2. Experimental

The tests were carried out on one low carbon and two micro-alloying steels, which chemical composition as well as corresponding carbon equivalent (CEIIW) and mean ferrite grain size (df) is given in Table 1.

All three steels were 10 mm thick while hot-rolling. The heat treatment was carried out on samples 20 mm wide and 90 mm long in the direction of rolling. The first series of the samples of all three steels were exposed to annealing to eliminate residual stress (marked as A samples) at temperature 600 °C for 60 minutes. The second series of samples were for purpose of obtaining ferrite-martensite microstructure exposed to intercritical annealing at 800 °C for 10 min and then were water quenched to room temperature (marked as IQ samples). All heat-treated samples were machined equally on both sides by grinding to the thickness ~8,4mm and cut into samples with size 15 x 15 mm. These samples were hot-mounted in PolyFast phenolic resin and then treated by standard metallographic methods. Specimens were drilled at cutting speed 12m/min with feed rate of 0.04 mm/rev. and drill diameter of 2.0 mm. The size of deformation zones (DZ) at the surface of the drilled samples was determined by means of differential interference contrast (DIC) light microscopy. The dimension of thickness of hardened layer (THL) close under surface as well as in the middle of the sample thickness (regions of 4mm under surface) was determined by hardness testing with microhardness tester Leco LM 700AT with 10 g load (HV0.01) and 10 s dwell time.

3. Results and discussion

3.1 Microstructure and mechanical properties of steels

All three steels in the received state had significantly heterogenous ferrite-pearlite microstructure with markedly different ferrite grain size. Some grains reached triple values of df which are given in Table 2. In contrast to conventional low-carbon steel (LC steel in the Tables 1 and 2) both microalloyed steels contained a certain amount of bainite.

Fig. 1 shows the microstructure of examined steels after intercritical quenching. It appears that microstructural heterogeneity of these samples is similar to heterogeneity of samples in the received state. Fig. 1 also indicates, that significant differences in the size and form as observed on ferrite grains were also observed on particles of martensite. In the structure of coarse-grain LC steel particles of martensite larger than 10μm frequently occured, while in the structure of MA-1 steel particles larger than 5μm occured only occasionally and in MA-2 steel there were observed also particles smaller than 1μm (Fig. 1).

It must be noted, that significant difference in values of carbon equivalent (Table 1) only slightly affected the volume fraction of martensite in the microstructure of investigated steels (evaluation by Image-J software), which for LC steel, MA-1 steel and MA-2 steel ranged: 37.3-39.2 %, 38.4- 39.5 %, 38.8-44.8 %, respectively. The yield stress (YS), ultimate tensile strength (TS), total reduction (TE), reduction of area (RA) and Vickers macro-hardness with 10 kg load value (HV100) of the steels obtained in the annealed (A) samples as well as on the samples after intercritical quenching (IQ) are given in Table 2. Table 2 shows that effect of the IQ on the changes of YS was negligible in the MA-1 steel, while in the case of the LC steel

Table 1

Chemical composition (in wt. %), carbon equivalent CE_{IIW} and ferrite grain size (d_f) of studied steels.

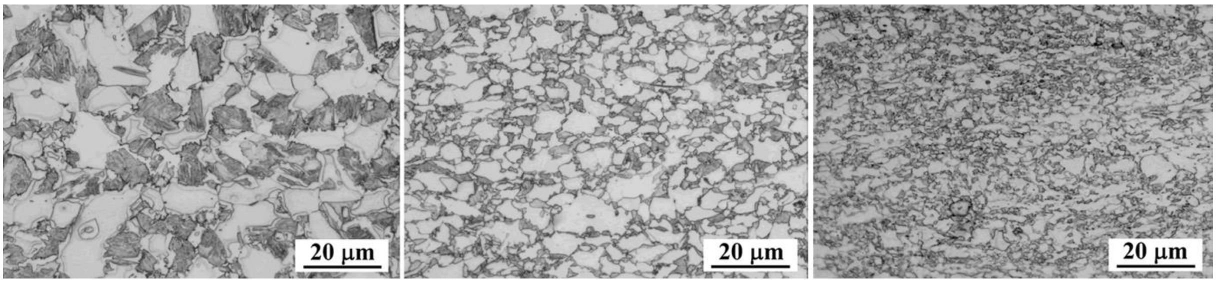
Steel	C	Mn	Si	Nb	V	Mo	Ti	CE_{IIW}^*	d_f (μm)
LC	0.12	0.46	0.04	-	-	-	-	0.197	14.8
MA-1	0.09	1.15	0.33	0.33	-	-	-	0.282	6.3
MA-2	0.1	1.65	0.27	0.053	0.021	0.43	0.125	0.476	2.7

$^*CE_{IIW}$ = %C + (%Mn)/6 + (Cr+ Mo + V)/5 + (%Cu + %Ni)/15

Table 2

Mechanical properties of steels.

Steel	State	YS (MPa)	TS (MPa)	TE (%)	RA (%)	HV_{100} (MPa)
LC	**A**	268	416	38.0	69.2	122
	IQ	373	556	23.6	60.8	193
MA-1	**A**	461	574	29.3	68.7	182
	IQ	474	747	24.0	53.1	221
MA-2	**A**	888	967	22.6	60.4	322
	IQ	564	899	16.8	48.1	294



a) LC steel *b) MA-1 steel* *c) MA-2 steel*

Fig. 1. Microstructure of steels after intercritical quenching.

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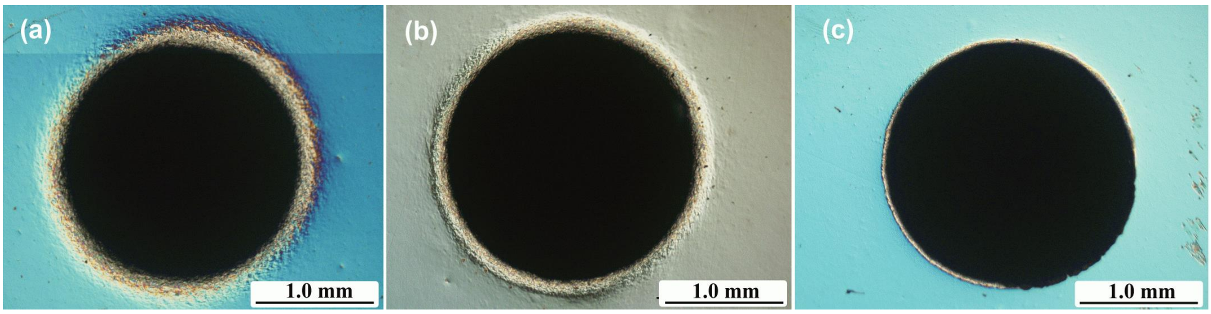

a) LC steel *b) MA-1steel* *c) MA-2 steel*

Fig. 2. Deformation zones around the drilled hole observed on the surface samples annealed at the temperature 600°C-60min (DIC light microscopy).

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increased and in MA-2 decreased. On the other hand, MA-1 showed the greatest increase of the TS of all steels. It is interesting that in contrast to others intercritical quenching of MA-2 steel resulted in decrease of both TS and HV100 values.

3.2 Deformation zones around drilling a hole

In the Figures 2(a)-2(c) is documented the appearance of the metallographic polished surfaces after drilling the hole (using DIC), observed on the samples annealed at the temperature 600°C for 60 min. It was determined that thickness of deformation zone (DZ) around the hole at LC steel ranged from 280 to 330 μm, and the average value was DZ = 308,4 μm (this value was calculated from all measured data around the perimeter of the drilled hole). The measured results of MA-1 steel and MA-2 steel ranged from 150 to 190 μm, DZ = 172.3μm and 40-60 μm, DZ = 52.4 μm, respectively.

The microhardness tests were carried out on the same samples after metallographic grinding, polishing and etching (approximately in depth 0.15mm under surfaces observed in Fig. 2a-c). By means of micro-hardness measuring following values of the thickness of hardened layer were obtained: THL = ~180 μm, ~105 μm and ~37 μm for LC, MA-1 and MA-2 steel, respectively. These values are approximately by 30-42% lower that DZ values measured by DIC method in light microscope.

On the same samples, but approximately 4 mm under the surfaces showed in Fig. 3a-c, other microhardness tests were made. In this area, which approximately corresponded to the middle of the sheet thickness, THL values were by~21-31% lower than values measured approximately in depth 0.15 mm under the surface, which can be seen in Fig. 2. The same experiments as on annealed samples were done also on intercritically quenched samples. The results obtained on both A and IQ samples are shown in Fig. 3.

The results in the Fig. 3 obtained on annealed specimens are similar to those that can be found in several works, e. g. [1, 3, 15 - 18], where also effects of various factors and parameters of drilling were studied. In contrast to these works, this work is specifically focused on effect of microstructure on deformation zone size of the steels around the drilled holes.

Scatter band micro-hardness data measured on the quenched samples were markedly greater than at annealed samples. Therefore, results measured on IQ samples are in Fig. 3 displayed only by means of dashed line (that represents average HV values measured).

The estimated results of hardened layer dimensions obtained on the A samples (empty arrow) compared with the IQ samples (full arrow) shows greater hardening depth. The intensity of strengthening, expressed by relative increase of maximum hardness measured close to the surface of drilled hole to the mean value of the bulk micro-hardness, reached the values ~41% (LC steel), ~34% (MA-1 steel) and ~14% (MA-2 steel) for A samples. On the both MA-1 and MA-2 steels similar levels of intensity of strengthening were calculated also for the IQ samples, however, in the LC steel achieved the value 74%.

From Fig. 3 it is also clear that approximately to depth 40 μm under the surface higher microhardness values were measured in the LC steel (IQ samples) in comparison to MA-1 steels (A samples) which had markedly higher yield strength and slightly higher tensile strength (Table 2). This is caused by higher capacity to deformation strengthening of the steels with ferrite-martensite structure (IQ samples) when compared to the steels with ferrite-perlitte or ferrite-carbides structure (A samples).

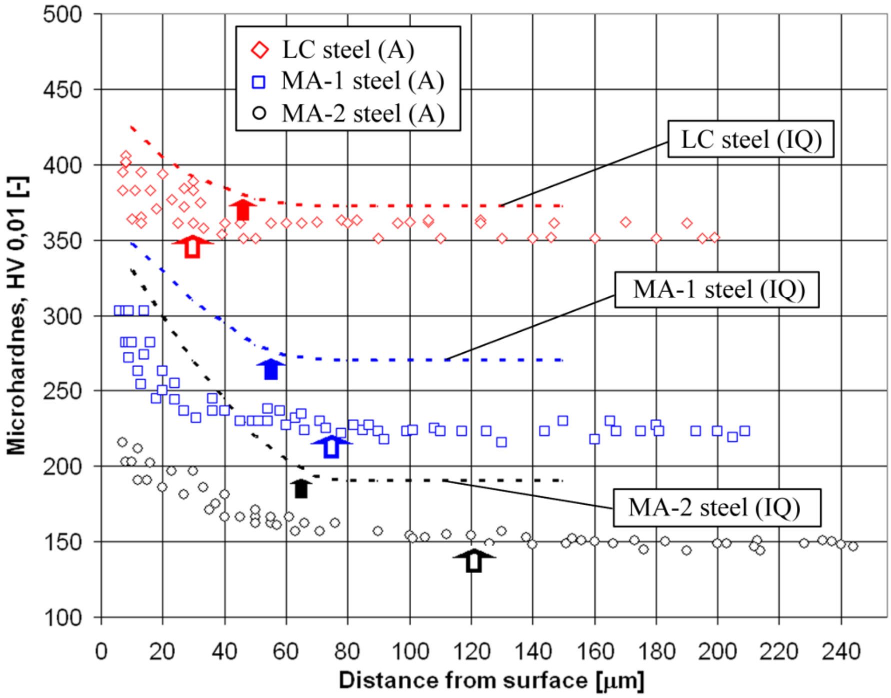

Fig. 3. Microhardness distribution profile near the surface of the drilled hole in LC, MA-1 and MA-2 steels measured on both annealed (A) and intercritically quenched (IQ) samples.
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Table 3

Deformation zones sizes (DZ) and thickness of hardened layer (THL).

Steel	State	ΔDZ (µm)	DZ (µm)	THL (µm)
LC	**A**	280-330	308.4	~120
	IQ	90-170	111.3	~65
MA-1	**A**	150-190	172.3	~75
	IQ	85-140	91.2	~55
MA-2	**A**	40-60	52.4	~30
	IQ	68-89	73.5	~45

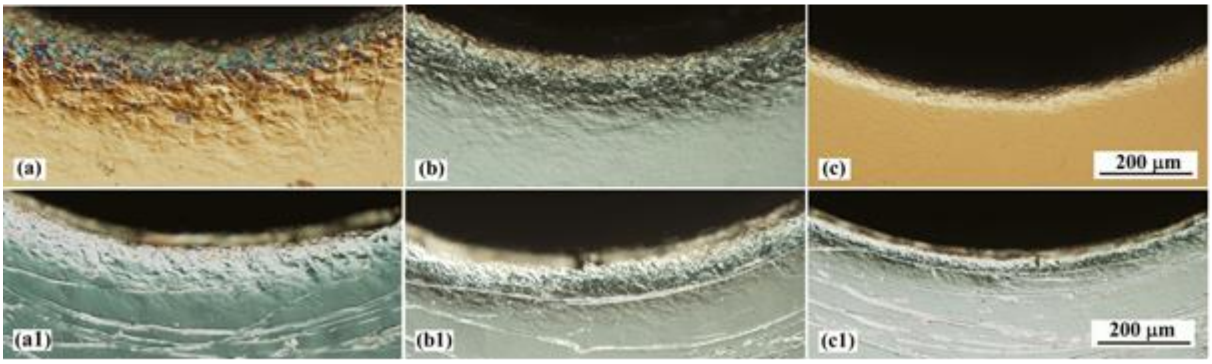

Fig. 4. Deformation zones (DZ) around the drilled hole observed on the surface of annealed samples: LC (a) MA-1 (b) and MA-2 steel (c). DZ observed on the surface of intercritically quenched samples: LC (a1), MA-1 (b1), and MA-2 steel (c1).
(fullcolour version available online)

The most important finding from Fig. 3 is that the difference between THL values, that were measured on the three steels on IQ samples are in comparison with THL values of A samples significantly lower, what may be caused by decrease in differences in strength properties observed at both sample series (Table 2.). Reductions of the differences in the DZ size between three investigated steels in the case of IQ samples can be clearly seen in Fig. 4 (IQ samples are depicted in Fig. 3a1-c1). This is apparent also from data in Table 3 where all experimental results obtained by both experimental methods for detection of the DF or THL values are summarized. The values ΔDZ in the Table 3 represent scatter of all measured data around the perimeter of the drilled hole.

When we compared DZ to THL values given in the Table 3, we found out that they differ ranging from 1.6 to 1.7-times (for annealed samples). However, in the case of IQ samples they differ in the range from 1.75 (MA-2 steel) to 2.5-times (LC steel).

Based on the principles of fracture mechanics, the size of the plastic zone around a crack under given loading conditions is inversely proportional to the yield stress squared ($\approx 1/(YS)^2$; for example see [19]). From the data presented in Table 2 and 3, it was evident that the dependence DZ, THL $\approx 1/(YS)^2$ was not confirmed. Similarly, neither other considered relations DZ, THL $\approx 1/(TS)^2$ or $1/(YS+TS)^2$ were confirmed. It was found, that the best results of all considered correlations showed the dependence DZ, THL $\approx 1/(HV_{100})^2$. It is also interesting to note that although IQ of MA-2 steel resulted in decreasing macro-hardness HV_{100} values (Table 2), average micro-hardness $HV_{0.01}$ values depicted in Fig. 3 are greater compared with $HV_{0.01}$ values measured on the A samples. On the other hand, as it could be expected from lower macro-hardness value, IQ samples compared to A samples showed larger hardening depth (Fig. 3).

4. Conclusions

In the work, there are given results of the tests, where the size of deformation zone (DZ) or the thickness of hardened layer (THL) near the drilled hole of three low carbon heat-treated steels were measured. In this study possibilities to predict DZ and THL size were also investigated. It was found, that DZ, THL are inversely proportional to value of macro-hardness of steels squared (DZ, THL $\approx 1/(HV_{100})^2$), but they are dependent also on their microstructure.

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