DISLOCATION STRUCTURE IN THE HAZ OF HSS STEEL AFTER SHOT PEENING

T. KRUML[1)], C. BUIRETTE[2)], G. DEGALLAIX [3)] AND J. POLÁK[1)]
[1)] Institute of Physics of Materials, ASCR, Brno, Czech Republic,
[2)]CDRM Sollac Atlantique, Dunkerque, France
[3)]LML (URA CNRS 1441), Ecole Centrale de Lille, Villeneuve d`Ascq, France

ABSTRACT

The welds of a high strength C-Mn microalloyed steel with ferritic-bainitic microstructure were shot peened in order to improve the fatigue resistance. Since the weakest point was the heat affected zone (HAZ), the dislocation structure in two depth of the zone was investigated before and after shot peening. No specific dislocation arrangement was found neither in the initial state nor after shot peening and the arrangement can be characterised as random. The dislocation density was elevated in the initial state due to bainitic transformation. The shot peening resulted in appreciable increase of the dislocation density with a very strong gradient. The results were discussed in terms of the effect of surface hard layer induced by shot peening on the fatigue life of the weld and on the initiation and growth of fatigue crack in HAZ.

KEYWORDS

HSS steel, HAZ, shot peening, dislocation structure, fatigue life.

INTRODUCTION

The fatigue life of structural materials and structural parts can be improved considerably by application of surface finishing treatments. One of the very effective methods is shot peening [1]. It is very useful for the welded joints since it can be applied to the weak link of a joint and the fatigue resistance can be increased considerably. Initial post-weld treatment consists usually of rounding-off the local weld toe geometry. Further improvement of the fatigue life can be achieved by the shot peening of the heat affected zone (HAZ), which is usually the weakest point of the weld.

The effects of shot peening on the material are multiple. Firstly, the surface layer of the material is hardened appreciably. In cyclic loading it results in the increase of the elastic strain amplitude and decrease of the plastic strain amplitude. The initiation of the fatigue cracks is thus suppressed and also the growth of initiated microcracks and short cracks is retarded. Secondly, the shot peening introduces appreciable macroscopic compressive residual stresses in the surface layer of the material. The compressive residual stress contributes to the retardation of the growth of short cracks. Both these effects are beneficial since they contribute to the increase of the fatigue strength or of the fatigue life. However, shot peening can also introduce some damage in the surface layer of the material in the form of surface cracks due to very high degree of the local plastic strain when small balls hit the material surface.

The degree of hardening of the material after shot-peening depends on the original state of the material, the intensity and the energy of striking balls and these parameters influence the resulting dislocation structure. The knowledge of the dislocation structure and its changes after shot-peening is important for the evaluation of the effect of postweld treatments on the state of the material and can contribute to the understanding of the effect of postweld treatments on the fatigue resistance of the welds.

Only limited information is available about the dislocation arrangement and densities in shot peened structural materials [2,3]. Martin et al. [3] studied the dislocation density in shot peened SAE 1045 steel and the changes of the dislocation arrangement due to cyclic loading. The highest dislocation density was present at the surface with a strong gradient in the interior of the sample. The dislocation density at the surface was so high ($5x10^{15}$ m^2) that it could not be measured by counting individual dislocations. The changes of the dislocation arrangement could be studied only in the near surface region. The dislocation structure resulting from shot peening has not yet been studied in the welds where the shot peening can considerably improve the fatigue life.

The aim of the present work is to study the dislocation structure and its changes due to shot peening in the HAZ of the welds of a high strength bainitic steel. It is part of a wider research program on the fatigue strength of a bainitic HSS steel [4-8].

EXPERIMENTAL

The material for welding was C-Mn microalloyed HSS hot rolled steel provided by SOLLAC. The sheet thickness was 6 mm. It had ferritic-bainitic microstructure with the fine grain size (5 to 10 μm). The sheets were butt welded using MAG welding. More details on material and welding procedure are given elsewhere [4-7].

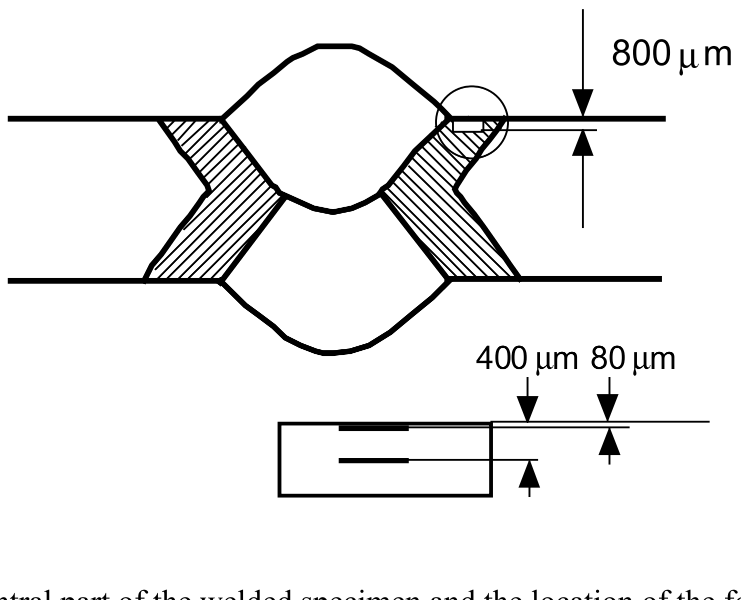

Fig. 1. Central part of the welded specimen and the location of the foil in HAZ.

From the welded sheet a specimen whose width was 15 mm was cut. Figure 1 shows schematically the central part of the specimen with the weld and HAZ on both sides. The

HAZ had the upper bainitic microstructure with prior austenitic grain size of 80 to 100 μm and bainite lath packet size of about 10 μm. The foils for observations in TEM were prepared from thin strips whose thickness was about 0.8 mm. The strips were cut using electro-erosion from the surface of the HAZ. Two types of thin foils were prepared from these strips (Fig. 1). The strips were thinned mechanically either symmetrically or asymmetrically to the thickness of about 80 μm. In asymmetrically thinned samples only surface roughness was removed from the surface side (about 40 μm) and the thinned part of the strip was thus close to the surface. The final electrolytic polishing was performed using Tenupol double-jet technique (another 40 μm). These two types of foil preparation resulted in thin foils from the depth approximately 80 μm below the surface and from the depth of about 400 μm below the surface. In both cases the distance from the fusion line was less than 1 mm.

The shot peening of the whole weld was done with the balls of 0.6 mm in diameter whose hardness was 60 HCR. The medium Almen intensity .25mmA (it corresponds to shot peening of a normalised sheet of a thickness 1.3 mm, which results in the bending of the sheet equal to 0.25 mm) with the coverage 400% was chosen.

The electron microscopy observations were performed in Philips CM12 transmission microscope at 120V. In order to evaluate the dislocation density the thickness of the foil has to be measured. The Kossel-Moellensted method based on the convergent beam electron diffraction was adopted. The dislocations from the micrographs were redrawn on a transparency and their length was evaluated using the image analysis program. The inclination of the dislocation lines in the foil was considered as random.

RESULTS

Figure 2 shows the internal structure of the bainitic region of the HAZ. Low magnification micrograph (Fig 2a) shows the equiaxed grains (3 to 6 μm in diameter) with carbides preferably on the grain boundaries. The equiaxed shape of the grains suggests that the observed region was closer to the basic material than to the weld joint, where typical needles are present. Irregular arrangement of dislocations from various slip systems is present in all grains. The dislocation arrangement at high magnification is shown in Fig. 2b. High dislocation density inside the grains has been found. No specific dislocation arrangement is

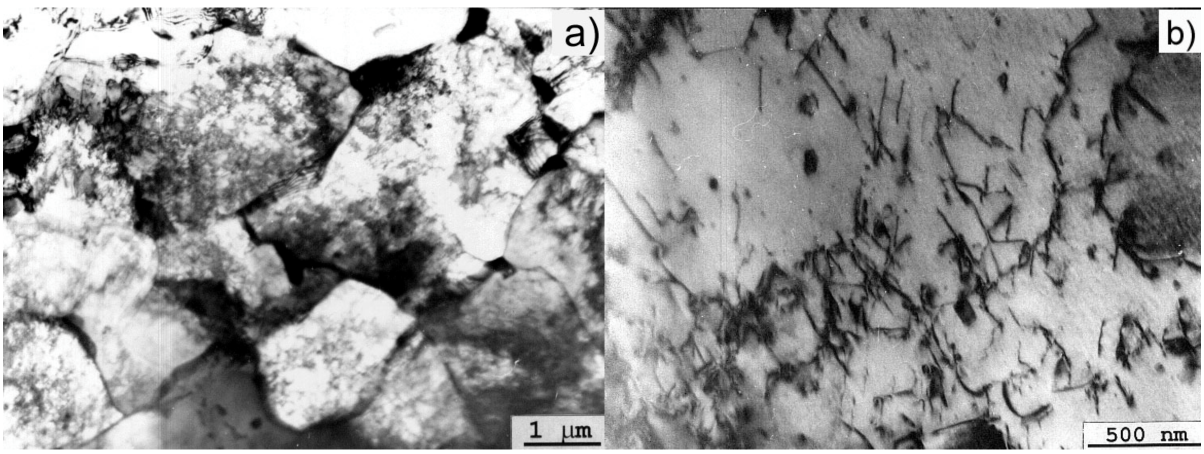

Fig. 2. Dislocation structure in HAZ in as-welded state.

apparent in several micrographs and the dislocation structure can be considered reasonably homogeneous. This observation is in agreement with the plasticity induced by bainitic transformation [9]. Although acicular ferrite can be also present in HAZ of the welds of low carbon steels it is less frequent and the structure observed in numerous micrographs of HAZ corresponds to the bainit. The dislocation density was evaluated according to its definition as the total length of dislocations divided by the investigated volume [10]. Several micrographs taken at high magnification (Fig. 2b) were analysed and the average value of the dislocation density is shown in Table 1.

Dislocation arrangement and density in as-welded state was not different in the depth of 80 μm and in the depth of 400 μm below the surface (see Table 1). This shows that in as-welded state no gradient of dislocation density is present in the HAZ.

Table 1. Dislocation densities in HAZ

state	as welded	shot peened
dislocation density 80 μm below surface(m^{-2})	$3.3x10^{13}$	~> $2x10^{15}$
dislocation density 400 μm below surface(m^{-2})	$3.5x10^{13}$	$2.1x10^{14}$

The shot peening introduces very high dislocation density. Figure 3 shows the dislocation arrangement in the depth of around 80 μm below the surface. It was very difficult to obtain good quality micrographs from these locations since the gradient of the residual internal stresses in the specimen resulted in the deformation of the foil after thinning. Nevertheless, the dislocation density in this depth can still be evaluated using transmission electron microscopy technique. The errors of evaluation are generally large due to uncertainty in foil thickness (30 to 50%). The estimated error for large dislocation densities in the surface layer

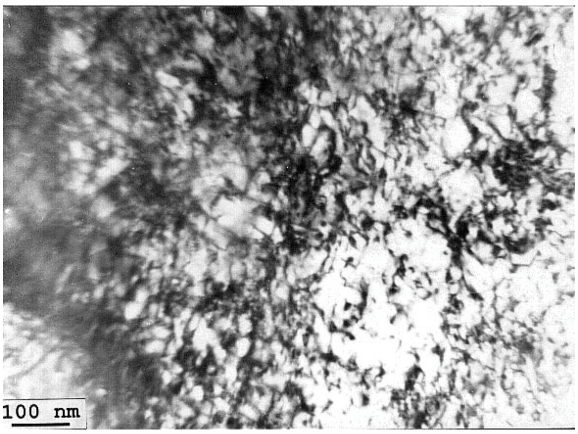

Fig. 3. Dislocation structure in HAZ in the depth 80 μm below the surface after shot peening.

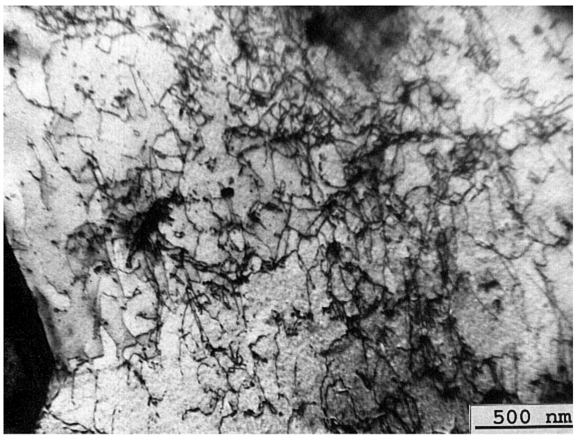

Fig. 4. Dislocation structure in HAZ in the depth 400 μm below the surface after shot peening.

can be even higher and we prefer to give only the lower limit. No specific dislocation arrangement in shot peened specimen was found and it can be again characterised as random. Only high magnification micrographs and thin areas of the foil could be used for the evaluation of the dislocation density. The lower limit of the dislocation density evaluated from several micrographs is shown in Table 1.

The foils prepared from shot peened specimens in the depth of 400 μm below the surface revealed lower dislocation density than that in the depth of 80 μm (Fig 4) but still very high. This result shows that a sharp gradient of dislocation density is present in the shot peened specimens and that the shot peening influences the internal structure in the appreciable depth below the surface.The dislocation arrangement can be again considered as random. The dislocation density was evaluated from several micrographs and average value is given in Table 1.

DISCUSSION

The study of the internal structure of the HAZ of the weld of a high strength steel revealed that the bainite in the zone consists of equiaxed grains. Inside the grains, but more preferably in the grain boundaries, the carbide particles are present. Already in the as-welded state appreciable dislocation density is present in the grains due to plastic deformation accompanying the bainitic transformation.

The shot peening of the HAZ of the weld with bainitic structure influences considerably the dislocation density in the surface layer. In this contribution the dislocation density and arrangement was documented in the depths of about 80 μm and 400 μm below the surface. In the depth of 80 μm, which corresponds to the average primary austenite grain size, very high dislocation density is induced by shot peening. However, even 400 μm below the surface the original dislocation density increased nearly an order of magnitude. Such a high dislocation density results in a strong hardening of the material.

The effect of the increased dislocation density on the yield stress can be estimated using the Taylor formula that gives the internal stress τ_i as a function of dislocation density ρ

$$\tau_i = \alpha b G \rho^{1/2} \qquad (1)$$

where α is a constant close to unity, b the magnitude of the Burgers vector and G the shear modulus. Since the dislocation density in the depth of 400 μm below the surface increased 6 times due to shot peening, the internal stress should increase 2.5 times. In the depth of 80 μm the dislocation density increased 60 times, which results in 8 times increase of the internal stress. These approximate evaluations of the internal stress show that hardening of the surface layer due to shot peening is so high that in the cyclic loading with stress amplitudes close to fatigue limit of the non-treated material the plastic strain amplitude drops to zero and the surface layer is deformed elastically.

The fatigue cracks can be initiated only in the subsurface layer, which requires higher stress amplitude. The fatigue limit of the shot peened specimen should increase, in agreement with experimental observations [4-7]. In the regime of finite life the decrease of the plastic strain amplitude in the hardened surface results not only in the suppression of the crack initiation

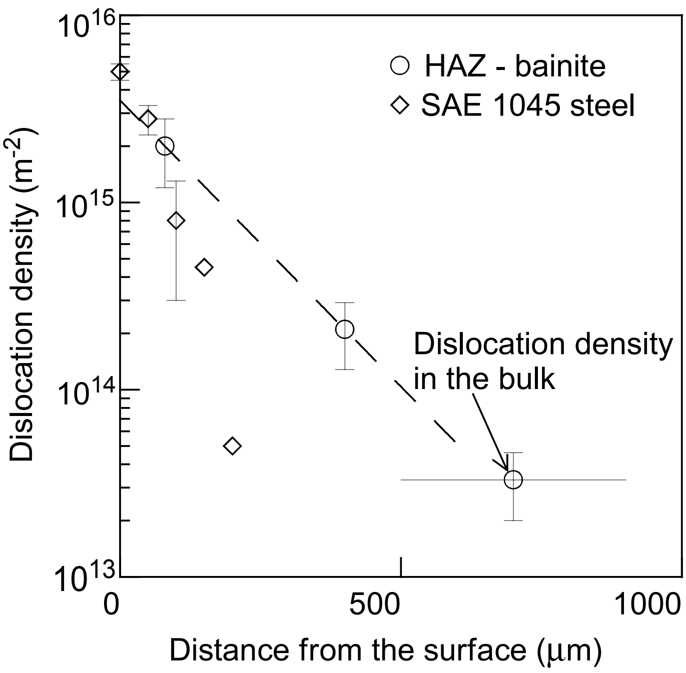

Fig. 4. Dislocation density vs. the depth below the surface in HAZ of the weld.

but also in the decrease of the crack growth rate. Since the plastic strain amplitude plays a decisive role in the short crack growth [11], the initial crack growth rate is reduced considerably. Both these factors contribute to the increase of the fatigue life, in agreement with experimental observations [7].

Since only a few results on the dislocation densities in shot peened surface layer are available in the literature, it is interesting to compare our result with the measurements of Martin et al. [3] in SAE 1045 steel. Figure 4 shows the dislocation densities in SAE 1045 steel [3] and in the bainitic structure of HAZ , studied here, in dependence on the distance from the surface in a half-logarithmic scale. Although the densities close to the surface are in good accord, an important difference in the depth of the layer influenced by shot peening is apparent. While in SAE 1045 steel shot peened with Almen intensity 0.175 mmA the dislocation structure is affected only to the depth of about 200 to 300 μm, in our case the high increase in dislocation density is present in the depth of 400 μm and assuming the drop according to exponential law it extends up to 500 to 600 μm. This difference can be explained by different material (presence of the pearlite in the SAE 1045 steel) and also by higher intensity of shot peening and higher coverage in our specimens. The depth of the affected zone in HAZ is in agreement with the depth of residual stressed estimated both experimentally and using modelling [7,8]. The study of the dislocation density distribution can be, therefore, also used for the estimation of the efficiency of the shot peening procedure.

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