Influence of Lightning Discharge on Microstructure, Mechanical Properties and Failure of Armature Steel

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Influence of lightning discharge on microstructure, mechanical properties and failure of armature steel was investigated. The studied specimens were picked out from the reinforcement construction destroyed during storm. Metallographic analysis by optical microscope LMA combined with video camera YCH15 was carried out. Pictures of the affected structure were picked out by electron scanning microscope SEM EVO 50 as well using secondary electron detector SE. Chemical composition was determined with the dispersive energy spectrometer INCAx-sight EDS. Micro hardness of the specimens was measured by ПМТ 3 device with load 0.49 N (in some cases 0.196 N and 0.098 N). Grey, black or white zones in the cross-section of steel samples were determined. It was found that these zones might be hard or brittle, may vary in shape, size and phase composition. It may have or not metallic properties. The article presents analysis of the chemical composition changes at the affected zones, but it also requires for further investigations of lightning discharge effect on armature steel.

Keywords: lightning, steel, microstructure, reinforcement, armature, failure.

INTRODUCTION

Lightning damage has intense destructive mechanical effect, concentrated electromagnetic impact; it causes fires [1]. Lightning discharge effect on various materials is different. Lightning discharge induces blast in no conducting and semiconductor materials: logs, stakes, tree stems are smashed up but not burned, masonry and stones are burst; thin conductors such as antennas are smelt [2]. Thermal influence of lightning discharges on temperature of aluminium, copper and steel specimens is investigated [3], however, analysis of literary material from various sources did not give any information about changes of metals structure under lightning discharge effect. It may be observed that thermal effect of lightning discharge on steel is particular and can be comparable with steel hardening by plasma, electron beam or laser. There are several works of scientists in this field [4, 5]. E. g., high current pulsed electron beam is now developed as a useful tool for surface modification of materials. When concentrated electron flux transferring its energy into a very thin surface layer within a short pulse time, superfast processes such as heating, melting, evaporation and consequent solidification, as well as dynamic stress induced may impart the surface layer with improved physico-chemical and mechanical properties [4]. Laser beam power treatment technique is now successfully investigated and developed as modification of very thin surface layer of steel [6, 7]. Small volumes of material are heated up close to the melting-point by concentrated energy during very short time in microsecond range.

The heat does not spread to the neighbouring volumes during such short time. After discharge heated volumes are cooled down very quickly by the heat drift into cool mass. Obtained structure is similar with the amorphous one; it has much higher hardness than martensitic structure of hardened steel (363 HB for armature steel) [8]. Investigating the electron beam effect on hard alloy WC-30 % steel microstructure, there was obtained, that the surface hardening is due to the formation on quenching from a melt of a nanocrystalline structure consisting of particles of WC (fcc and hcp lattice) and of type $M_{23}C_6$ and M_7C_3 complex carbides and to the decrease in the fraction of the binder caused by its selective evaporation [9]. On the other hand, these processes proceed in great electromagnetic field. The aim of this work is to investigate influence of lightning discharge on the structure, chemical composition and properties of the steel reinforcement.

Destructive effect of lightning discharge on the armature steel of high-rise reinforcement construction and influence of this effect on the demolition of construction is analysed. Changes of the steel structure are determined metalographically in the rods of armature affected by lightning discharge. Grey and black zones with various shape and size are observed on the surface and in the depth of steel rods. Their micro hardness varies in wide ranges. Separate zones are dispersed widely; their grey areas are fragmented. Changes of the chemical composition are obtained by electron scanning microscope SEM EVO 50. The results of research allow analyzing distribution of lightning discharges in conductor material and investigating its destructive effect.

EXPERIMENTAL

Two armature rods with 1 m length and 24 mm diameter (initial chemical composition of the steel: C = 0.270 %, Si = 0.731 %, Mn = 1.050 %, Cu = 0.150 %, Cr = 0.080 %, Mo = 0.008 %, Ni = 0.075 %) were picked

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out from the destroyed reinforcement construction of concrete preparing unit. The armature steel is hot laminated and its initial microstructure consists from ferrite and pearlite. The rod No. 1 is from collapsed reinforced concrete and it has clean surface without corrosion affected zones. The rod No. 2 was taken from the bottom of the reinforced concrete. The lower part of this rod has lied about 0.5 m above the ground surface and was strongly affected by corrosion (diameter of the rod was decreased until 21 mm – 22 mm). The rods were examined and four specimens were made from the most affected parts of these rods: one was taken from the corrosion affected zone and others from the rod No. 1. The specimens were investigated metallographically by optical microscope LMA with video camera YCH15. Pictures of the structure were picked up by electron scanning microscope SEM EVO 50 using secondary electron detector SE. Chemical composition was determined by dispersive energy spectrometer. INCAx-sight EDS. Equipment ПМТ 3 with load 0.49 N was used for micro hardness measurement. When cracks appeared around the dint determining micro hardness of grey zones, the load of measurement was decreased until 0.196 N and 0.098 N.

RESULTS AND DISCUSSION

Metallographic investigation showed radical changes of microstructure of the surface and deeper volumes of investigated armature rods affected by lightning discharge. There was observable:

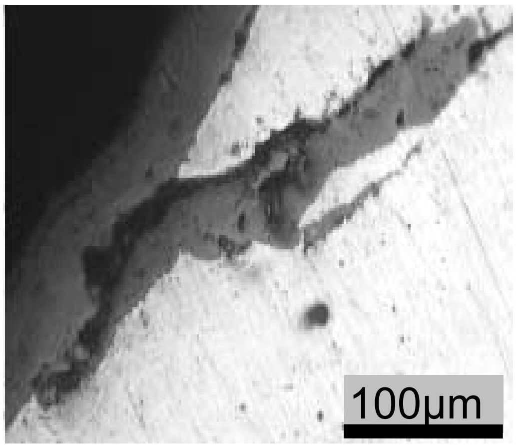
1. Hardened zones looking grey at the polished surface (Fig. 1, a) and resistant to etching by 3 % HNO_3 solution in ethanol (Fig. 1, b);
2. Wedge-shaped interposed formations going from surface and tapering to the depth lengthwise the rod (Fig. 1, a; Fig. 2, b) or locating near the borders of armature across the rod (Fig. 2, a). The formations have various depth, shape and phase composition, they are grey or grey and black;
3. Micro hardness $HV_{0.49}$ of grey formations varies in wide ranges: 4325...10071 MPa in bright grey homogeneous zones, and 916...2834 MPa in dark grey inhomogeneous areas (micro hardness $HV_{0.49}$ of matrix ferrite is 1540 MPa, micro hardness $HV_{0.49}$ of pearlite is 2210 MPa).

Depth of wedge-shaped formation varies from several tens of micrometers to 2 – 3.8 millimetres. Width of the wedge is several micrometers and often admits in the range of grain size. Small grey wedge-shaped insertions are generally homogeneous at the surface of rod (Fig. 1, a), but black colour areas are observable in deeper insertions (Fig. 2, a, c), showing that metallic material is changed by non-metallic insertions. Black insertions are also visible at the dividing line between the main metal and grey formations or can locate as series of small black insertions in the grey one (Fig. 1). There was assumption, that lightning discharge affected this part of specimen more than one time. Especially clear black dividing line between the main metal and grey formation is observable in the specimen made from bottom part of armature rod lied in the foundation of reinforced concrete. Deep grey formation with centres of fragmentation is apparent (Fig. 3). Investigating by electron scanning microscope SEM EVO 50, micro cracks and separate white non-metallic zones were detected (Fig. 4).

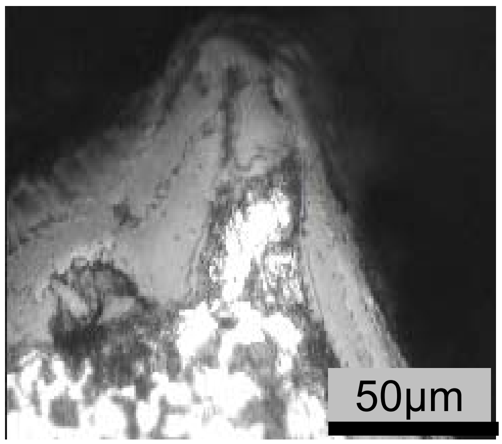
Analyzing element composition by INCAx-sight EDS in 200 μm^2 zone of unchanged microstructure, which locates about 50 μm from the zone affected by lightning discharge (Fig. 5, Table 1) carbon amount was found 4.3 %. Determining element composition of the 500 μm^2 affected zone (Fig. 6, Table 2) that locates approximately 90 μm from the dividing line, amount of carbon has increased up to 17.49 %. Content of silicon and manganese changed fractionally near the affected zone.

This formation contains also oxygen (26.32 weight percent), calcium (1.06 weight percent), an amount of silicon has increased from 0.73 % until 1.07 %, but manganese has disappeared (Table 2).

Cylindrical formation as 700 μm diameter circle and located about 300 μm from the surface was dedicated (Fig. 7). Distribution of its chemical composition was determined and is listed in Table 3. There was no carbon found near this formation. Itself it has contained decreasing amount of carbon – from 5.57 % till 6.90 %. This formation has not contained magnesium, although the investigated steel has 1.10 % Mn.

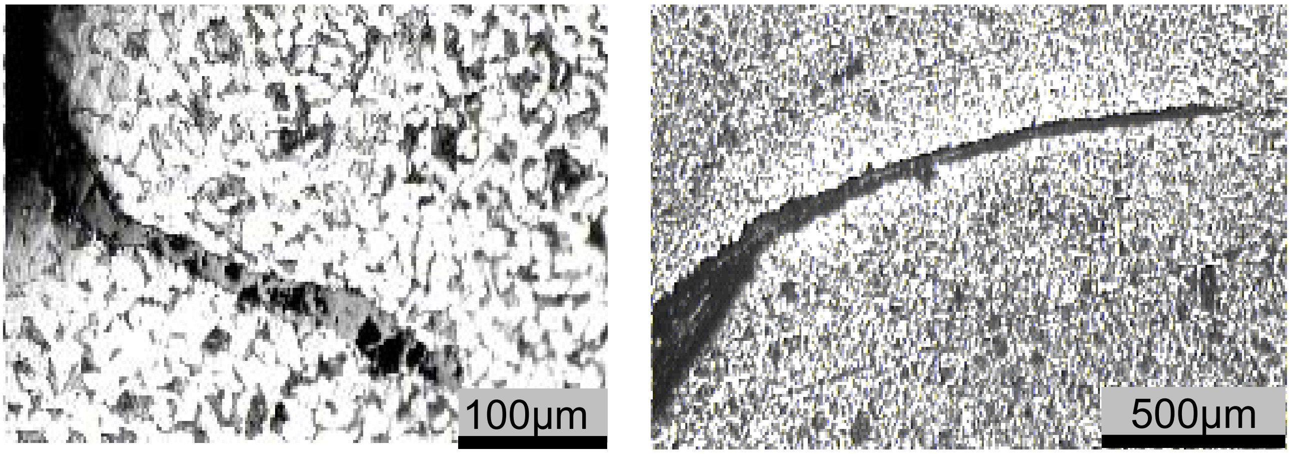


a



b

Fig. 1. Surface of armature steel rod No 1 affected by lightning: a – polished; b – etched by 3 % HNO_3 solution in ethanol



a b

Fig. 2. Cracks caused by lightning discharge in armature rods No 1: a – across the rod (magnification ×16); b – along the rod. Etching by 3 % HNO_3 solution in ethanol

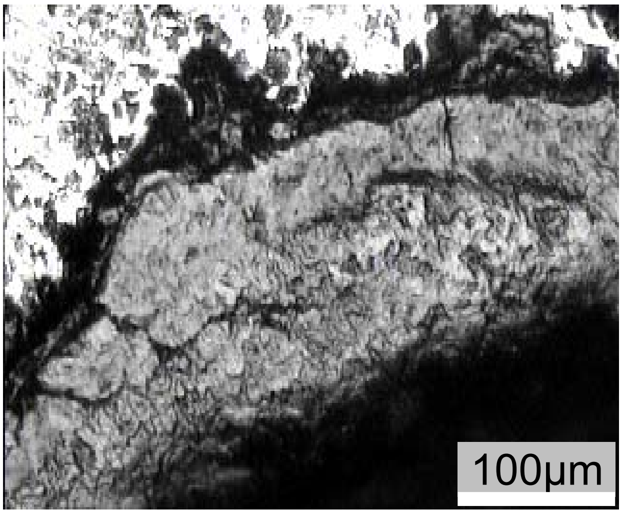


Fig. 3. Microstructure of surface of armature rod No 1 affected by lightning discharge picked up by optical microscope LMA. Etched by 3 % HNO_3 solution in ethanol. Structure: ferrite, pearlite, grey and black formations

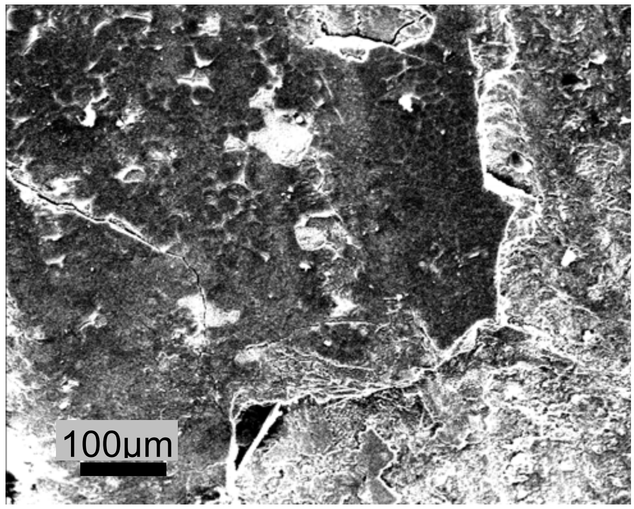
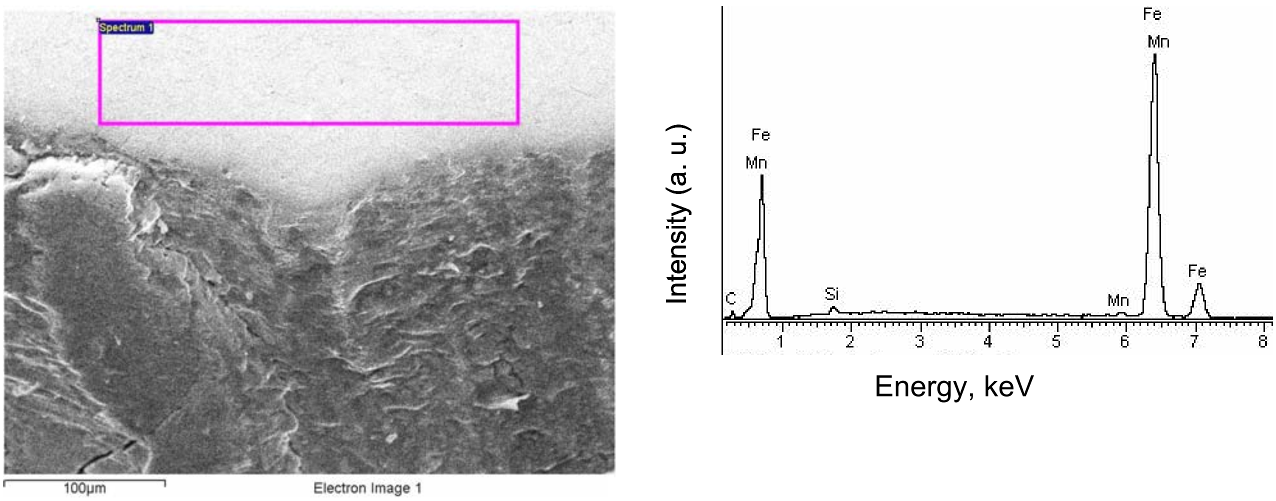
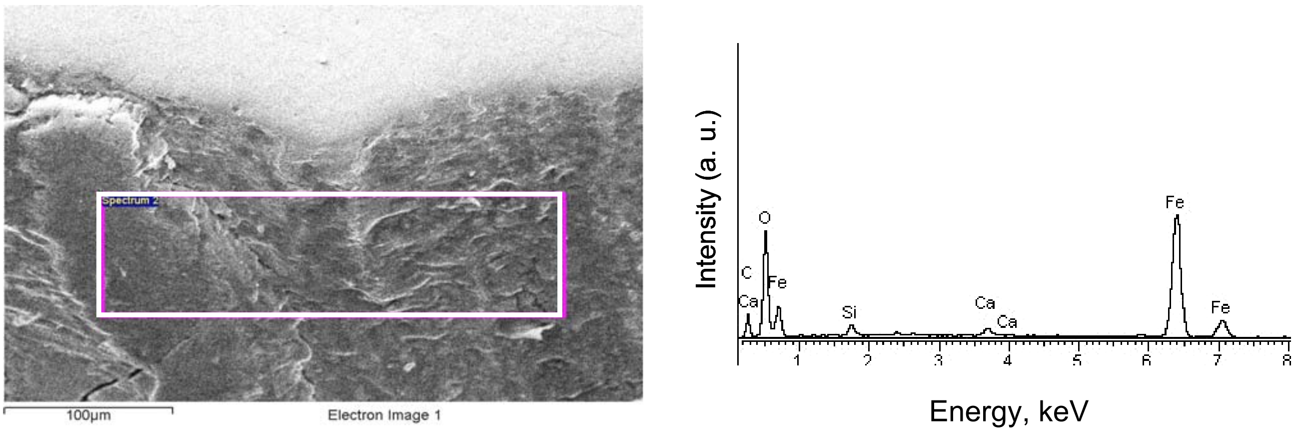


Fig. 4. Microstructure of surface of armature rod No 1 affected by lightning discharge picked up by electron scanning microscope SEM EVO 50. Cracks and metal formations are black, non-metal formations – white



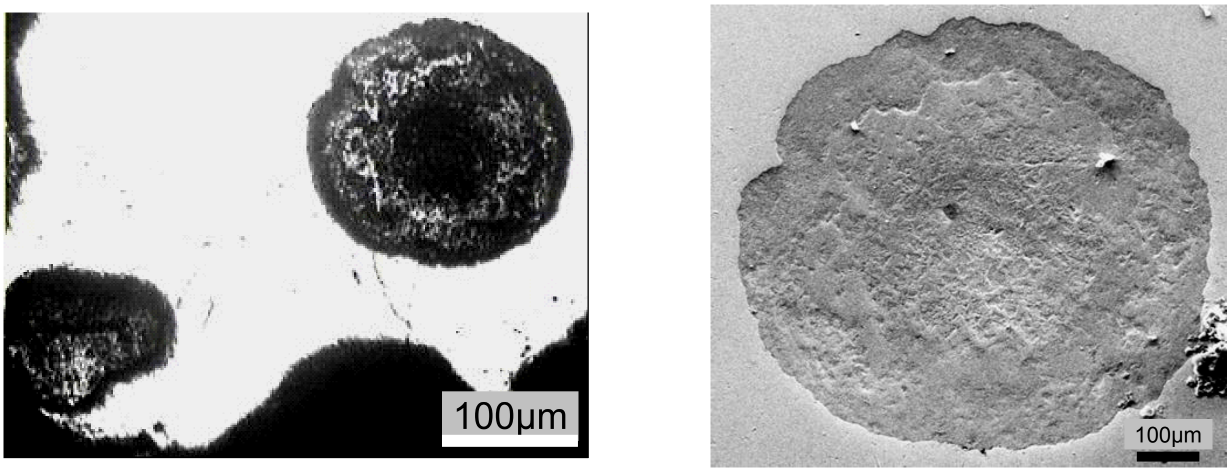
a b

Fig. 5. Influence of lightning discharge on chemical composition of at the surface armature steel rod No 1: a – zone of spectrum analysis; b – spectrum analysis of elemental composition of the main metal. SEM EVO 50 (chemical composition is presented in Table 1)



a b

Fig. 6. Influence of lightning discharge on chemical composition of at the dividing line between main metal and affected zone (rod No 1): a – zone of spectrum analysis; b – spectrum analysis of elemental composition of the main metal. SEM EVO 50 (chemical composition is presented in Table 2)



a b

Fig. 7. Surface structure of specimen rod No 2 affected by lightning discharge observing by optical microscope (a) and by SEM EVO-50 (b)

Table 1. Chemical composition of steel rod No 1 near the zone affected by lightning discharge

Elements	C	Si	Mn	Fe
Weight %	4.3 (0.27*)	0.80 (0.73*)	0.94 (1.05*)	93.96
Atomic composition, %	17.16	1.36	0.82	80,65

*Amount of element in steel far away from affected zone.

Table 2. Chemical composition of steel rod No 1 near the zone affected by lightning discharge

Elements	C	O	Si	Mn	Ca	Fe
Weight %	17.49	26.32	1.07	–	1.06	54.06
Atomic composition, %	35.23	39.79	0.92	–	0.64	23.42

Table 3. Chemical composition of cylindrical formation detected at the surface of steel rod No 2

Location	C	O	Si	Mn	Cr	K	Ca	Fe
520 μm from the centre of formation	–	–	0.65	1.41	–	–	–	97.94
390 μm from the centre of formation	5.57	34.32	1.38	–	–	0.97	0.65	57.11
280 μm from the centre of formation	6.01	34.70	1.04	–	–	0.59	–	57.27
Centre of formation	6.90	33.59	1.77	–	0.86	1.20	0.68	54.99

These incredible changes of chemical composition may be explained by the assumption, that materials are dissoluble during lightning discharge and their atoms are ionized and inserted into steel. This effect might be comparable with laser effect on steel structure [7] and is confirmed indirectly by decreased amount of pearlite at the both side of wedge formed after lightning (Fig. 2, b), showing that decomposition of cementite Fe_3C caused decreasing of an amount of combined carbon. At the moment of lightning discharge, atoms of carbon, oxygen, calcium, silicon and other elements are inserted into steel during dissolving of calcium carbonate and other minerals consisting concrete. But where does manganese disappear? And what conformation carbon has, when its concentration is so high? This may be transpired exercising further circumstantial investigation.

CONCLUSIONS

1. There were obtained hard, homogeneous and conductive (having metallic properties) zones and inhomogeneous, brittle and nonconductive (having non-metal properties) areas with cracks and vacancies investigating steel structure affected by lightning discharge.
2. Elemental composition is fundamentally changed in affected zones: everyplace has oxygen and anomalous amount of carbon. Calcium has come into being, quantity of silicon has increased and manganese has disappeared.
3. These elements have segregated at the affected zones from the concrete at the conditions of high temperature of lightning plasma and great electromagnetic field. During lightning discharge, materials of concrete are dissociated into separate elements; atoms are ionized and inserted into iron. The material is either strengthened or destroyed.

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