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INFLUENCE OF WOOTZ STEEL MICROSTRUCTURE TO FORGING

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Abstract *Cast (real) damascus steel (so-called "wootz") is an ancient tool/weapon material. Due to relatively high carbon amounts, the wootz is hard to forge (or other hot-forming shaping). In some cases, the forging of wootz is impossible. During forging, cracks are often created that lead to absolutely disintegration of bulk material. In this paper is given one relationship between wootz microstructure and the forging impossibility.*

Keywords *damascus steel, wootz, formability, microstructure, metallography*

1 INTRODUCTION

Damascus steel was for several centuries the best in smith art. The name of damascus steel they got from Damascus city. This Persian city was the trade centre for (not only) best steels in the ancient world. The main attribute of these steels was characteristic patterns. These patterns are usually highlighted by etching or specific heat-treating processes.

Damascus steels were used for high-end tool making – mainly for knives and swords. The outstanding property of damascus steels over ancient common steels was excellent toughness with very high wear resistance (and high hardness). This combination of properties is given by the microstructure of damascus steels. Damascus steels are composite materials that combine a relatively soft steel matrix with a very large amount of hard carbide grains. From history are two types of damascus steels known.

i. cast damascus (wootz, real damascus, bulat, …)

ii. pattern welding damascus.

Wootz (cast damascus) is produced by slow cooling of a liquid alloy with a specific composition. After the cooling period, a specific forging is necessary. Final properties of the wootz steel obtained by specific heat treatment (Ustohal and Stránský 2003). The previous three steps are probably the first composite steelmaking process. The wootz making process was limited in place and time. For the production of wootz it is necessary to use only ores with specific compositions from several fields. After exploitation of these fields, it was impossible to reproduce the wootz making.

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Pattern welding damascus is produced by forge-welded a billet stacked from several different pieces of steel. Pattern welding damascus is also a composite material. But in pattern welding damascus alternate the layers of soft (tough) and hard (brittle) steels.

Correctly made and heat-treated damascus steels are characterised by high toughness with high wear resistance. This combination of relatively opposite properties is caused by variations in the soft and hard steel phases. The soft phases originate from a low amount of carbon in the structure. The hard phases originate from high-carbon steel (forge weld damascus) or from carbide bands (wootz). At present the high alloyed steels with similar properties are made. At ancient times it was not possible to prepare steels with exact amounts of alloying elements to modify steel properties. For this reason, damascus steels were only one ancient method of modification of steel properties.

The first scientific papers focused on wootz-making was published at the end of the 18th century (Pearson 1975; Mushet 1805). These papers described the empiric blacksmith forging from imported ingots from India. The papers are describing an important carbon quantification method. The amount of carbon was analysed by reducing lead from flint glass during smelting (ratio of wootz to glass = 1:4).

Present papers describe the same wootz microstructure on ancient and modern samples. The wootz pattern originates as carbide bands in a steel (iron) matrix. During the specific type of forging, the carbides are aligned to specific, macroscopic visible patterns (Ustohal and Stránský 2003; Verhoeven 1987; Sukhanov and Plotnikova 2020). For wootz pattern formation in steels is a very important chemical composition of steel. Typical wootz steels composition is (pure) low-alloy steel with about 1.8% of carbon. Other alloying elements are present at very low concentrations. For the formation of the wootz pattern carbides is necessary the presence of vanadium at concentrations over 0.03%. In modern wootz steel, vanadium may be replaced by similar concentrations of other strong carbide-forming elements (Sukhanov and Plotnikova 2020).

Modern wootz-making reproduction started at the end of the twentieth century (Verhoeven and Jones 1987). These making reproductions enable us to explain the characteristic pattern formation. Verhoeven et. al. (1998) published paper in which carbide patterns formation was explained as a result of vanadium microalloying. In this paper authors assumes vanadium carbide segregation in interdendritic volumes during wootz ingots cooling. During the next forging steps, this carbide grid forms macroscopic visible bands.

A detailed description of ingot forging is given in (Verhoeven and Pendray 1992). Papers identify some forging problems. At initial forging steps, the cracks may form. These cracks grow and disable the next forging. The solution of this problem may be long-time annealing – 'held at 1200-1250 ° C in iron oxide for 5 h to establish the low carbon ductile iron rim'. It enables the forging of graphite-containing ingots.

In Czechia, Fabiánek (2003) describes the preparation of wootz blades. The blades were forged from a wootz ingots melted by Pavel Řiháček. Ingots that were used in these experiments did not show any crack formation during blade forging.

2 EXPERIMENTAL PART

The Wootz described in this paper was prepared by the bladesmith Petr Dohnal (Czech Republic). Pieces of steel ČSN 19 191 weighing 800 g were inserted into the graphite crucible. As vanadium source the 50 g of K390 steel (manufactured by Bohler-Uddeholm) was used. The surface of the crucible charge was covered with a 10 mm layer of crushed charcoal and cow leather scraps. For protection of melted steel, the cullet from a wine bottle was used. The glass forms a slag on the surface of the melt, which prevents it from entering the furnace atmosphere. The smelting was done in a gas furnace. The temperature of 1600°C during smelting was controlled by a pyrometer. The total smelting time was 4 hours. After the heating was finished, the crucible with the charge was left in the furnace for slow cooling.

After the furnace cooled, the graphite crucible was broken and the ingot was removed. The ingot had a mostly metallic surface with a visible dendritic structure (Fig. 1). The ingot was cut into half. One part was forged immediately (without tempering). The second part was annealed 10 times to an austenitizing temperature of approximately 1000 ° C in a forge with subsequent cooling in air to approximately 700 ° C. The forging temperature range of both halves was from 850 to 700 ° C.

The blade was forged from the austenitized part of the ingot. After heat treatment and etching, it showed a characteristic wootz pattern (Fig. 2). In the case of a part forged without austenitizing annealing, cracks were formed repeatedly during forging (Fig. 3). Therefore, the forging of these samples was terminated.

Fig. 1 Detail of the ingot surface after cooling

Fig. 2 Macrostructure of the wootz blade

Standard metallographic samples were prepared from a partially forged ingot (part without austenitizing annealing) with many cracks. The samples were hot pressed into Bakelite for easier handling. The surface was wet grinded with SiC sandpapers to P1200 grit. The final polishing was performed with D0.7 diamond paste. Microstructure evaluation was performed on Neophot 3 metallographic microscope equipped with a 5Mpx camera Olympus ColorView III. SEM microscopy was performed at the TESCAN VEGA 3 EasyProbe scanning electron microscope (SEM). The chemical microanalysis of the elements was carried out with a Bruker EDX (Energy-dispersive X-ray spectroscopy) analyser, which is part of the electron microscope.

3 RESULTS AND DISCUSSIONS

The final polishing of the non-austenitized sample shows a considerable number of cracks. Cracks were perpendicular to the direction of formation, see Fig. 3. Micrograph of unetched sample showed a significant number of voids filled with dark matter. A closer examination revealed that the cavities had rounded ends and that the filling was probably graphite (Fig. 4). The microstructure of the metal matrix revealed lamellar pearlite (Fig. 5)

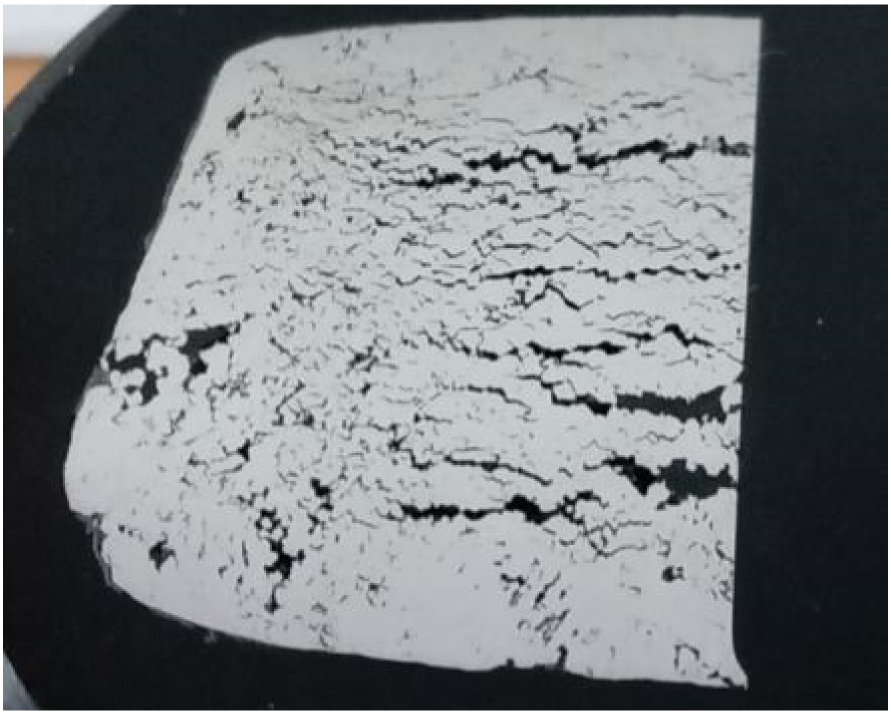

Fig. 3 Macrograph of nonannealed sample cracks after forging

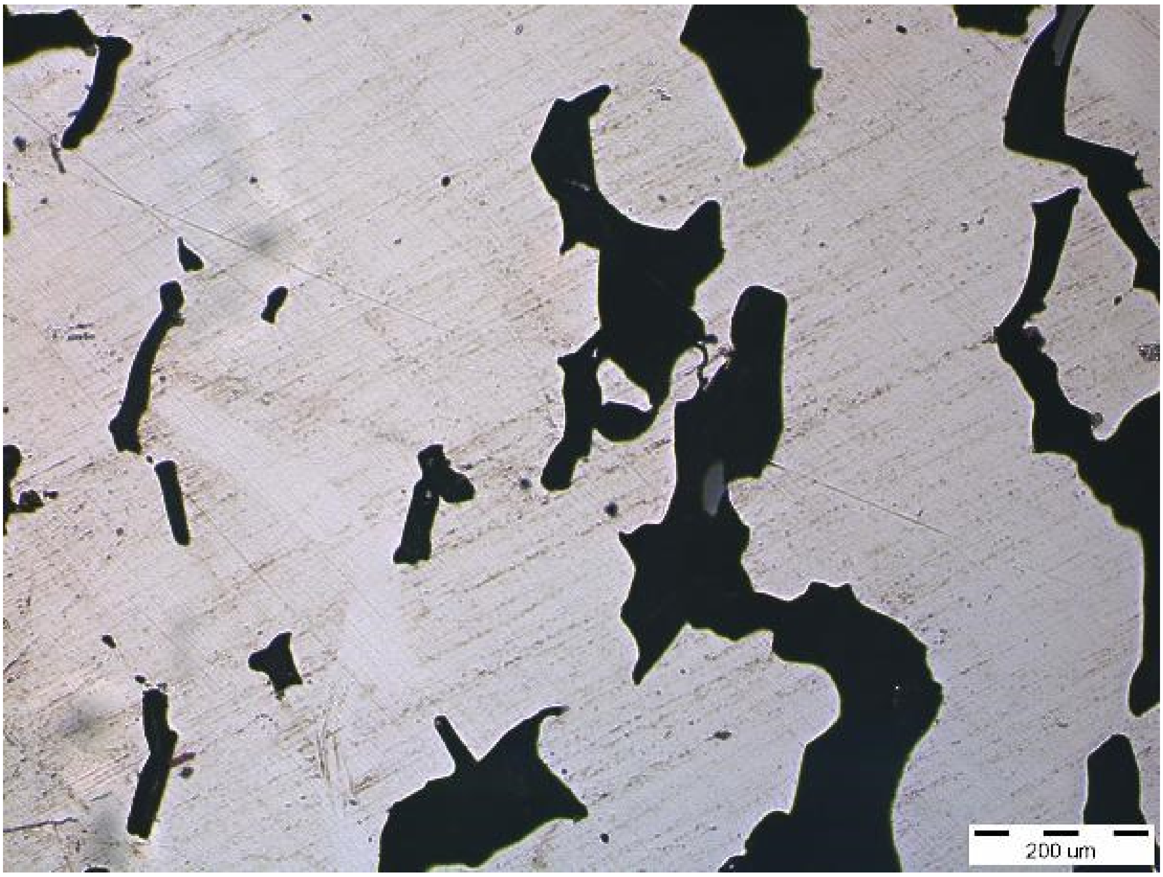

Fig. 4 Non heat-treated sample microstructure, unetched; mag. 100x

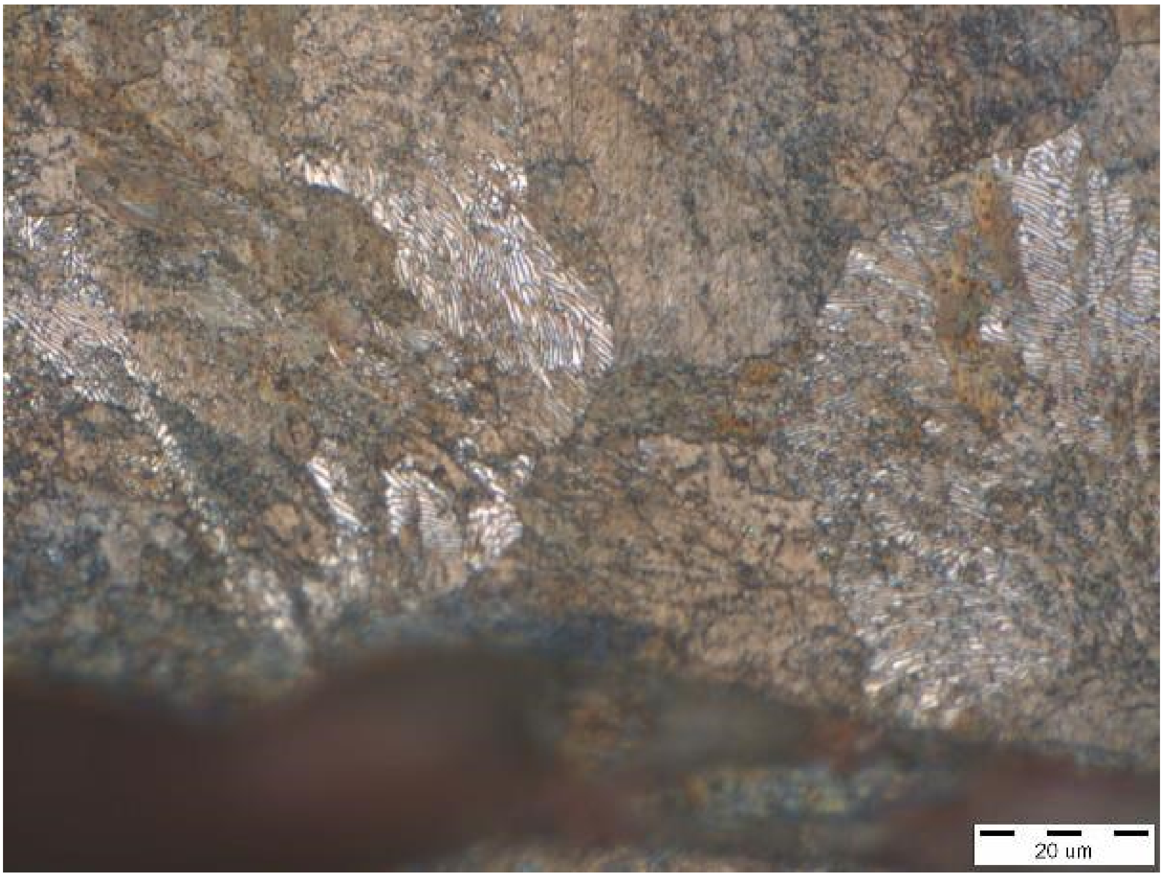

Fig. 5 Microstructure near crack, Nital etch; mag 1000x

A more detailed characterisation and identification of the present phases was performed using SEM. A pearlitic structure was confirmed in this analysis. The alloying elements were evenly dispersed in the pearlite. Only a limited amount of carbide network was found at the grain boundaries (see Fig. 6). This structure was compared to another blade that had been forged in the correct manner from a second part of the ingot. In properly forged material, a significant carbide network and larger carbides were formed (Fig. 7, pos. #2 and #3)

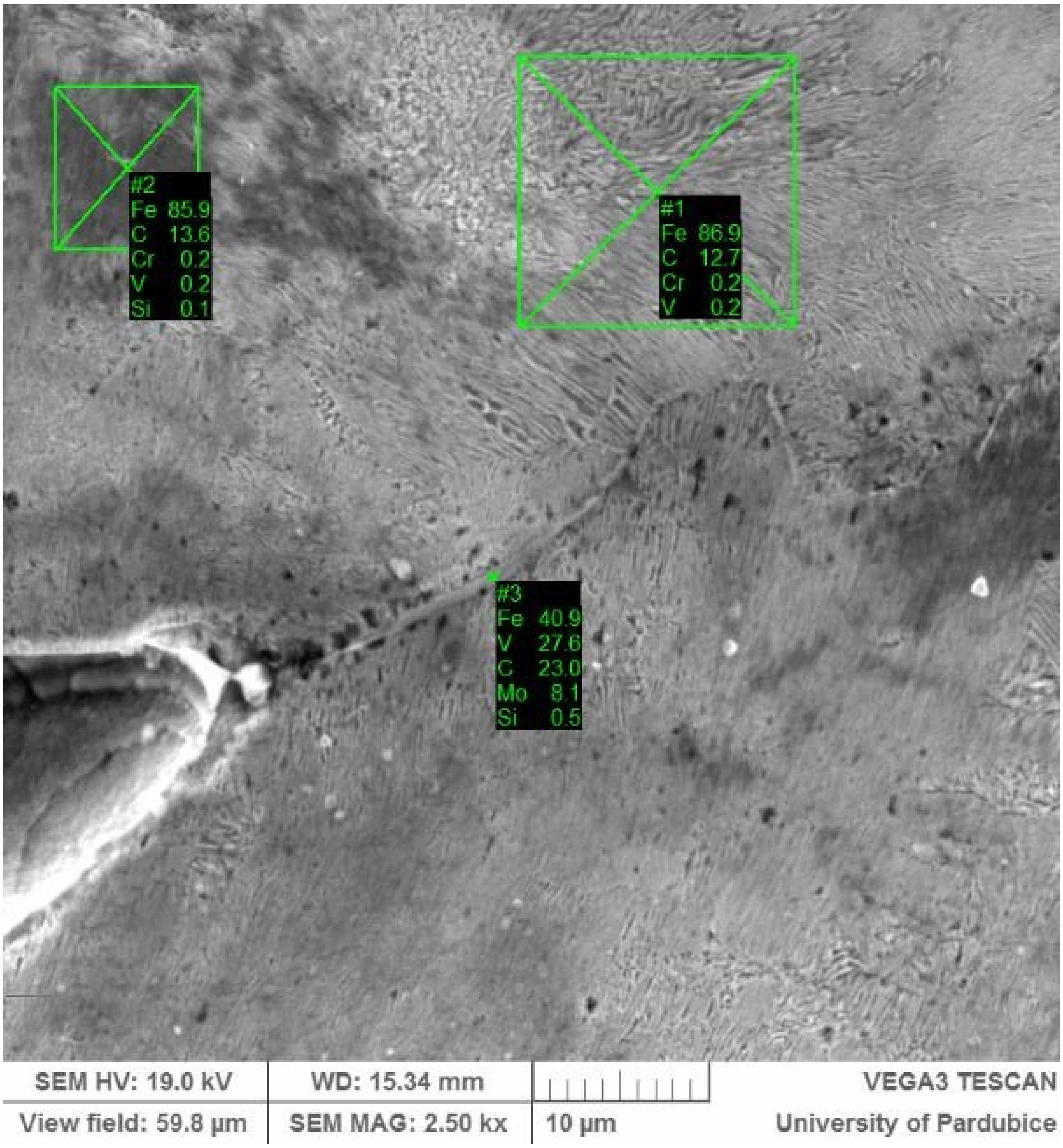

Fig. 6 EDX analysis near graphite grain (bottom left is cavity that was primarily filled by graphite)

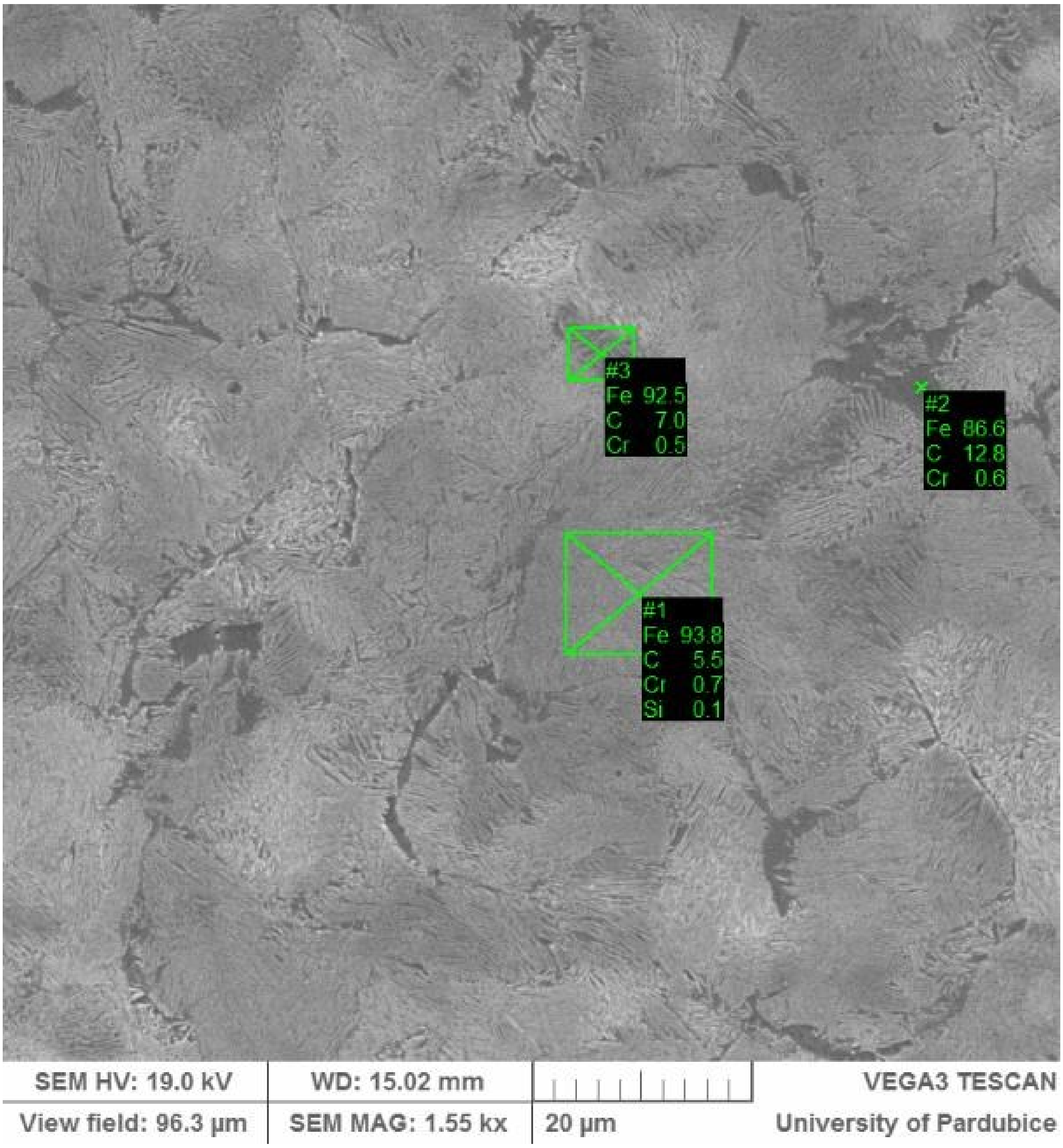

Fig. 7 EDX analysis of annealed sample

4 CONCLUSIONS

The results of the performed analyses show that the reduction (impossibility) of forgeability was due to the presence of carbon in the form of graphite. Carbon bonded in carbides does not have an adverse effect on crack formation during the correct forging process. However, if carbon is present in the form of graphite (basically vermicular shape), then the malleability of the ingot is practically excluded. In this case, the graphite generates natural microcracks. During forging, the stress is concentrated at graphite grain ends, and cracks may grow. The growth of cracks is then accelerated by the presence of a carbide network at the grain boundaries – the crack progresses along the carbides (hard, but very brittle).

The limitation or complete exclusion of the presence of graphite in the microstructure can be achieved by two ways:

i. a suitable cooling regime;
ii. heat treatment of the ingot prior to forging.

In the case ad i.), there is necessary slow cooling of the melt in the crucible for dissolving of graphite in the steel matrix. During slow cooling, carbon dissolves in the austenitic matrix, and during next cooling, the carbon form the coarser carbides.

In the case ad ii.) it is necessary that the present graphite dissolve by repeated austenitization. Austenitizie annealing allows the formation of coarser carbides, which do not influence the formation of cracks in the forged semi-finished product (Verhoeven and Pendray 1992; Perttula 2001).

Therefore, it can be assumed that, in the case of a low rate of solidification of the melt in the crucible and subsequent cooling of the ingot, it is possible to skip the austenitization of the starting ingot. The appropriate cooling rate depends on the specific composition of the melt. Therefore, if the melts are made from the same raw materials under the same temperature regime, the same microstructure forms. If the microstructure after correct cooling regime enables initial forging cycles without crack formation, it is possible to skip the initial austenitizing cycles. However, if the composition of the input raw materials is not precisely known and the cooling mode is not sufficiently tuned, it is desirable to apply the initial heat treatment before forging.

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