IMPACT STRENGTH AND FAILURE ANALYSIS OF WELDED DAMASCUS STEEL

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Resume

The aim of this work was the experimental research of damascus steel from point of view of the structural analyze, impact strength and failure analyzes. The damascus steel was produced by method of forged welding from STN 41 4260 spring steel and STN 41 9312 tool steel. The damascus steel consisted of both 84 and 168 layers. The impact strength was experimentally determined for original steels and damascus steels after heat treatment in dependence on temperature in the range from -60 to 160 °C. It has been found that the impact strength of experimental steels decreased with decreasing temperature behind with correlated change of damage mode. In the case of experimental tests performed at high temperature ductile fracture was revealed and with decreasing temperature proportion of cleavage facets increased. Only the STN 41 9312 steel did not show considerable difference in values of the impact strength with changing temperature.

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1. Introduction

Swords made from damascus steels have become renowned because of the uncontested retention of their cutting edge, the beauty of their characteristic surface patterns and fascinating legends concerning the way these materials were manufactured [1 – 4]. They were made from cakes originating in India (called ‘wootz’), the exact composition of which and the subsequent processing were crucial for the success and dealt with as top-secret. The recipe of blades of that type has been rediscovered several times, e.g. by Anoçoff [1] in the nineteenth century and by Sherby and Wadsworth [5], recently.

In the past 15 years, blade smiths in the United States have learned to produce beautiful knives of pattern-welded steels, and a market has developed for these knives [6]. There are some interesting metallurgical aspects to these modern blades, and this paper addresses two of them.

The process for making pattern-welded damascus steel blades consists of stacking alternating sheets of two different kinds of steels on top of each other and then forge welding them together. After this composite has been forged to roughly twice its original length, it is folded together and forged again, thereby doubling the number of layers in the composite. The folding and welding is continued until a large number of layers have been formed [7]. It is common to select a low-carbon and a high-carbon steel for the two kinds of steels. As the number of folds increases, the number of layers in the forged blade rises dramatically. After 3 folds, the 5 layers have increased to 40 layers, after 6 to 320, and after 9 to 2560 layers. The result of this process is an attractive damascus pattern on the surface of the blade that could be observed by the eye [8, 9].

Despite of repeated increase of popularity of damascus steels a number of key metallurgical and mechanical properties of the damascus blades are still not yet understood [4, 7, 10]. The aim of this study is to introduce the experimental results of the structural analyze, impact strength and failure analyzes in dependence on temperature performed in the welding damascus steel.

2. Material and experiments

Experimental material used in this work was damascus steel with 84 and 168 layers produced by forge welding. Damascus steel was produced from STN 41 4260 spring steel (54SiCr6) and STN 41 9312 tool steel (90MnCrV8). The selection of both steels for production of damascus steel was on the base of similar parameters of heat treatment (HT). Damascus steel was consequently heat treated (HT). HT included austenitization at 830 ± 5 °C for 40 min., oil quenching (temperature of oil was 60 °C), tempering for 90 min. at 220 ± 5 °C and air cooling.

The microstructure of damascus steel after HT observed by light microscopy is shown in Fig. 1. The structure consists of alternating layers of both steels i.e. STN 41 4260 and STN 41 9312. The chemical analyze revealed that wider layer (marked "A") corresponds to the STN 41 9312 steel and thinner layer (marked "B") consists of the STN 41 4260 steel. Both steels had nonpolyhedral microstructure with bainite and martensite after HT. In some cases layers of the same material were separated by thin layer (size of some tenths microns) marked with arrow in Fig. 1.

The detail of this layer observed by scan electron microscopy (SEM) is shown in Fig. 2. This is so-called "welding layer" arising during forge welding. The structure of this layer is very difficult identified but this layer had evidently ductile character on the fracture surfaces of test specimens after Charpy U-notch impact tests (Fig. 7). In the Fig. 2 there are clearly visible black particles with different size and shape. There are fragments of silica sand which is generally used for desoxidation of forging surface during forge welding.

Damascus steels with 84 and 168 layers had identical structure; steels only differed in number of steel layers. The damascus steel with 168 layers had these layers thinner in measured bulk and also more welding layer were observed than that with 84 layers.

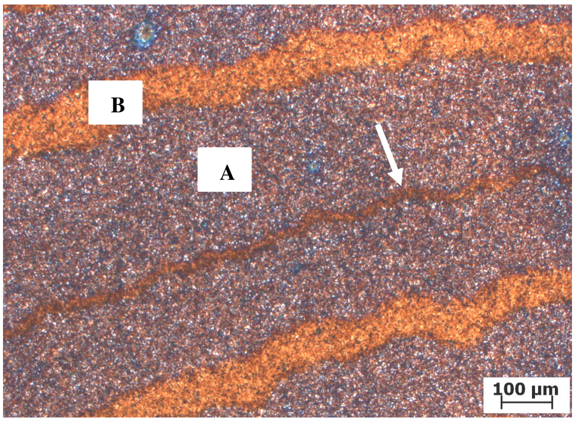

Fig. 1. Microstructure, damascus steel, light microscopy
(full colour version available online)

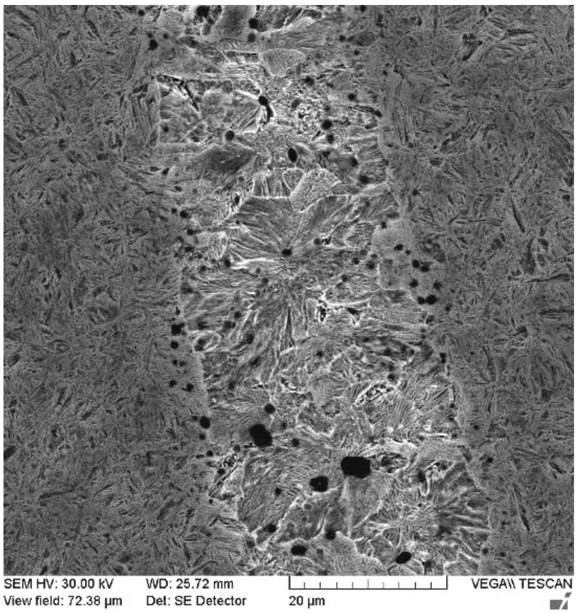

Fig. 2. Detail microstructure in the welding layer, SEM

Micro-hardness of particular layers of damascus steel was also determined. Micro-hardness tests were performed in micro-hardness tester Zwick Roell ZHμ with test loading 500 gf / 10 sec. Average value of micro-hardness determined from 6 measurements was 710 HV0.5 for layer from STN 41 4260 steel and 637 HV0.5 for layer from STN 41 9312 steel.

The Charpy U-notch impact test was performed in 150 J impact test machine according to EN 10045-1. The U-notch was produced in perpendicular direction to the layers running (Fig. 3) because the damascus steels had higher value of impact strength in perpendicular direction than that in longitudinal direction. The impact strength (KCU) was calculated according to the formula KU/S, when KU is impact energy and S is cross-sectional area at the notch. Particular values of impact strength measured at T = 20 °C was KCU = 4.7 J.cm^{-2} in perpendicular direction and KCU = 3.7 J.cm^{-2} in longitudinal direction. These values of impact strength correspond to damascus steel with 84 layers before HT. The impact tests were performed in temperature interval from -60 to 160 °C. In low-temperature impact tests the test specimens were cooled by liquid nitrogen and in high-temperature impact tests (160 °C) the test specimens were heated in furnace.

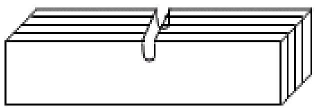

Fig. 3. Test specimen for U-notch Charpy impact test. The notch direction is perpendicular to the layers running

The microstructure was observed on mechanically polished and etched radial sections of test specimens by optical microscopy and scanning electron microscopy. The observed surface was etched by picric acid. Fracture surfaces of test specimens were observed by optical and scanning electron microscopy.

3. Results and discussion

The results, impact strength versus temperature (($KCU = f(T)$)), are shown in the Fig. 4. Each point is average value from two measurements. In the case of STN 41 9312 steel and damascus steel with 84 layers the temperature interval was from -60 °C to 160°C, in the case of STN 41 4260 steel from -80 °C to 160 °C let us say from -40 °C to 160 °C for damascus steel with 168 layers.

Very strong influence of temperature on the notch toughness was observed for the STN 41 4260 steel; at T = 160 °C the KCU = 48.8 J.cm^{-2} and at T = -80 °C only KCU = 17.5 J.cm^{-2}. The decrease is more than 50 %. For the STN 41 9312 steel the notch toughness was KCU = 4.9 J.cm^{-2} at T = 160 °C and KCU = 2.70 J.cm^{-2} at T = -60 °C. The decrease of KCU was very small and the steel in this temperature interval is practically temperature – independent. From obtained results it is clear, that the steel STN 41 260 has expressively higher notch toughness than the STN 41 9312 steel.

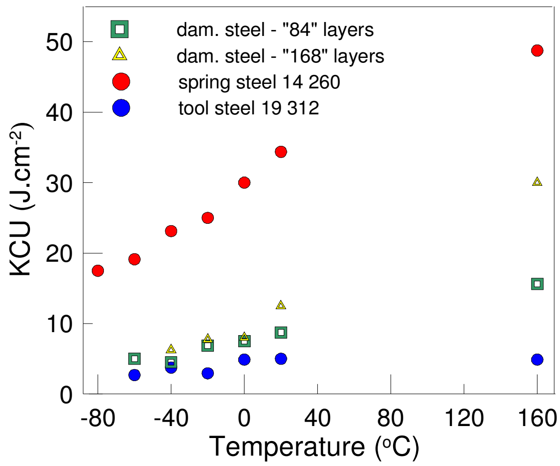

Fig. 4. Temperature influence on the notch toughness of tested steels
(full colour version available online)

Damascus steel with 84 layers had KCU = 15.6 J.cm^{-2} at T = 160 °C and KCU = 5.0 J.cm^{-2} at T = -60°C, damascus steel with 168 layers had KCU = 30.0 J.cm^{-2} at T = 160 °C and KCU = 6.3 J.cm^{-2} at the T = -40 °C. These results are approximately between the values obtained for steel STN 41 4260 and steel STN 41 9312. From the Fig. 4 it is clearly seen, that the notch toughness decreases for both damask steels with temperature decrease and the higher notch toughness is observed for the damascus steel with 168 layers. The notch toughness of the damascus steel with 168 layers is in the whole temperature interval higher than for the damascus steel with 84 layers. This difference rises with temperature increase.

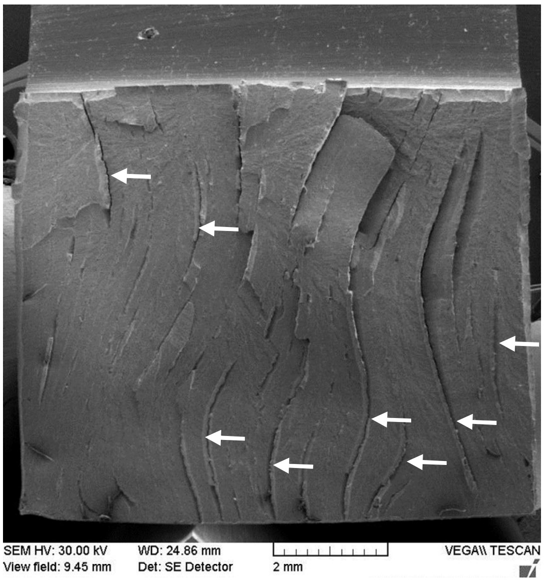

Fig. 5. Fracture surface, damascus steel with 84 layers, T = 160 °C, KCU = 15.6 J.cm^{-2}, SEM

In the Fig. 5 there is fracture surface of the specimen from damascus steel with 84 layers after Charpy U – notch impact test at T = 160 °C (KCU = 15.6 J.cm^{-2}). The obviously seen layers of both used steels with impressive decohesion on the layers interface including small secondary cracks on the specimen surface which propagate to the specimen inside were observed. From the macroscopic point of view the fracture surface has character of transcrystalline ductile fracture, see the Fig. 6. On the fracture surface there are visible the regions or zones with „more ductile" fracture character with expressive dimple morphology (marked with arrows, Fig. 6) than the rest of the fracture surface. The detail is shown in the Fig. 7. It is „welding layer" created by forge welding. The fine Si and Ca particles determined by EDX analysis were observed in the dimples. These particles are Si sand fragments used for deoxidation of body surface during heating before forge welding. In the process of the forge welding these particles penetrated into the bulk of the material.

The welding layers were found to be the places of multiple secondary microcrack initiation and propagation. Detail of the secondary crack initiation through the ductile part of weld revealed typical ductile tearing.

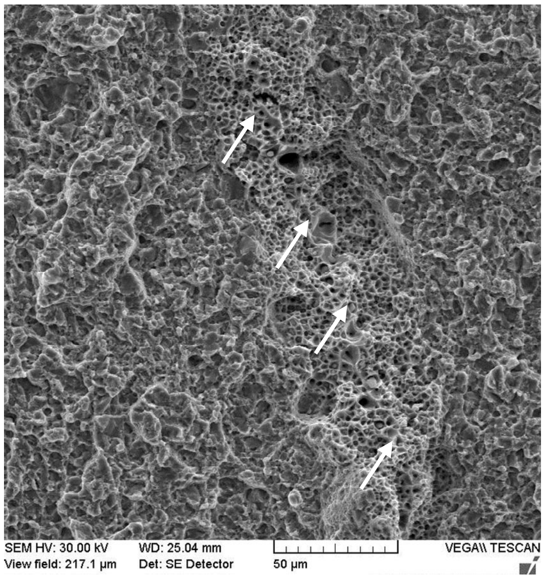

Fig. 6. Detail of the welding zone, transcrystalline ductile fracture, damascus steel with 84 layers, T = 160°C, KCU = 15.6 J.cm^{-2}, SEM

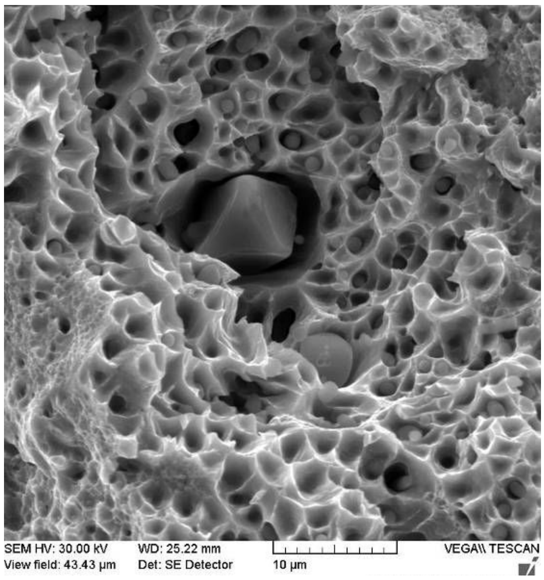

Fig. 7. Detail, welding layer, transcrystalline ductile fracture with expressive dimple morphology, damascus steel with 84 layers, T = 160°C, KCU = 15.6 J.cm^{-2}, SEM

As can be seen in Fig. 8, the edge of the secondary crack origin is a region with expressive dimple morphology.

The fracture surface of the specimen from damascus steel with 84 layers after Charpy U -notch impact test at T = -60 °C (KCU = 5.0 J.cm^{-2}) is shown in the Fig. 9.

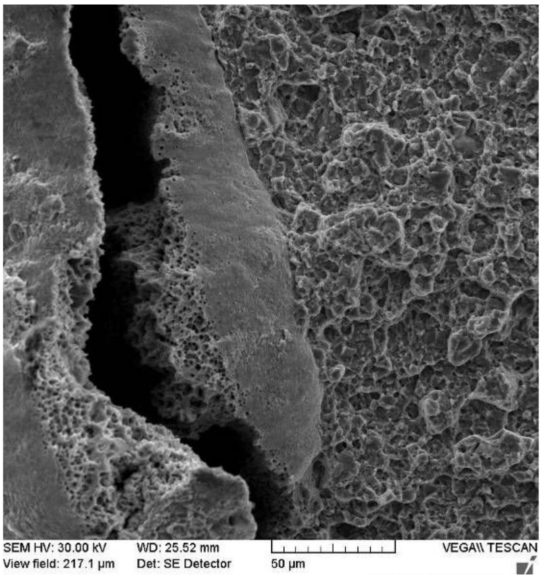

Fig. 8. Crack in the welding layer, damascus steel with 84 layers, T = 160°C, KCU = 15.6 J.cm^{-2}, SEM

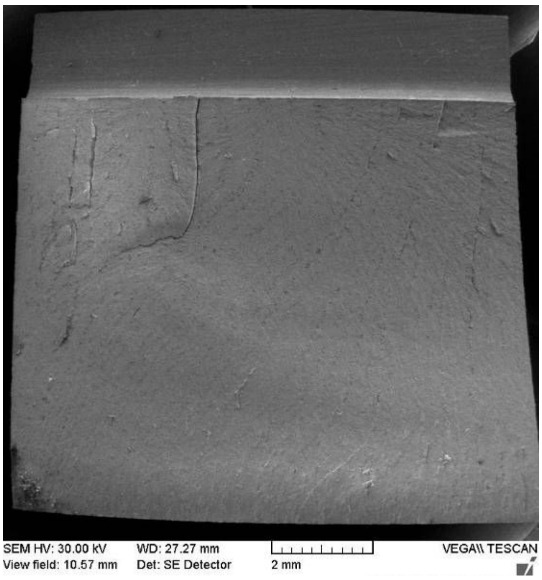

Fig. 9. Fracture surface, damascus steel with 84 layers, T = -60 °C, KCU = 5.0 J.cm^{-2}, SEM

From the macroscopic point of view the specimen fracture has transcrystalline character (also there are visible secondary cracks and „welding layers“) but the fracture surface morphology is essentially finer (this fact confirm the change of the notch toughness with decreasing temperature, KCU = 5.0 J.cm^{-2} versus KCU = 15.6 J.cm^{-2}).

At higher magnification a mixture of quasi cleavage and ductile fracture can be observed in Figs. 10 and 11.

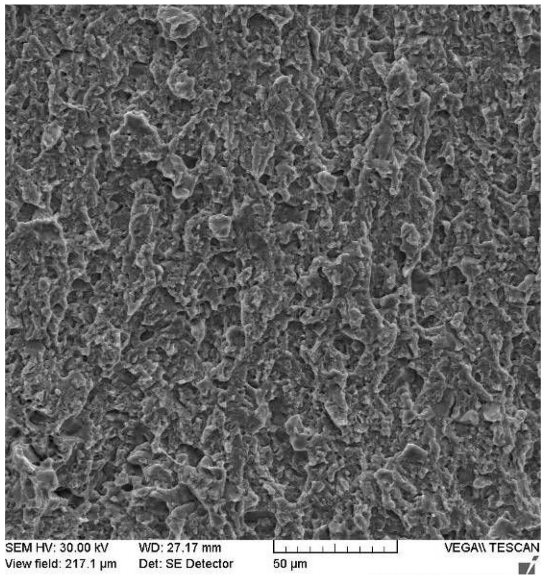

Fig. 10. Mixture of the quasi cleavage and ductile transcrystalline fracture, damascus steel with 84 layers, T = -60 °C, KCU = 5.0 J.cm^{-2}, SEM

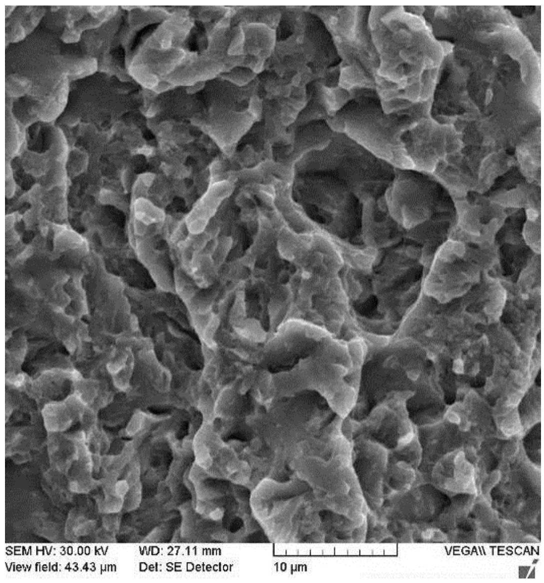

Fig. 11. Detail, transcrystalline quasi cleavage and ductile fracture, damascus steel with 84 layers, T = -60 °C, KCU = 5.0 J.cm^{-2}, SEM

A detailed fracture surface observation revealed also a small amount of intercrystalline facets located in some layers comprised of SNT 41 9312 steel, as documented in Figs. 12 and 13. The fine juts and dimples (see arrows in Fig. 13) which are probable the fragments of original martensite needles occur on these intercrystalline facets.

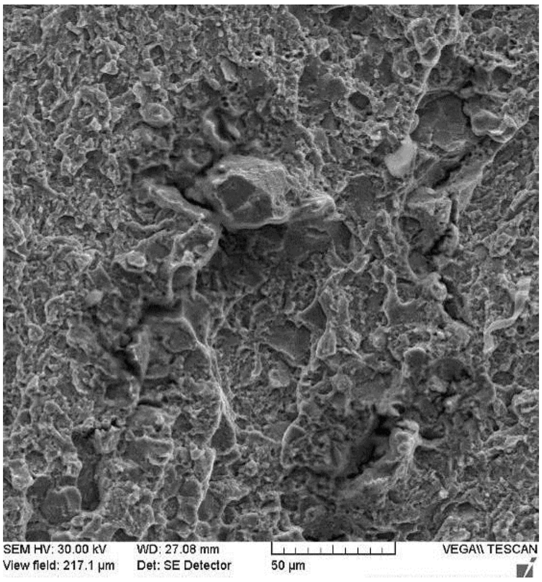

Fig.12. Detail, intercrystalline facets in layers of STN 41 9312 steel, damascus steel with 84 layers, T = -60 °C, KCU = 5.0 J.cm^{-2}, SEM

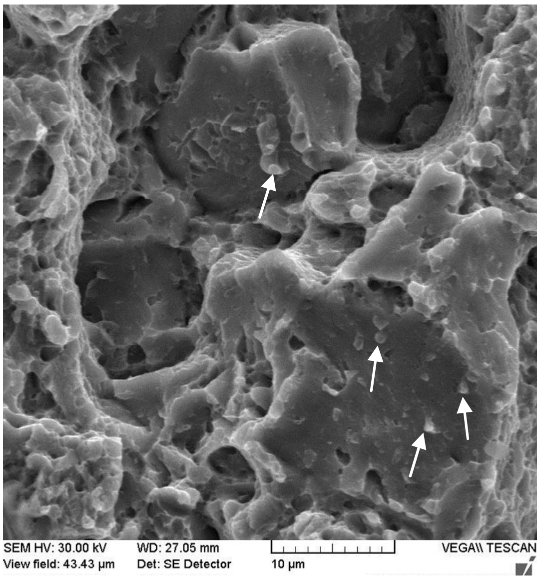

Fig.13. Detail, intercrystalline facets with rest of the martensite needles on the surface, damascus steel with 84 layers, T = -60 °C, KCU = 5.0 J.cm^{-2}, SEM

The fracture surface of damascus steel specimen with 168 layers after Charpy U – notch impact test at T = 160 °C (KCU = 30.0 J.cm^{-2}) is documented in the Fig. 14. From this figure is clear, that the damage character is analogous as at damascus steel with 84 layers tested at the same temperature. If we compare results (Fig. 5 and Fig. 14) we however must state that in the case of damascus steel with 168 layers is observed the higher degree of reforming.

This fact is probably caused by the higher amount of welding layers (with dimple morphology); it resulted in different value of the notch toughness – the KCU for damascus steel with 168 layers is about 50 % higher than that for damascus steel with 84 layers.

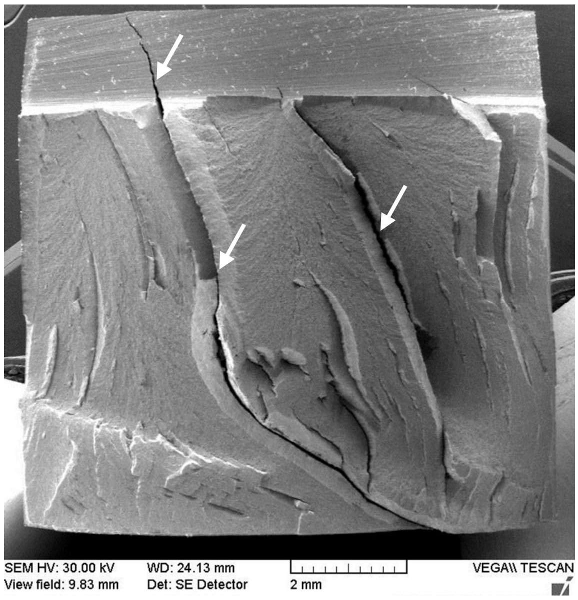

Fig. 14. Fracture surface, damascus steel with 168 layers, T = 160 °C, KCU = 30.0 J.cm^{-2}, SEM

4. Conclusions

The impact strength of damascus steel with 68 and 164 layers was examined in dependence on temperature. Damascus steels were produced by forge welding from STN 41 4260 spring steel and STN 41 9312 tool steel. It has been found that the impact strength of both damascus steels decrease with decreasing temperature. The impact strength of damascus steel with 164 layers is slightly higher then that with 68 layers in the temperature region from 20 to 160 °C. With decreasing temperature this difference became neglectable. It is related to the presence of welding layers with ductile character (damascus steel with 168 layers has essentially higher number of welding layers than that with 84 layers) that result in increasing impact strength of damascus steel with 168 layers at high temperature.

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