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The possibilities for reuse of steel scrap in order to obtain blades for knives

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ABSTRACT: The paper presents the characterization results of various types of steel component at the end of product life with the unknown chemical composition, mechanical properties and previously implemented thermo–mechanical treatment. This study was done aiming to examine the possibilities for reuse of some end–of–life agricultural and industrial steel products in order to obtain blades for knives in non–industrial conditions with appropriate and acceptable properties. Demanded shapes of the blades were obtained by applying various types of thermo–mechanical treatment. Chemical analysis of the investigated steel components was done using the energy–dispersive spectrometer. The microstructure was analyzed using optical and scanning electron microscopy. Hardness of analyzed steel scrap and obtained blades was measured using Rockwell C scale. The hardness values of the obtained blades (with optional quenching or not) indicate to a good selection of the steel end–of–life products for this purpose.

KEYWORDS: Blade for knife; Hardness; Microstructure; Steel scrap

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RESUMEN: *Posibilidades de reutilización de la chatarra de acero para la obtención de cuchillas para cortar*. El trabajo presenta los resultados de la caracterización de diversos tipos de aceros que han llegado al final de su ciclo de vida útil, y de los que se desconocía su composición química, propiedades mecánicas y tratamiento termomecánico aplicado previamente. El estudio se realizó con el objetivo de analizar las posibilidades de reutilización de algunos de estos materiales en aplicaciones agrícolas e industriales, obteniendo hojas de corte. Las formas exigidas a las hojas de corte se consiguieron aplicando diversos tipos de tratamientos termomecánicos. El análisis químico de la chatarra de acero de acero se realizó utilizando Energías Dispersivas de Rayos X. La microestructura se estudió utilizando Microscopía Óptica y Microscopía Electrónica de Barrido. La dureza de la chatarra de acero y de las cuchillas obtenidas se midió utilizando la escala Rockwell C. Los valores de dureza de las cuchillas obtenidas indican una buena selección de los productos finales de acero.

PALABRAS CLAVE: Chatarra de acero; Cuchilla; Dureza; Microestructura

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1. INTRODUCTION

Steels refer to alloys of iron with up to approximately 2 wt. % of carbon, very complex by structure, and widely used as engineering materials because of high iron content in the Earth's crust, very good features and low price (Zeng *et al.*, 2009; Kumar and Bhushan, 2015). They are characterized by a wide range of mechanical properties, due to corresponding microstructures, generated during phase transformations. The special significance of these alloys represents a possibility for a very precise properties modification during thermal treatment under controlled conditions (Goune *et al.*, 2015).

Any steel product has its own life cycle consisting of ore extraction, production, processing and finishing, product use, recycling or withdrawal at the end of its life cycle (Morfeldt *et al.*, 2015). All steel products have limited usable life cycle after which they lose their properties and become scrap that can be returned to the reproductive cycle (Bramfitt and Brenscoter, 2002).

Steel production can be divided into two techniques: primary and secondary production techniques which use iron ore or steel scrap, respectively, as a ferrous resource. Steel primary production requires high process energy and large amounts of coal, resulting in high CO_2 emissions (steel production is the major source of carbon dioxide emissions). Secondary production technique has a lower energy requirement (about one–third of the energy for primary production) and CO_2 emissions (less than one–quarter of the emissions during the primary production) (Oda *et al.*, 2013; Morfeldt *et al.*, 2015). Recycling and reuse of steel component influence to the decrease in CO_2 emissions, decrease in use of iron ore as ferrous resource, reduction of waste and used energy. Steel recycling includes melting of steel components, their recasting and reshaping into new products. Recycling is always more acceptable option wherever the primary production can be avoided. Steel reuse is a nondestructive method of reshaping steel components at the end of product life without melting. It can be very effective due to the avoiding of the high costs of energy required for recycling and conserving the microstructure and properties of the initial components (Cooper and Allwood, 2012).

During the exploitation and maintenance of agricultural and industrial machineries, certain amount of steel scrap is being produced. The maintenance of these machineries, among other things, includes consumable machinery components replacement at the end of their useful life. Therefore, agricultural and industrial steel scrap is of a great environmental and economic potential (Pacelli *et al.*, 2015). Reuse of steel components at the end of product life offer even greater advantages for the environment than recycling. Because of that, this article studies the possibilities for reuse of some end–of–life agricultural and industrial steel products in order to obtain blades for knives (hereinafter termed as blades) in non–industrial conditions with appropriate quality. The article presents the characterization results of four different steel scrap materials with various structural, chemical, mechanical properties and previously implemented thermo–mechanical treatment in order to study the possibility for blades production.

2. EXPERIMENTAL

For the experimental research, four different steel components were selected, which represent consumable parts (at the end of their life) of the agricultural and industrial machineries with the unknown chemical composition, previously implemented thermo–mechanical treatment and mechanical properties. The labels of the steel scrap (SS1, SS2, SS3 and SS4) and a pre–given purpose of these components at the end of their life are listed in Table 1.

Figure 1 shows the macrophotographs of the investigated steel components at end of products life. Experimental procedure included production of blades from the steel scrap by applying different thermo–mechanical treatment. End–of–life products marked with SS1 and SS4 were mechanically treated by cutting, grinding, and polishing in order to obtain the desired shape of the blades. The steel scrap marked as SS2 was heated in a forge fire at temperature 800 – 850 °C for scrap straightening and reshaping it to the straight product. Further shaping to the final blade was done in the same route as in samples SS1 and SS4. The steel scrap sample marked as SS3 was heated to 400 °C and further mechanically treated in the same way as samples SS1 and SS4. After processing and obtaining the desired blade shapes, the blades made from SS2 and SS3 were further annealed in a forge fire to red–heat and quenched in oil. Figure 2 shows the obtained knives as the final products made from the initial steel scrap defined by Table 1.

The samples of the initial steel scrap, obtained blades and blades made of SS2 and SS3 after oil quenching were subjected to hardness measurement using the WPM Leipzig Rockwell C hardness tester.

TABLE 1. Labels and pre–given purpose of the investigated steel scrap

Label	Pre–given purpose of steel scrap
SS1	Hacksaw
SS2	Steam turbine moving blade
SS3	Sword of a chainsaw
SS4	Rototiller hoe

FIGURE 1. Macrophotographs of the investigated steel scrap.

FIGURE 2. Knives as the final products made from different steel scrap: (a) SS1 – hacksaw; (b) SS2 – steam turbine moving blade; (c) SS3 – sword of a chainsaw; and (d) SS4 – rototiller hoe.

The hardness of the blades was measured at five points, depending on the distance from the cutting edge. The average value was taken for further analysis. The microstructure of the initial steel scrap was analyzed after standard procedure for microstructural preparation (grinding, polishing and etching with 2% solution of nital). Only the sample SS2 was etched using a solution prepared by mixing 15 ml HCl, 5 ml HNO_3, and 80 ml H_2O. Microstructure was analyzed using Carl Zeiss Jena Epityp 2 optical microscope (OM) and Tescan Vega 3LMU scanning electron microscope (SEM). Oxford Instruments X – Act energy–dispersive spectrometer (EDS) was used to determine the chemical composition of the initial steel scrap samples and the element distribution maps of the sample SS4.

3. RESULTS AND DISCUSSION

In Fig. 3, the results of SEM – EDS analysis for the steel scrap SS1 are given. Chemical analysis of the area in the Fig. 3a was given by EDS spectrum in Fig. 3b. It can be observed that the investigated material is a tool steel with tungsten, molybdenum, chromium and vanadium, corresponding to the high speed tool steel with grade HS 6–5–2 according to EN ISO 4957 (1999). The numerical designation in the steel grade refers to the content of W, Mo and V in wt.%, respectively. This steel has got improved cutting performance due to a high content of tungsten, and it is often used in the manufacturing of a numerous cutting tools (Da Silva Rocha *et al.*, 1999), hacksaws among others. Results of EDS analysis of white phase (carbides) at points 1, 2 and 3 in Fig. 3c were given in Fig. 3d. It is shown that this phase was the complex carbide phase with W, Mo, Fe, V and Cr.

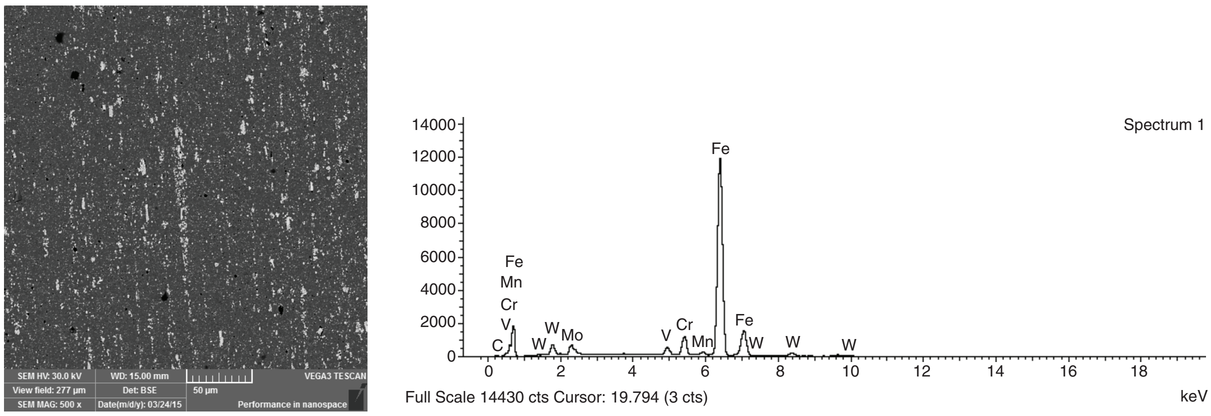
Figure 4 shows the results of SEM – EDS analysis for the steel scrap SS2. Chemical analysis of the area in Fig. 4a is given by EDS spectrum in Fig. 4b. It shows that the investigated material is a chrome–alloyed steel with medium carbon content with grade X20Cr13, according to EN 10250 standard (EN 10250–2, 2000). This was expected, because the steel scrap SS2 was the end–of–life steam turbine moving blade. Due to its high chrome content, this steel has got good corrosion resistance, plasticity and high shock resistance (Xi *et al.*, 2008).

SEM microstructure of the steel scrap SS3 is shown in Fig. 5a. Fig. 5b shows the EDS spectrum of the area in the microphotograph in Fig. 5a. The EDS analysis shows that the investigated end–of–life product SS3 is a spring steel of grade 38Si7, according to EN 10089 standard (EN 10089, 2002). Its chemical composition contains 0.4 – 0.45 wt.% C, 1.8 – 1.9 wt.% Si, 0.8 – 1 wt.% Mn.

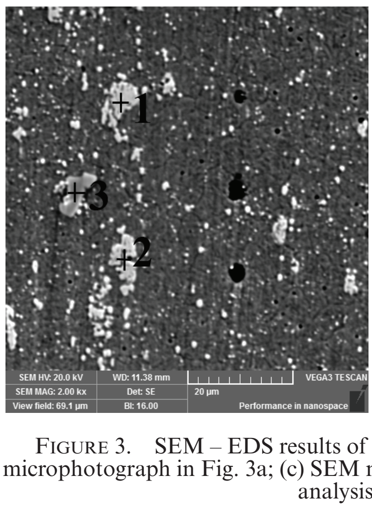
Figure 6a represents the SEM microstructure of the steel scrap SS4. In Fig. 6b, the EDS spectrum of the area in the microphotograph in Fig. 6a is shown. Having into account the chemical composition,

(a)

(b)



(c)



(d)

Point	Elements' content, at . %					
	C	Ti	V	Cr	Fe	Mo	W
1	34.27		12.10	6.40	15.67	19.76	11.81
2	26.93		9.86	4.81	30.00	16.86	11.54
3	42.77	1.53	16.31	3.00	28.72	4.29	3.38

FIGURE 3. SEM – EDS results of the steel scrap SS1: (a) SEM microphotograph; (b) EDS spectrum of the area in the microphotograph in Fig. 3a; (c) SEM microphotograph with higher concentration of the white phase; and (d) Results of EDS analysis of white phase (carbides) at points 1, 2 and 3 in Fig. 3c.

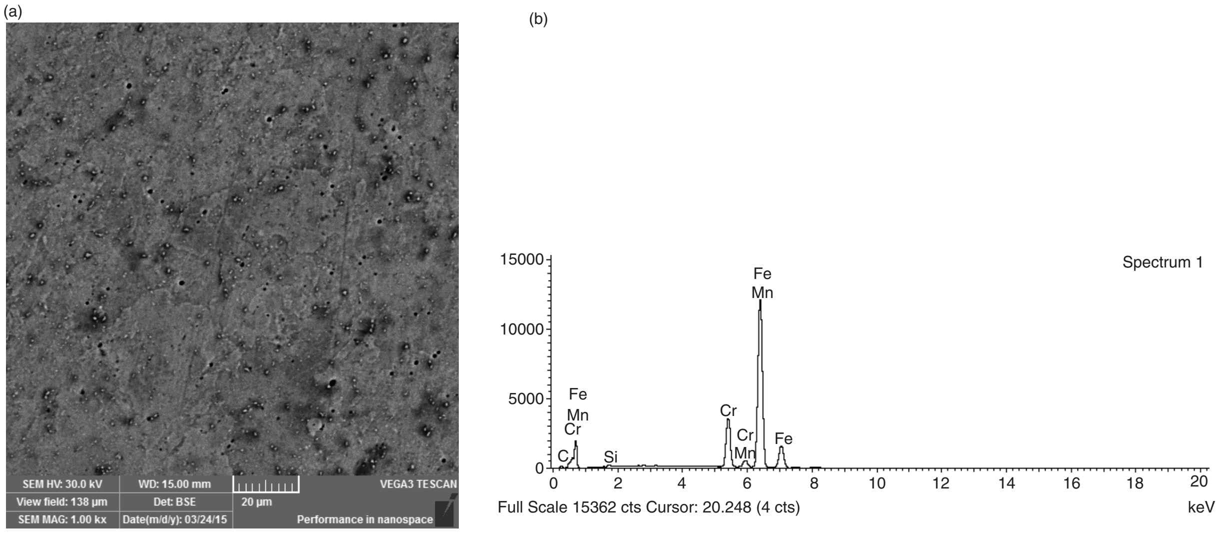


FIGURE 4. SEM – EDS results of the steel scrap SS2: (a) SEM microphotograph; and (b) EDS spectrum of the area in the microphotograph in Fig. 4a.

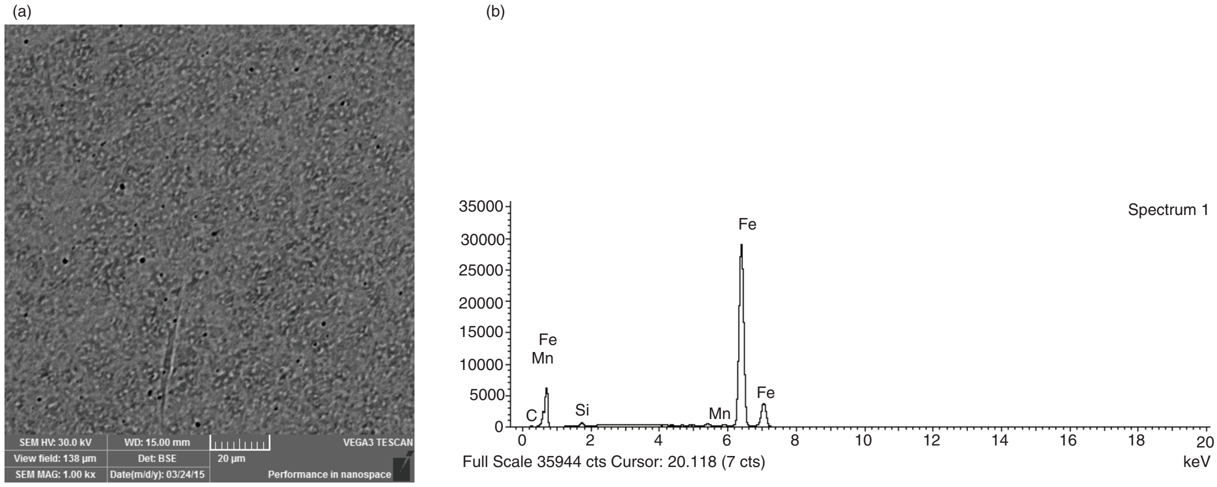


FIGURE 5. SEM – EDS results of the steel scrap SS3: (a) SEM microphotograph; and (b) EDS spectrum of the area in the microphotograph in Fig. 5a.

it is concluded that the material used in the production of this component is a low–alloy steel of grade 59Si7 according to ISO 683 – 14 standard (ISO 683–14, 2004). Its chemical composition contains 0.58 – 0.61 wt.% C, 1.8 – 2 wt.% Si, 0.8 – 0.9 wt.% Mn, 0.2 – 0.37 wt.% Cr. The distribution maps of elements Fe, Cr, Mn, Si and C in the scanning region in Fig. 6a are shown in Fig. 7. From the distribution maps, the even distribution of all elements on the investigated region can be observed.

The optical microphotographs of the initial steel scrap are given in Fig. 8. SEM and optical microphotographs of the steel scrap SS1, given in Figs. 3a and 8a, respectively, show a fine–grained structure with directed distribution of complex carbides, which has been achieved by the specific methods of production and thermo–mechanical treatment in order to product a hacksaw. A 2% nital solution was used for etching steel scrap SS1 because it is the most commonly used etchant for tool steels. It is a suitable etchant for showing structure of carbides (Small *et al.*, 2008). The microstructure is consisted of tempered martensitic structure and un–dissolved eutectic carbide particles (Leskovsek and Ule, 1998). In this kind of steel, directed carbide particles of the following types can occur: M_6C, MC, M_2C and M_7C_3, indicating previous deformation (Dziedzic, 2007). The chemical composition of the carbides done by EDS (Figs. 3c and 3d) shows that the carbides are mainly of the type M_2C or M_7C_3. Additionally, some primary carbides of the type MC are visible.

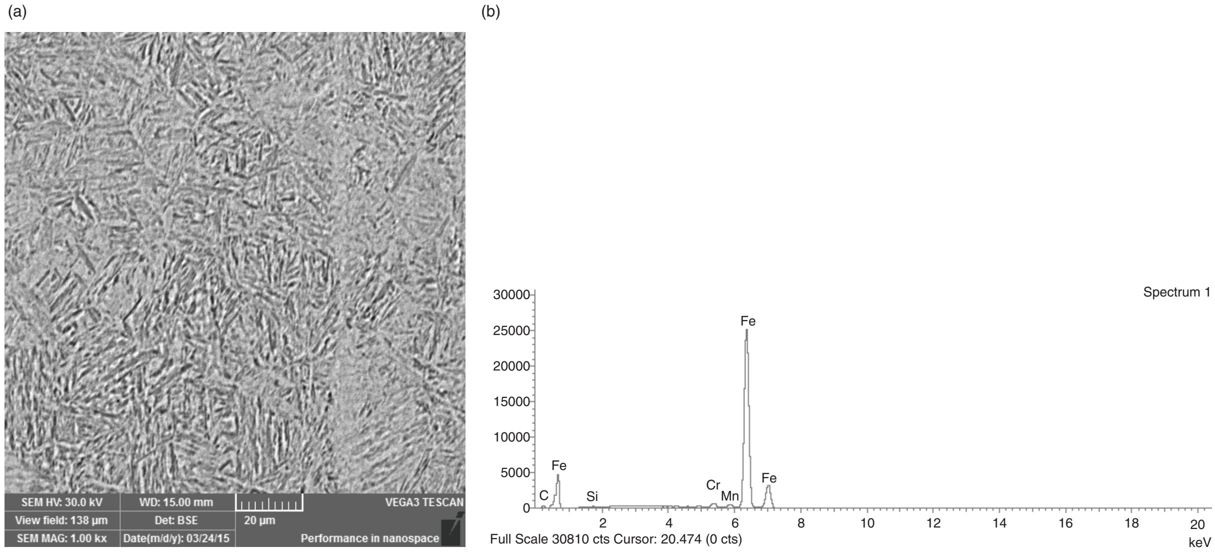


FIGURE 6. SEM – EDS results of the steel scrap SS4: (a) SEM microphotograph; and (b) EDS spectrum of the area in the microphotograph in Fig. 6a.

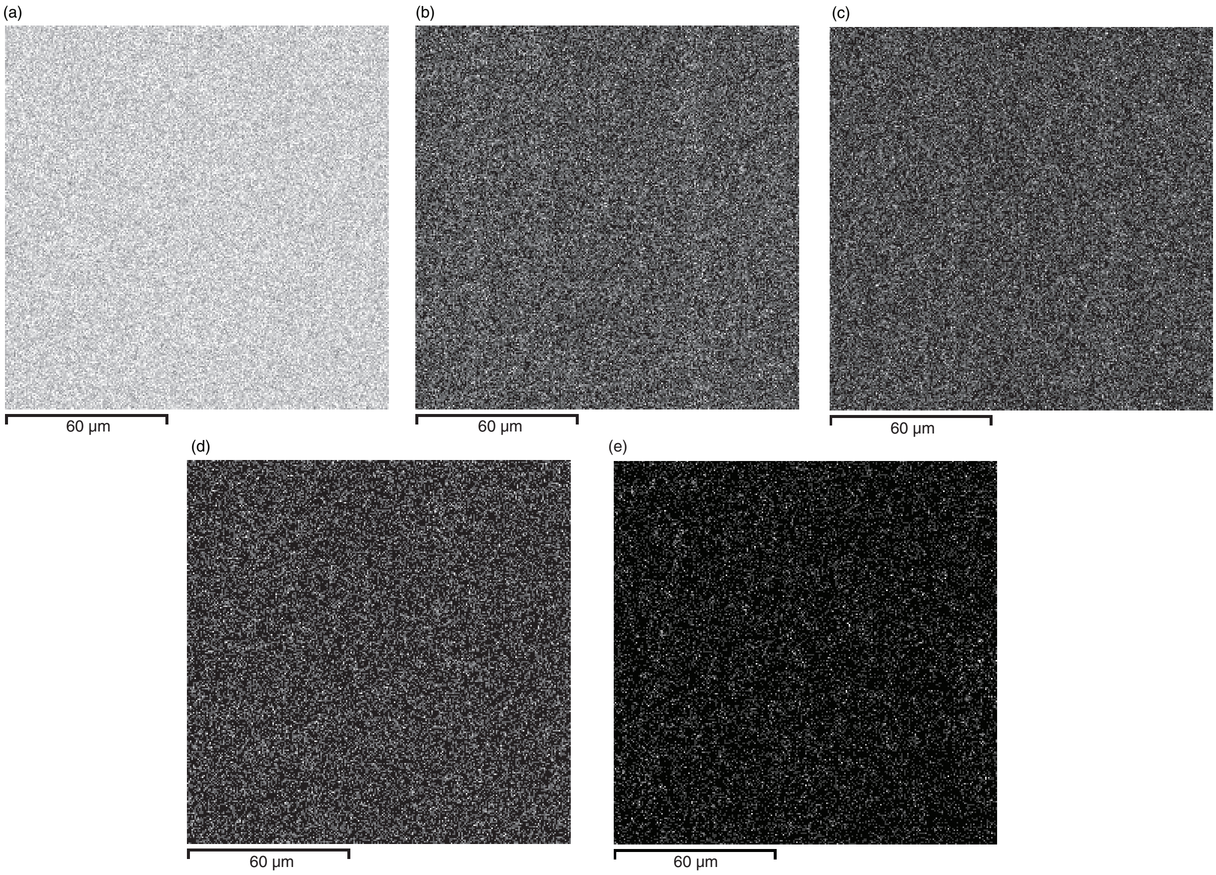


FIGURE 7. Distribution map of elements in the scanning region in Fig. 6a: (a) Fe; (b) Cr; (c) Mn; (d) Si; and (e) C.

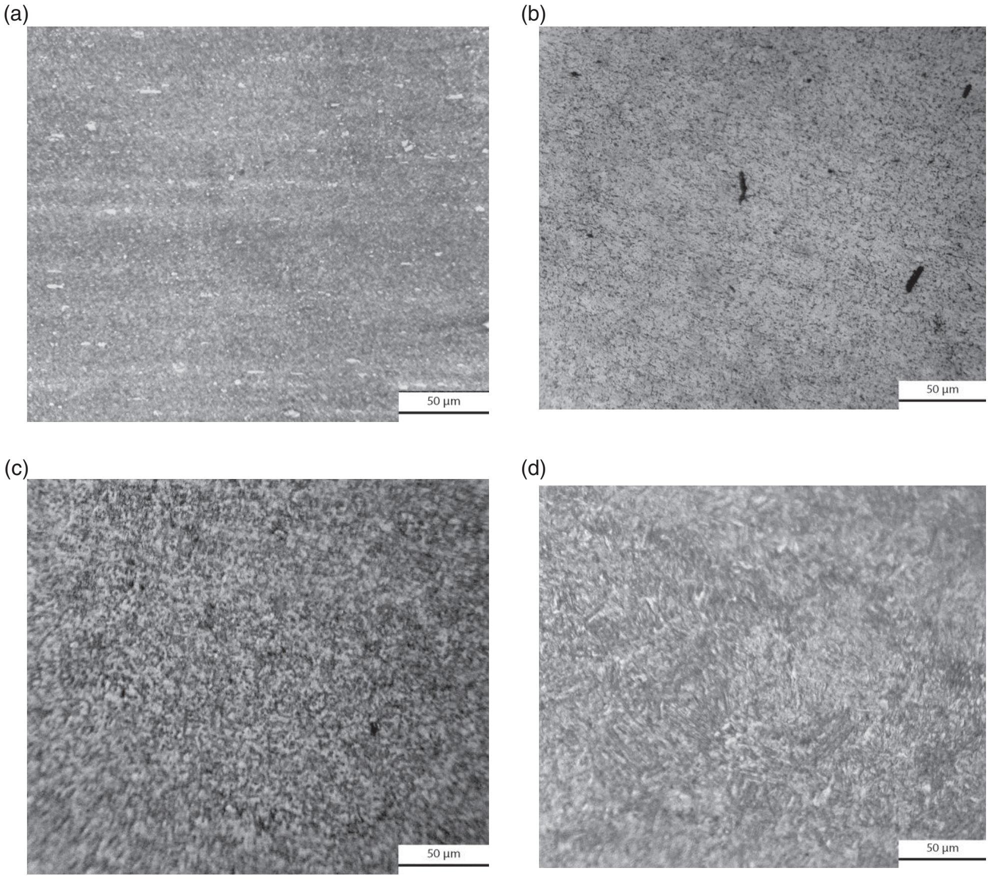


FIGURE 8. Optical microphotographs of the starting steel scrap: (a) SS1; (b) SS2; (c) SS3; and (d) SS4.

The microstructure of the steel scrap SS2 is shown in Figs. 4a and 8b. For steel of this composition, homogene martensitic structure is expected to be formed after air cooling from austenitiziting temperature (Mann, 2013; Gupta, 2015). Depending on a heat treatment conditions, various phases can occur in the microstructure. The most appropriate procedure for heat treatment of this steel involves quenching from the temperature of about 1000 °C in oil or in the air, following tempering at 700 °C. The resulting microstructure which consists of uniformly distributed globular carbides in the ferrite matrix can be expected in the structure (Masters, 1989), which corresponds to the microstructures shown in Figs. 4a and 8b. Gooch (Gooch, 1982) identified these precipitates as $M_{23}C_6$ carbides.

SEM and optical microphotographs of the steel scrap SS3 are shown in Figs. 5a and 8c. The microstructure of the steel scrap SS4 is shown in Figs. 6a and 8d. According to their composition, both steel scrap, SS3 and SS4, belong to spring steel of type Si2Mn, which have a good combination of high strength, good ductility and high shock–resistance in the quenched condition as well as in the tempered condition. These types of steel belong to the hypo–eutectoid class (Qinghua *et al.*, 2003). It is known that in the steel which contains 2% silicon, a large amount of austenite is retained during cooling to room temperature. With increasing the amount of retained austenite, both ductility and strength increase. Silicon is an inhibitor of carbide precipitation and ferrite stabilizer (Matsumura *et al.*, 1987; Chen *et al.*, 1989). The microstructure of steel with silicon may contain retained austenite, ferrite and martensite or bainite, depending on heat treatment (Chen *et al.*, 1989). Microstructural constituents vary with annealing temperature and time. For a shorter annealing time during tempering, a martensite–ferrite structure is a predominant, with a small fraction of bainite and retained austenite, similar to the microstructures shown in the Figs. 6a and 8d. Longer holding time at annealing temperature results in removal of retained austenite and formation of ferrite–bainite structure (Matsumura *et al.*, 1987).

Figure 9 shows the hardness values of the initial scrap (first column), obtained blades (second column) and hardness values of the blades made of end–of–life products SS2 and SS3 after oil quenching (third column).

The hardness value of the scrap SS1 is 63 HRC, while the blade made of this steel scrap only by

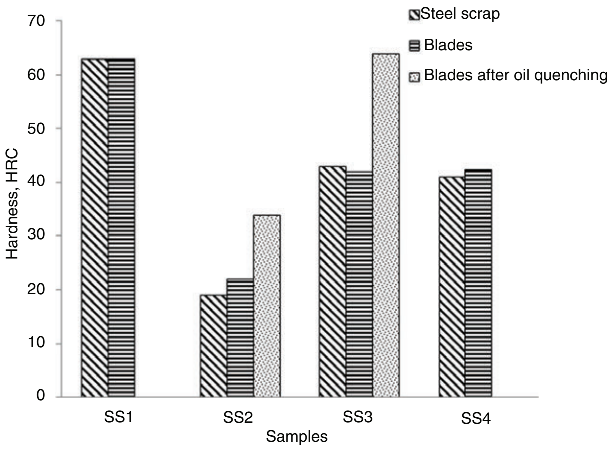


FIGURE 9. Hardness values (HRC) of steel scrap SS1, SS2, SS3, and SS4; blades made of SS1, SS2, SS3, and SS4; and blades made of SS3 and SS4 after oil quenching.

using mechanical treatment (cutting, grinding and polishing) shows the same hardness value.

The steel scrap SS2 has a significantly lower value of hardness of about 19 HRC. The blade made of this type of steel scrap has a slightly higher hardness value of about 22 HRC, as a result of the applied thermo–mechanical treatment in order to shape scrap to final blade. This blade was further quenched from the austenitization temperature, which additionally increased its hardness value to 34 HRC.

Steel scrap SS3 has a hardness value of about 43 HRC. The performed thermo–mechanical treatment has not affected the hardness value. However, quenching of the obtained blade in oil caused a significant increase in hardness, up to 64 HRC.

Steel scrap SS4 has a similar hardness value (about 41 HRC) as steel scrap SS3. Applied mechanical treatment, which was aimed to form steel scrap into blade, had no effect on the hardness value.

4. CONCLUSIONES

Various end–of–life agricultural and industrial steel products are very valuable for reusing. Therefore, this paper studies the possibilities of reusing of some end–of–life agricultural and industrial steel products in order to obtain blades. The characterization of chosen steel scrap showed that the initial materials were very different in structural, chemical and mechanical properties. The blades obtained in non–industrial conditions, using four different steel scrap as initial materials, had a wide range of hardness values (from 22 HRC to 64 HRC) depending on the type of steel scrap and implemented thermo–mechanical treatment. The blade made from steel scrap SS1 showed the highest value of hardness, which was achieved without further quenching, only by mechanical shaping of the starting steel scrap. The same hardness value was obtained on the blade made of steel scrap SS3 after thermo–mechanical treatment followed by quenching. The hardness values of blades made of steel scrap SS2 and SS4 were lower, 34 HRC and 43 HRC, respectively. By reusing steel scrap for different purposes various benefits can be achieved (reduction costs, saving energy, less raw material usage and decrease in waste disposal costs), which is in accordance to the basic requirements of the European Union waste management strategy (Vehlow *et al.,* 2007).

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