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EXPERIMENTAL ASSESSMENT OF CHANGES IN STRUCTURAL STEEL COMPOSITION BY PROGRESSIVE TECHNOLOGY CUTTING

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Abstract:
The submitted paper deals with the issue of change in structure, hardness and thermally affected zone of the samples of a toothed wheel part produced by technology of cutting by plasma, laser and water jet. The cutting process by laser and plasma technology causes intensive thermal affection of material and change in structure and microhardness in the cutting area referred to as thermally affected zone. The paper describes three material cutting technologies of the toothed wheel part. The experimental part contains description of experimental sample preparation, its hardness measurement and examination of structure along with further evaluation through graphs and photo documentation of structures.

***Key words:** laser, plasma, water jet, cutting, structure, microhardness*

INTRODUCTION

Material cutting still represents significant and inevitable production operation which applies a series of methods with inherent area of optimal utilization. Each method disposes of a drawback hindering its universal use and thus further and new procedures and technologies occur. Progressive methods applied in material machining do not use standard cutting tool. They are utilized in the sphere of machining of materials with high strength, hardness and wear resistance. The methods are based on chemical, physical and electrical phenomena. These methods include material cutting by laser, plasma and water jet. Such technologies make effective use of cutting material, minimize waste in the cutting process, considerably shorten the length of the material cutting process and, on the whole, make the machining process cleaner technology.

PROGRESSIVE CUTTING TECHNOLOGIES

Laser Cutting

Through invention of laser the science and technology gained a new source of light with properties not possible to be reached in the past. It rests in accumulation of energy in atoms which gets released at once in the form of rather intensive beam. The core of laser can be represented by solid mass, by gas or by fluid being referred to as an active environment. Laser beam cutting of materials (Figure 1) uses high concentration of laser beam energy (as standard the value exceeds 10^7 W/cm^2). When the laser beam impinges upon opaque material located in the lens focus, the light energy changes to the thermal one and causes local heating to the temperature of 10^4°C. Each material vaporizes at this temperature. The molten metal residues are removed from the cutting edge by working gas which flows through cutting nozzle coaxially with the laser beam axis [10].

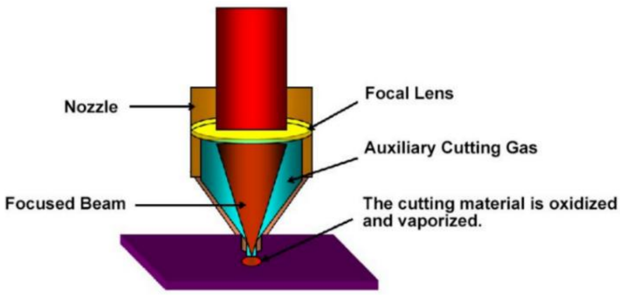

Fig. 1 Principle of laser cutting
Source: [24].

Plasma Cutting

Common feature of welding and cutting plasma technologies rests in utilization of plasma as of a source of thermal and of dynamic action influencing the material. Plasma is electrically conductive condition of gas exceptionally occurring on the Earth. Based on the observations of natural phenomena such as lightning and aurora, the existence of plasma as of the fourth mass state dates back to the period before our era. The term of “plasma“ refers to denotation of high number of particles (atoms, ion molecules, electrons) without solid mutual bond out of which at least a few dispose of electric charge and to a high degree the total of both positive and negative electric charges is zero [23].

In plasma cutting, a workpiece material is gradually burned off and vaporized. From the physical point of view, the ionized gas consists of ions, electrons, and neutral particles. Due to high temperatures in plasma arc, plasma is used in thermal cutting of metal material. The principle of plasma cutting (Figure 2) is based on driving the neutral gas (Ar, Ar+H_2, He, N_2, CO_2, air) at high speed through the nozzle to an electric arc which is usually generated by high-voltage spark and thus the gas is ionized, the electric circuit is enclosed with the metal material surface, and the plasma arc of high temperature is generated (from 10000°C up to 20000°C) which melts down the metal intended for cutting and gas floating at high speed. At the same time, it removes the molten metal from the cutting space [12].

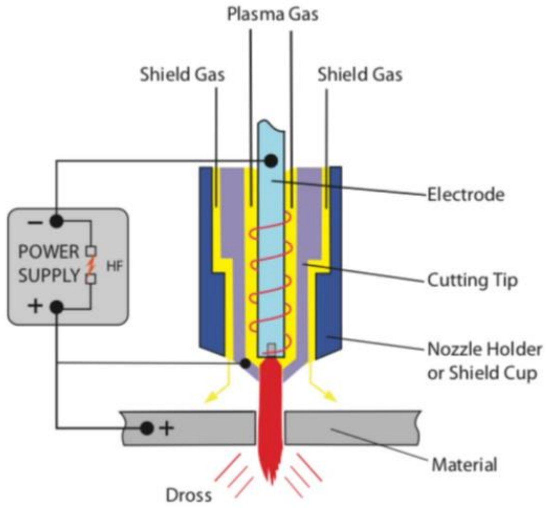

Fig. 2 Principle of plasma cutting
Source: [25].

Water Jet Cutting

Water Jet Machining – all over the world referred to as WJM – is applicable in any of the manufacturing and industrial spheres with the lowest possible impact on environment. The technology is currently known as cold manufacturing operation with minimum force effects acting on the machining material. At the same time, the technology is characterized by precise cutting and by producing little waste. Contrary to preceding beam technologies, the thermally influenced zone is absent. The technology is dust free and ecological [8].

Based on the medium applied, two methods can be distinguished as follows:

– WJM – Water Jet Machining.
– AWJ – Abrasive Water Jet Machining [10].

Water jet machining rests in material removal by means of mechanical water jet impact. Water pressure ranges from 300 up to 400 MPa. Water jet speed behind the nozzle with diameter, for instance, of 1 mm, reaches from 600 up to 900 m·s^{-1}. Vacuum, not representing any risk for working area, is formed in the environment. Porous substances, composites, thermoplastics with thickness ranging from 200 up to 250 mm are cut with water [3]. Metal material is cut with abrasive water jet (abrasive water jet machining). Abrasive is delivered through a side feeder and is dragged by water. Figure 3 shows the water jet cutting machine. Cutting along the side areas results in surface roughness of Ra = 10 up to 20 μm, according to cutting material thickness. Diameter of abrasive nozzle ranges from 1.2 up to 2.5 mm. Nozzle wear is rather intensive and thus results in increase of cutting costs [1].

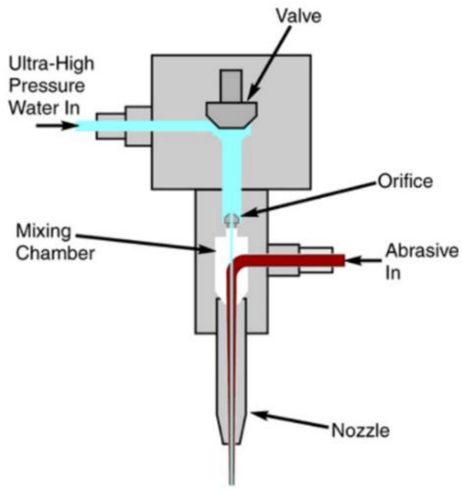

Fig. 3 Principle of water jet cutting
Source: [8].

PREPARATION OF EXPERIMENTAL SAMPLES

The design of samples was realized with regards to desired progressive technologies to be used in their manufacturing. The sample shown in Figure 4 was produced from a tooth part of the toothed wheel with a tip circle diameter of Ø 228. Samples with material thickness of 15 mm were produced by all technologies. Structural steel S355 J2G3 was used in the experiment [16].

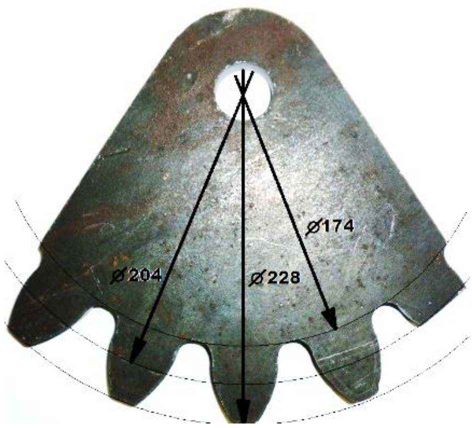

Fig. 4 The toothed wheel section intended for taking the sample of a tooth part

Laser cut sample – manufactured by a laser of the TRUMATIC type, TruLaser 3050 with performance of 5 kW produced by the TRUMPF company (Table 1). The machine is characterized by high-performance laser and by a concept of linear drives offering extremely high dynamics and providing productivity increase at lower cost [13]. The toothed wheel sample (see Figure 5) was manufactured within 59 seconds at cutting speed of 22.53 mm·s^{-1} and with overall cutting length of 1329.69 mm.

Table 1
Technical parameters of TruLaser 3050 Classic

	TruLaser 3050
Dimensions (L x W x H)	11250 x 4600 x 2400 mm
Axes working range (X – Y – Z)	3000 x 1500 x 115 mm
Maximum thickness of cutting material	steel: 25 mm; stainless steel: 20 mm; aluminium: 12 mm
Axis parallel speed	200 m/min.
Simultaneous speed (X a Y)	300 m/min.
Maximum cutting speed	170 m/min.
Precision	0.1 mm
Process gas	oxygen, nitrogen, helium
Compressed air consumption	57 m^3/hour
Laser performance	5 kW

Plasma cut sample – manufactured by a CNC – plasma cutting machine Arrow 2.000 x 6.000 with plasma source Hi Focus 160i produced by the company of KJEBERG (Table 2). The equipment allows plasma marking and cutting with high-quality cut within the material thickness ranging from 0.5 up to 35 mm. If a high-quality cut is not required, the depth can reach even 50 mm in dependence on material [17]. The plasma cut sample of toothed wheel part (see Figure 5) was manufactured within 44.3 seconds at cutting speed of 30 mm·s^{-1} and with overall cutting length of 1329.69 mm.

Table 2
Technical parameters of HiFocus 160i KJELBERG

	HiFocus 160i
Power source	Soft-Switch-Inverter
Cutting current – Cutting	10-160 A (100% d.c.)
Cutting current – Marking	4-25 A (100% d.c.)
Connecting load	33 kVA
Dimensions (L x W x H)	960 x 540 x 1050 mm
Cutting current	max; 160 A
Cooling	Circulating direct cooling
Plasma gases	Oxygen, Air, Argon, Nitrogen and mixtures
Swirl gases	Oxygen, Air, Nitrogen and mixtures

Water jet cut sample – manufactured by a water jet cutting machine VT with a pump SL II50 HP (Table 3). It represents precise and highly productive CNC machine – i.e., cutting machine designed for cutting of diverse material types by a pure water jet or abrasive material can cut all types of metal (stainless steel, aluminium, titanium, doped nickel alloys), construction material (stone, marble, tiles, ...), glass (safety glass, laminated glass), food, paper as well as other special material such as leather, rubber, plastic materials, foam materials with thickness of up to 250 mm in dependence on material type [2]. The sample of toothed wheel part (see Figure 5) was manufactured within 1380 seconds at cutting speed of 0.96 mm·s^{-1} and with overall cutting length of 1329.69 mm.

Table 3
***Technical parameters* of machine SL II50 HP**

	WJ – SL II50HP
Input power	35 kW
Water consumption	3.1 l/min
Abrasive consumption	100-300 g/min (according to cutting thickness)
Output water speed from nozzle	900 m/s
Cutting pressure	200-350 MPa
Cutting gap thickness	1.1-1.2 mm
Service life of nozzle	100; max. 250 hours
Intrapolation	linear
Distance between nozzle and material	3-4 mm
Bearing capacity of a pulley block	2.5 t
Maximum dimensions of cutting material	2 x 3 m

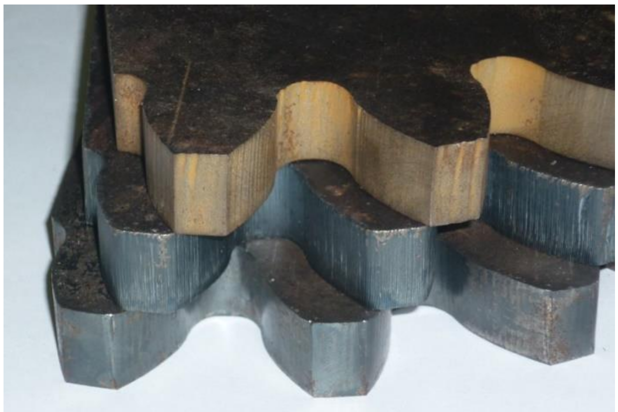

Fig. 5 Samples of toothing manufactured by cutting in ascending order – AWJ, laser, plasma

EXPERIMENTAL DETERMINATION OF STRUCTURE CHANGE AFTER MATERIAL CUTTING

Preparation of samples for metallographic analysis includes standard procedures and following operations:

- Material cutting (sampling – Figure 6)
- Casting-up/forcing-in of sample
- Grinding
- Polishing
- Etching

The sampling (part of a tooth of toothed wheel) was carried out so that deformation or thermal affection of material is avoided. Material can be affected in considerable depth under the prepared surface and neither further grinding nor polishing can eliminate such affection. Undesired sample heating during sampling can result in changes in material microstructure (phase transformations, precipitations, diffusion might be triggered). Band saw Ergonomic 275.230 DG produced by the company of BOMAR was used in sampling [4].

Fig. 6 Experimental sample after cutting

Casting-up/Forcing-in of Samples

The main aim of casting-up or of forcing-in of samples is to improve sample manipulation (see Fig. 7) in case of further steps of its preparation. Other reason for casting-up and forcing-in of samples is to protect sample edges against grinding and polishing. Casting-up of metallographic samples is carried out with the use of special resins and the process is realized either under cold or hot conditions. Selection of casting-up agent depends on prepared material. The aim is to provide adequate abrasive properties of samples and of casting-up agent. Casting-up agent should be chemically stable in case of use of diverse polishing or etching solutions [7].

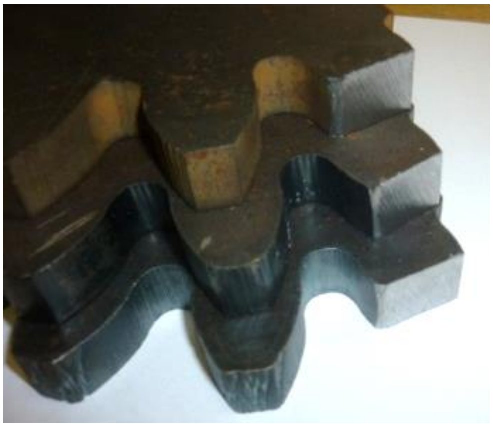

Fig. 7 All samples after band saw cutting

Casting-up of experimental samples was realized with two-component methyl methacrylate pourable resin DENTACRYL intended for technical application (Fig. 8). Material is resistant to acids, alkalis, and salt. It has very good electro-insulation properties, i.e., it is a very good thermal insulator with the unique mechanical strength and is also known as filling material on which heavy demands are placed as to ultimate tensile strength, compressive strength and bending strength. According to the type of used fluid, it gets solidified spontaneously and merges into substance similar to organic glass. At room temperature of approximately 25°C dissolved DENTACRYL can be poured into moulds and when solidified, it can be shaped as desired [22].

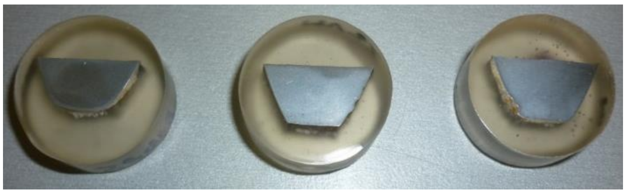

Fig. 8 Experimental samples cast-up in DENTACRYLE

Grinding of Samples

Traditional procedure of metallographic sample grinding is wet grinding. Its advantage rests in direct cooling effect of the water jet (with regards to the fact that heat is generated on the machined surface during grinding) and the water jet washes away the particles of ground material and releases abrasives. Water grinding process utilizes the waterproof sand paper with abrasive particles such as SiC, Al_2O_3, Al_2O_3-Fe_3O_4 of diverse grain size marked with a number ranging from 60 up to 4000 which indicates quantity of grains per 1 cm^2. With increasing number, the size of abrasive grains becomes smaller [7].

In grinding process, the sample is in a fixed position on a rotating grinding wheel and with the change of the sand paper with higher number the sample is turned at angle of 45-90°. Each sand paper change should be followed by a visual sample test with a microscope. The procedure is repeated unless the grooves occur on the sample surface [21].

Experimental samples were ground with sand paper with grain size of 280, 400, 600, 1200, 2500 and with grinding and polishing machines of the MHT-HRAZDIL KOMPAKT 1031 type.

Polishing of Samples

Smooth and mirror glaze surface is achieved by means of cloth polishing wheels and abrasives. The wheel rotates, an operator rotates the sample in counter direction to the wheel rotation or the sample is alternately rotated around its axis. Diamond paste or suitable emulsions of metal oxides (Al_2O_3, MgO, SiO_2, Cr_2O_3, Fe_2O_3) are used for polishing which are applied onto a polishing cloth. Mechanical polishing based on water emulsions of Al_2O_3 is followed by additional polishing based on water emulsion of Al_2O_3 with grain size of approximately 1 µm [6].

Experimental samples were polished with the use of artificial diamond filament with additional suspension of Al_2O_3 with grain size of 5µm and with grinding and polishing machines of the MTH-HRAZDIL KOMPAKT 1031 type.

Etching of Samples

Etching of samples serves to make the structure visible. Borderlines of grains are made visible by etching agent which forms etch pits. In examination with the microscope, the impinging light creates shades on the grain borderlines which can be observed [19].

The experimental samples were etched in 3% solution of HNO_3 referred to as Nital and remaining 97% was ethyl alcohol.

Study and Testing of Produced Samples

The experimental samples were tested in a laboratory. The samples were subjected to a microhardness test with a hardness tester of the CV-400 DAT type and material structure change was studied with a light microscope NEOPHOT 21.

Sample Microhardness Testing

The experimental samples were subjected to a microhardness test the result of which was expressed in the Vickers or Knoop hardness scale. The hardness tester of the CV-400 DAT type was used. To calculate the sample microhardness, the hardness tester applies the method of indenting the diamond pyramid indenter with specific force and consequently, when the sample is released, the indentation diagonals are measured [20].

Hardness value is assessed according to the equation as follows:

- Vickers
  $HV = 1854.4\ F/d^2$
  with HV – Vickers hardness value [kg/mm^2]
  F – applied load [g]
  d – indentation diagonal [µm]
- Knoop
  $HK = 14\ 229\ F/d^2$
  with HK – Knoop hardness value [kg/mm^2]
  F – applied load [g]
  d – longer length of indentation diagonal [µm]

To calculate the experimental samples, the Vickers hardness formula was used. The samples were loaded with 200 g within the period of 10 seconds [19]. All three samples were subjected to 15 measurements which were realized in graded distances from the cutting point towards the core (thermally unaffected sample part) [11]. The results of measurements are presented in the following tables (Table 4-6). The further section contains the graphs.

Table 4

Values measured after laser cutting

Number of measurements	1	2	3	4	5	6	7	8
Distance [mm]	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75
Hardness [HV]	405.2	259.2	219.8	219.8	197.5	224.7	221.6	217.9
Number of measurements	9	10	11	12	13	14	15	
Distance [mm]	0.85	0.95	1.05	1.15	1.25	1.35	1.45	
Hardness [HV]	201.9	194.6	208.2	210.7	204.4	198.2	190.4	

Table 5

Values measured after plasma cutting

Number of measurements	1	2	3	4	5	6	7	8
Distance [mm]	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75
Hardness [HV]	302.7	255.1	221.7	237.7	223.3	209.7	210.2	203.5
Number of measurements	9	10	11	12	13	14	15	
Distance [mm]	0.85	0.95	1.05	1.15	1.25	1.35	1.45	
Hardness [HV]	205.6	212.1	209.0	201.3	203.2	198.3	200.3	

Table 6

Values measured after AWJ cutting

Number of measurements	1	2	3	4	5	6	7	8
Distance [mm]	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75
Hardness [HV]	169.9	181.1	192.3	187.2	173.8	176.2	171.5	185.2
Number of measurements	9	10	11	12	13	14	15	
Distance [mm]	0.85	0.95	1.05	1.15	1.25	1.35	1.45	
Hardness [HV]	179.5	171.8	170.2	170.8	166.8	169.7	169.7	

Examination of Sample Structure

Examination of microstructure was carried out with the light microscope NEOPHOT 21. NEOPHOT 21 is an inverted metallograph microscope imaging raw material and standard materials such as metals, nonmetals, composites, etc. The results gained through observation of samples are presented and described in the further part of the paper [15].

EVALUATION OF EXPERIMENTAL TESTS

Evaluation of Microstructure

Plasma cut sample

Figure 9 shows thermally affected zone which is specific for the change of microstructure (i tis more obvious in Figure 10) and reaches the distance of approximately 250 µm from the point of cutting by progressive technology. The original structure of steel S355 J2G3 is Ferrite + Pearlite. The bainite microstructure was formed in the point of cutting by progressive technology [5].

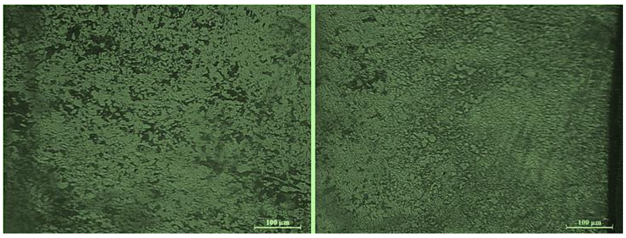

Figure on the left: thermally unaffected part (original structure)
Figure on the right: thermally affected part (in the cutting point)
Fig. 9 Microstructure of steel S355 J2G3 after plasma cutting 100x

Fig. 10 Microstructure of steel S355 J2G3 after plasma cutting 600x

Laser cut sample

Figure 11, on the right, shows thermally affected zone which is specific for the change of microstructure (it is more obvious in Figure 12) and reaches the distance of approximately 300 µm from the point of cutting by progressive technology. The original structure of steel S355 J2G3 is Ferrite + Pearlite [09]. Alike in case of plasma cutting, the bainite microstructure was formed in the point of cutting by progressive technology.

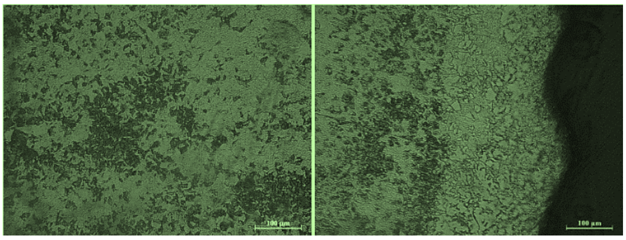

Figure on the left: thermally unaffected part (original structure)
Figure on the right: thermally affected part (in the cutting point)
Fig. 11 Microstructure of steel 11 523 after laser cutting 100x

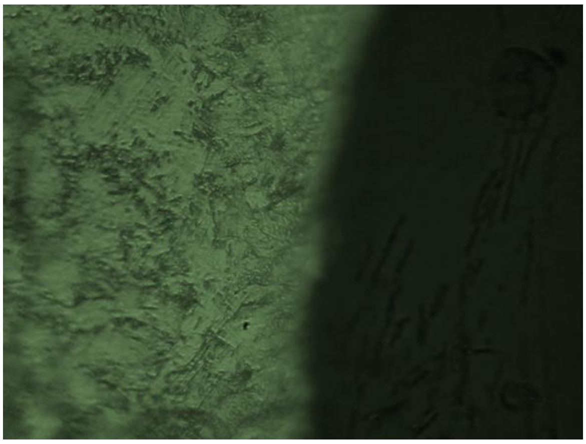

Fig. 12 Microstructure of steel S355 J2G3 after laser cutting 600x

AWJ cut sample

Figure 13, on the right, shows that thermally affected zone specific for microstructure change is not formed (it is more obvious in Figure 14). It emphasizes the fact that water jet cutting is a cold technology not inducing thermally affected zone or material structure change in the cutting point [14]. The original structure of steel S355 J2G3 is Ferite + Pearlite. In the point of cutting by progressive method it remains unchanged.

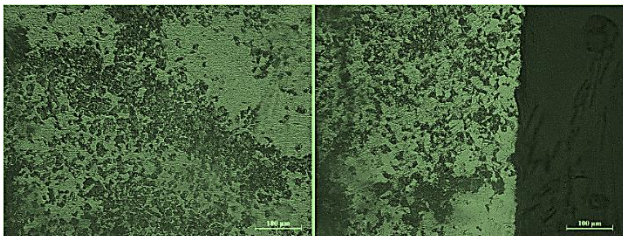

Figure on the left: thermally unaffected part (original structure)
Figure on the right: thermally unaffected part (in the cutting point)
Fig. 13 Microstructure of steel S355 J2G3 after AWJ cutting 100x

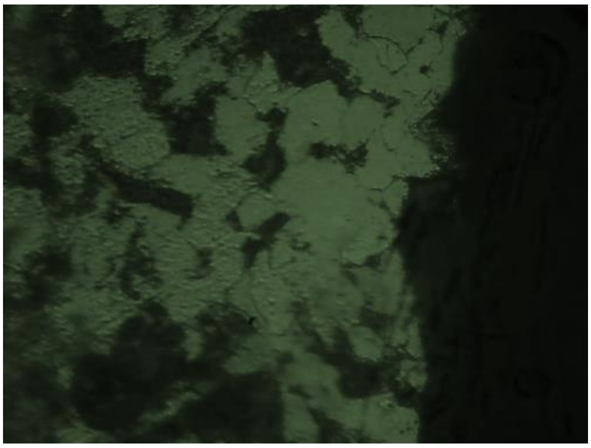

Fig. 14 Microstructure of steel S355 J2G3 after AWJ cutting 600x

Evaluation of Microhardness

Evaluation was realized by means of graphs in EXCEL based on values measured by the hardness tester of the CV-400 DAT type.

Microhardness in plasma cutting reached the value of 300 HV in the cutting area. It began to reach original hardness, which was approximately 200 HV (see Figure 15), in the distance of 0.25 mm from the cutting area. The distance can be referred to as the thermally affected zone.

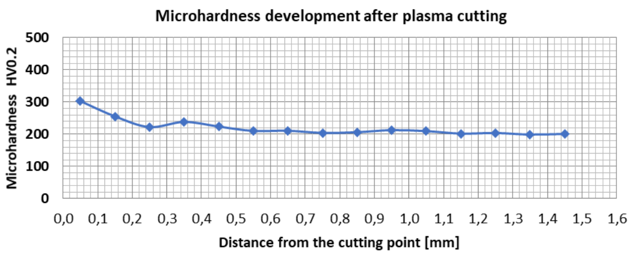

Fig. 15 Development of microhardness after plasma cutting

Microhardness in laser cutting reached the value of 400 HV in the cutting area. It began to reach original hardness, which was approximately 200 HV (see Figure 16), in the distance of 0.40 mm from the cutting area. The distance can be referred to as the thermally affected zone.

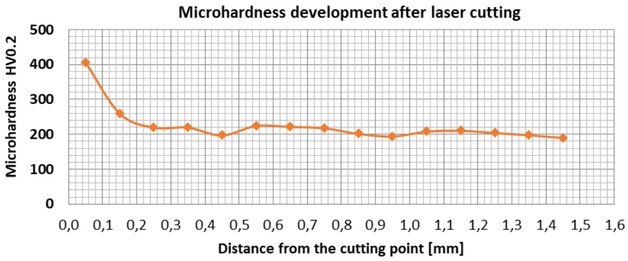

Fig. 16 Development of microhardness after laser cutting

In water jet cutting (AWJ) the microhardness remained unchanged as the technology ranks among the cold ones in case of which thermally affected area is not created (see Figure 17). The hardness value in the graph is slightly lower contrary to the original hardness value, however, it can be caused by imprecise measurement.

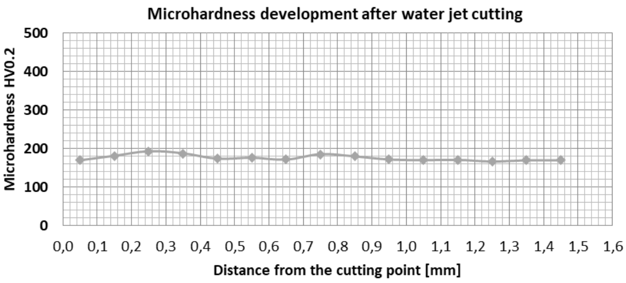

Fig. 17 Development of microhardness after water jet cutting (AWJ)

The graph (Figure 18) compares all three technologies from the point of view of their influence on material microhardness. Development of functions measured and plotted in the graph shows that laser cutting affected material most as to microhardness [22].

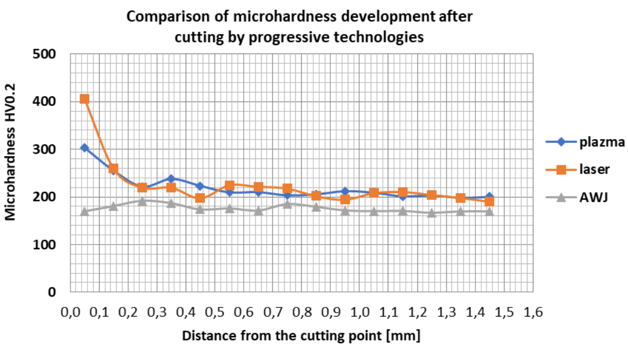

Fig. 18 Comparison of microhardness development after cutting by progressive technologies

CONCLUSION

The submitted paper deals with the issue of thermal affection of the material part, specifically of the change in structure and hardness after cutting by laser, plasma, and water jet. The TRUMPF machine was used in laser cutting, the ARROW machine was used in plasma cutting, and water jet cutting was carried out with the application of the VP pump SL II50 HP [18]. Each technology produced part of the toothed wheel and consequently, the structure and the hardness change was experimentally assessed with the sample taken. The samples were prepared for a metallographic research in which they were subjected to a few stages ranging from casting-up to polishing and etching. Furthermore, the results of hardness and structure of samples were gained. Hardness measurement results were evaluated in the form of tables and graphs. The structure results were evaluated according to photo documentation. Based on the measured results, it can be concluded that the hardness change in case of laser cutting of structural steel S355 J2G3 was largely influenced by 400 HV, in plasma cutting it was by 300 HV and in water jet cutting the material hardness reached the range of its original values. It can be stated that based on the expectation the water jet cutting did not cause hardness change as the technology ranks among the cold ones. In laser and plasma cutting, the structure in the proximity of cutting point changed to microstructure of bainite despite the fact that original structure was Ferrite + Pearlite. In water jet cutting technology the cutting point structure remained unchanged due to low or absent thermal affection of material.

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