

Dependence of the Abrasive Water Jet Cutting Quality on Steel Properties

Závislost kvality řezání abrazivním vodním paprskem na vlastnostech oceli

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The article is aimed at machining of steels by abrasive water jets. The relations between the water jet parameters, material properties, and qualitative indicators are still being investigated by research teams dealing with water jets. This article tries to add few findings reflecting the linkage between strength and hardness of steels and the declination angle values measured at striations on the walls of the kerfs. As observed, the higher percentage of alloying chemical elements can substantially influence resistivity of material to an abrasive water jet. The low alloyed steels, however, evince the linear relation between strength and/or hardness and the declination angle of striations.

***Key words**: Abrasive water jet (AWJ); Cutting; Steel; Strength; Hardness; Declination angle*

Článek je zaměřen na obrábění ocelí abrazivním vodním paprskem. Výzkum souvislostí mezi parametry vodního paprsku, vlastnostmi materiálu a kvalitativními indikátory je stále v centru pozornosti výzkumných týmů věnujících se vodním paprskům. Tento příspěvek doplňuje několik poznatků týkajících se vazby mezi pevností a tvrdostí ocelí a hodnotami deklinačního úhlu měřenými pro striace na stěnách drážek. Vlastnosti ocelí, zejména pevnost a tvrdost, jsou dobrými indikátory kvality řezání abrazivním vodním paprskem, pokud množství legujících přísad nepřekračuje několik procent. Jak bylo pozorováno, vyšší obsah legujících přísad může podstatně ovlivnit odpor materiálu proti abrazivnímu vodnímu paprsku. Závislost mezi pevností a/nebo tvrdostí materiálu a deklinačním úhlem stanoveným na striacích stěn řezné drážky se u vysokolegovaných ocelí může proti závislosti zjištěné u nízkolegovaných ocelí posouvat do vyšších či nižších hodnot. Nízkolegované oceli však vykazují téměř lineární závislost mezi pevností a/nebo tvrdostí a deklinačním úhlem striací. U vysokolegovaných ocelí nemusí mít závislost lineární průběh, zejména pokud bude materiál podroben dalšímu tepelnému zpracování – kalení, popouštění apod.

***Klíčová slova**: abrazivní vodní paprsek (AWJ); řezání; ocel; pevnost; tvrdost; deklinační úhel*

Abrasive water jets (AWJ) are used for machining of a broad range of materials when the suitable parameters are set for respective processes. Almost all machining processes using the rigid tools in past were tested using the AWJ: turning [1, 2], milling [3], grinding [4] and polishing [5]. The most frequent application remains, however, the cutting of shapes from plate-type materials, mainly metals, rocks, glass and plastics. This method can achieve very good standards of quality by selecting lower traverse speeds. The process could be more economical with higher traverse speeds. However, it is necessary to know the amount of product distortion to keep it in acceptable tolerances. Modern machines have compensation techniques applied automatically without the input of operators. This investigation is aimed at searching for relations between properties of materials, namely steels, and some qualitative indicators, e.g. declination angle.

The quality of cutting, with a particular focus on the role of material parameters and AWJ parameters, has been studied by Hashish [6], Zeng and Kim [7], Kovacevic and Yong [8, 9], Paul et al. [10, 11], and by many others [12 – 15]. A specific approach to the explanation of several phenomena occurring during AWJ material cutting was presented by Hlaváč [16]. His model, based on the laws of conservation of energy and momentum together with the geometric analysis [17] of phenomena caused by AWJ on economical cut walls, can be used for quality determination. The curve of the jet trajectory passing through material has been described also by other authors [13 – 15]. Their conclusions can be combined with other findings, like those presented in [17]. The most often studied characteristics left by the AWJ process on the material surface are the so-called striations (see e.g. [12, 13, 17]). Surface roughness can be also used as an important phenomenon [18 – 20], but it is not so significant. Therefore, the declination angle and studies examining its dependence on the cutting head traverse speed are used for studies of the relation between the AWJ parameters and material properties [17, 21]. The two most important material properties, strength, and hardness, were used for this study. Relations with toughness were tested, but they did not bring clear results.

The aim of this investigation is studying the dependence between the declination angle produced by AWJ on the cut walls and steel hardness or steel strength. The used

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methods and processes were presented in past namely in [17, 21, 22]. The testing cuts were performed on steel samples with identical thickness, 10 mm, on the CNC device with identical AWJ parameters. The results of the presented comparison can be used for further improvement of all steel machining devices applying AWJ.

Experimental layout

The experiments were performed in the Laboratories of Liquid Jet at the VŠB – Technical University of Ostrava. The AWJ parameters selected to match typical ones used in practice are summarized in Tab. 1.

Tab. 1 Values of pre-set parameters of cutting
Tab. 1 Hodnoty přednastavených parametrů řezání

Variable	Value	Unit
Pressure in pump	380	MPa
Water jet diameter	0.254	mm
Focusing tube diameter	1.02	mm
Focusing tube length	76	mm
Abrasive mass flow rate	250	$g \cdot min^{-1}$
Mean abrasive grain size*)	0.25	mm
Abrasive type**)	AG	AG
Traverse speed 1	50	$mm \cdot min^{-1}$
Traverse speed 2	100	$mm \cdot min^{-1}$
Stand-off distance	2	mm

*) Measurements of AG garnet 80 mesh was performed in the certified Laboratory of Powder Materials at the VŠB – Technical University of Ostrava on the machine Mastersizer 2000 and it was confirmed on the Fritsch Analysette 22 MicroTec plus.

**) Abrasive type is almandine Australian garnet (AG)

The rectangular samples 60 × 10 mm were cut in a way, that the first two lines of rectangle perimeter were cut with the traverse speed of 50 $mm \cdot min^{-1}$, the next two ones with the traverse speed of 100 $mm \cdot min^{-1}$. Then the photos of the longer side walls were taken and studied. The walls prepared with traverse speed of 50 $mm \cdot min^{-1}$ were usually very smooth (Fig. 1), hence the striations were not marked sufficiently on the photos. Therefore, the sides, prepared with traverse speed of 100 $mm \cdot min^{-1}$, were investigated and used for this study (see the example of the cut wall presented in Fig. 2).

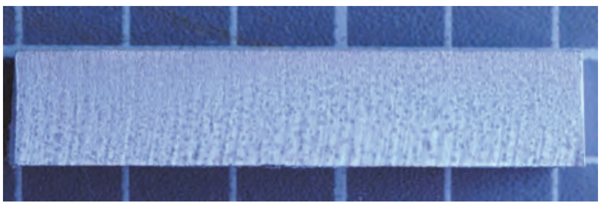

Fig. 1 An example of smooth wall of the kerf prepared with traverse speed of 50 $mm \cdot min^{-1}$
Obr. 1 Příklad hladké stěny drážky připravené postupovou rychlostí 50 $mm \cdot min^{-1}$

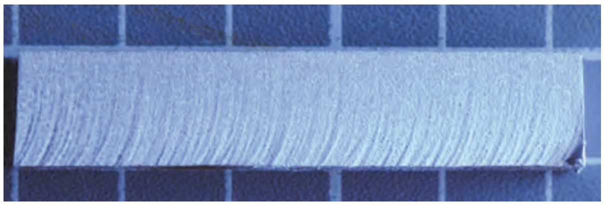

Fig. 2 An example of the kerf wall produced by traverse speed of 100 $mm \cdot min^{-1}$ – striations are evident
Obr. 2 Příklad stěny drážky vytvořené postupovou rychlostí 100 $mm \cdot min^{-1}$ – striace evidentní

Ten significant striations on each cut wall were identified and their declination angles were measured according to the procedure described in [17]. The average values calculated from the 10 individual values measured on each material were used for comparison with respective material properties – strength and hardness. The values of strength, hardness, and average declination angle are summarized in Tab. 2.

Tab. 2 Parameters of investigated steels and mean declination angles measured on cut walls of the AWJ kerfs for traverse speed of 100 $mm \cdot min^{-1}$
Tab. 2 Parametry zkoumaných ocelí a průměrný deklinační úhel měřený na řezných stěnách AWJ drážek pro postupovou rychlost 100 $mm \cdot min^{-1}$

Steel grade	σ_m (MPa)	HV10	ϑ (deg)
St 52-3	445	125	10.1
C45	621	170	16.7
16MnCr5	880	252	11.6
42CrMo4	658	191	16.1
X6CrNiTi18 9	515	166	14.0
X210CrW12	656	245	20.4
34CrMo4 – 850 – 620*)	1060	330	12.5
34CrMo4 – 850 – 580*)	1190	363	13.6
34CrMo4 – 850 – 510*)	1340	391	14.6
34CrMo4 – 850 – 400*)	1560	459	15.5
34CrMo4 – 850 – 250*)	1865	521	16.9
34CrMo4 – 850 – 20*)	2230	589	18.6

*) Steel 34CrMo4 was austenitized at the temperature of 850 °C, then quenched in polymer and immediately tempered at six temperatures from 20 to 620 °C.

Discussion

Mutual relations between strength, hardness, and declination angle (presented in Tab. 2) are demonstrated by graphs drawn in Fig. 3 and 4. Both graphs clearly demonstrate that higher amount of alloying chemical elements, such as Mn, Cr, Ti, W, shifts the resistivity of steel to AWJ machining to higher values, i.e. the values of declination angle are higher. The higher values of declination angle cause greater distortion of the products prepared with the identical AWJ parameters used for common steels (or steels of certain composition and well-studied behaviour regarding their heat treatment).

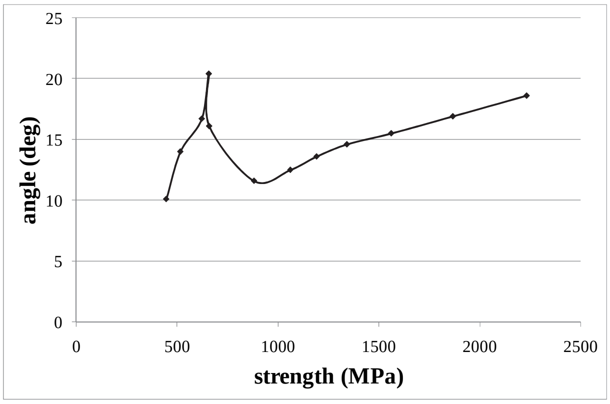

Fig. 3 Relation between material strength and declination angle for all studied steels

Obr. 3 Vztah mezi pevností materiálu a deklinačním úhlem pro všechny studované oceli

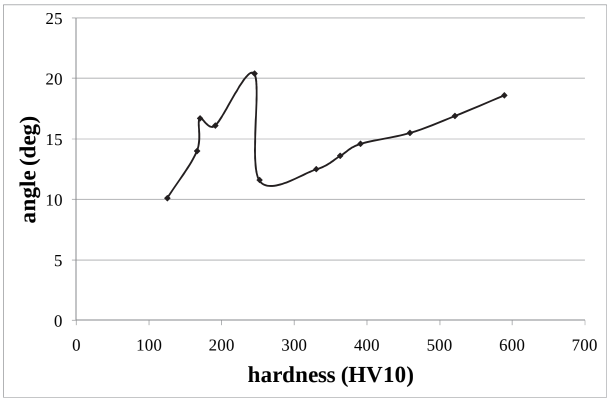

Fig. 4 Relation between material hardness and declination angle for all studied steels

Fig. 4 Vztah mezi tvrdostí materiálu a deklinačním úhlem pro všechny studované oceli

When the extremely alloyed steels are removed from the studied dependences, the shape of the relationship tends to a linear relationship between material properties – strength or hardness – and respective quality evaluating the quantity, i.e. the declination angle produced on kerf walls during AWJ cutting. The situation is demonstrated in Fig. 5 and 6, presenting the results from Tab. 2 without extremely alloyed steels.

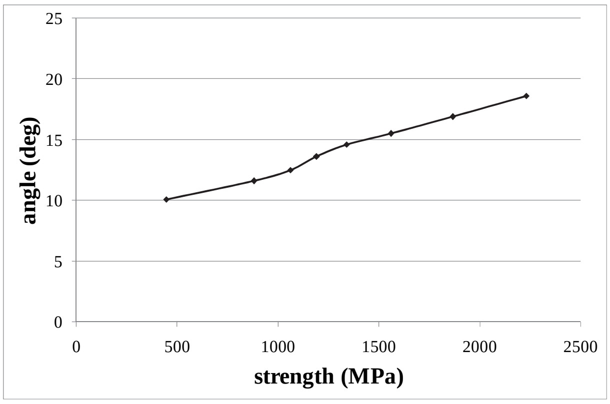

Fig. 5 Relation between material strength and declination angle for low alloyed steels

Obr. 5 Vztah mezi pevností materiálu a deklinačním úhlem pro nízkolegované oceli

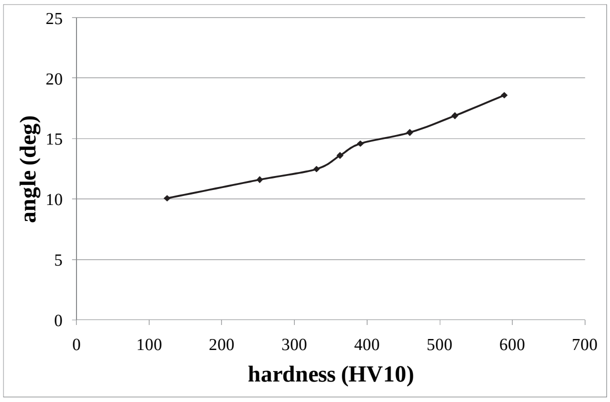

Fig. 6 Relation between material hardness and declination angle for low alloyed steels

Obr. 6 Vztah mezi tvrdostí materiálu a deklinačním úhlem pro nízkolegované oceli

Finally, it can be stated that declination angle measured at striations on the cut walls of the kerfs produced by AWJ is a sensitive quantity that makes it possible to judge machining quality for the set parameters of AWJ. The steel properties, namely strength, and hardness are good indicators of cutting quality provided that amount of alloying ingredients is not exceeding several per cents (up to 5 per cent for the total amount of them). The high amount of alloying components (typically more than 10 per cent), namely Mn, Cr, Ti, and W, can shift the trend of the relationship between strength and/or hardness and declination angle to either lower or higher values regarding the low alloyed steels. The relationship between strength and/or hardness and declination angle is almost linear for a large range of material characteristics. Some deviations from the linear trend can be caused not only by measurement uncertainties but also by small differences in steel alloying elements percentage influencing the amount and size of carbides produced during thermal treatment of steels [23].

Conclusions

The steel properties, namely strength, and hardness are good indicators of AWJ cutting quality if the amount of alloying ingredients is not exceeding several per cent (below 5%). The high amount (over 10%) of alloying components, namely Mn, Cr, Ti, and W, can shift the trend of the relationship between strength and/or hardness and declination angle to either lower or higher values regarding the low alloyed steels. The relationship between strength and/or hardness and the declination angle is almost linear for a large range of material characteristics for low alloyed steels. Deviations from this trend can be caused by measurement uncertainties and variation in the percentage of the steel alloying elements.

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