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Article

A Fuzzy Evaluation of Tool Materials in the Turning of Marine Steels

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Abstract: To recommend one suitable tool material for the cutting of marine steels under special conditions and requirements in emergency rescues of capsized steel ships, the cermet tools, cemented carbide tools and coated carbide tools were evaluated using a fuzzy evaluation method concerning cutting force, cutting temperature, surface roughness and tool wear. Experimental results indicate that the tool cutting performance was diverse and difficult to evaluate with a single evaluation index. The cemented carbide tools presented bad cutting performance with severe wear. Compared with the cemented carbide tools, the cermet tools showed excellent wear resistance with about 60.3% smaller tool flank wear value and good surface quality with about 46.8% smaller surface roughness. The coated carbide tools presented low cutting temperatures about 15.6% smaller than those of the cermet tools. The result of fuzzy evaluation demonstrates that the cermet tools presented the best cutting performance, followed by the coated carbide tools, and then the cemented carbide tools. The cermet tools are recommended to cut marine steels in emergency rescues of capsized steel ships.

Keywords: fuzzy evaluation; cutting performance; tool materials; marine steels

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1. Introduction

In recent years, many ships have been in distress, among which the capsizing accident is particularly serious [1]. In emergency rescues of capsized ships, it is usually necessary to cut a hole in the hull to rescue trapped people [2,3]. Nowadays, marine steels with excellent properties are widely used in shipbuilding. As is known, marine steels belong to high-strength steels, which are difficult to machine with high cutting temperature [4], difficulty in chip breaking [5], built-up edge [6], severe tool wear [7], etc. Meanwhile, for the tool used to cut the hull, the cutting process should meet the following requirements [8]: a small cutting force to make the cutting process smooth and reduce power consumption with lightweight rescue equipment, a low cutting temperature to avert a gas explosion inside the ship, small surface roughness of the hole to avoid hurting the rescued people and a long tool life to make the cutting process efficient and reliable without changing tools. However, there is little research into the machinability of marine steels.

Ravi et al. [9] demonstrated that the cryogenic cooling decreased the cutting force, cutting temperature, surface roughness and tool wear in the cutting of hardened D3 steels with cemented carbide tools. Szczotkarz et al. [10] reported that the wear of coated carbide tools decreased when turning 316 L steels with minimized lubrication. Özbek et al. [11] investigated the effects of vibration and cutting temperature on surface roughness and tool wear in the turning of AISI D2 steels using coated carbide tools. Fernández-Abia et al. [12] found that a high cutting speed was beneficial for the machining of austenitic steels with coated carbide tools, although the tool wear was high. Zou et al. [13] reported that the cermet tool life was mainly affected by the cutting speed when machining stainless steels. Sarjana et al. [14] pointed out that in the turning of hardened steels, the uncoated cermet tool was better in the amount of material removal, while the coated cermet tool was better in the quality of surface finish. Li et al. [15] found that the multi-coated tool was suitable for the high-speed milling of AISI 4340 steel due to the high resistance of element diffusion. Boing [16] reported that the increase of tool wear rate with the cutting speed was different for each tool material in the hard turning of AISI 52100 steel.

As stated above, the tools of cemented carbide, coated carbide and cermet are commonly chosen for the cutting of high-strength steels. Moreover, different tool materials presented various cutting force [17], cutting temperature [18], surface quality [19] and tool life [20]. Thus, the requirements for the cutting of capsized steel ships can be met by selecting a suitable tool material. Besides, because the cutting conditions and requirements in the cutting of a steel hull are different from those in production, the cutting performances of tool materials need to be evaluated by multiple evaluation indexes of cutting force, cutting temperature, surface quality and tool life.

Several scholars have studied the applications of evaluation methods in the engineering field. Taha et al. [21] developed a machine tool selection system based on the fuzzy analytic hierarchy process and artificial neural network. Cheng et al. [22] evaluated the performance of layer face milling cutters concerning structures and geometrical parameters in the milling of 508III steels by a multi-level fuzzy evaluation system. Choudhuri et al. [23] optimized parameters for multiple performance features in the machining of 316 stainless steels by the grey-fuzzy algorithm. Gok [24] used the fuzzy TOPSIS, multi-objective grey design and RSA in the cutting of ductile irons and obtained the smallest cutting force and the best surface quality. Xu et al. [25] accomplished the optimal selection of tool materials for the machining of high-strength steels based on the fuzzy evaluation method. Yue et al. [26] adopted the grey-fuzzy analytic hierarchy method to evaluate the tool cutting performance in the milling of titanium alloy.

Based on the cited researches, it is clear that the fuzzy evaluation method can make a quantitative evaluation of the objects affected by multiple factors. However, there is little research into the evaluation of tool cutting performance for the cutting of marine steels. For the cutting of marine steels under special conditions and requirements in emergency rescues of capsized steel ships, it is necessary in particular to evaluate the cutting performances of different tool materials concerning cutting force, cutting temperature, surface roughness and tool wear by the fuzzy evaluation method.

In this research, the fuzzy evaluation method was adopted to select the optimum tool material for the cutting of marine steels among the cermet tools, cemented carbide tools and coated carbide tools with considerations of cutting force, cutting temperature, surface roughness and tool wear. This work can provide reliable theoretical and technical references for the cutting of marine steels in emergency rescues of capsized steel ships.

2. Materials and Methods

The workpiece used in the experiment was an AH36 marine steel bar (Tianjin Nanshan Steel Sales Co., Ltd., Tianjin, China) of 85 mm in diameter and 500 mm in length with a hardness of 128 HV and chemical compositions presented in Table 1. This workpiece was processed by a continuous wet turning using a CA6140A lathe (Shenyang Machine Tool Co., Ltd., Shenyang, China). Because the cutting speed has an important impact on tool cutting performances, the low and high cutting speeds of 40 and 80 m/min were chosen, and the constant cutting depth and feed rate were 2 mm and 0.15 mm/r, respectively.

Table 1. Chemical compositions of AH36 marine steel (wt.%).

C	Si	Mn	P	Fe
0.168	0.244	1.62	0.018	Balance

The cermet tools of NX2525 (Mitsubishi Materials Corporation, Tokyo, Japan) and TN620 (Kyocera Corporation, Kyoto, Japan), cemented carbide tools of UTi20T (Mitsubishi

Materials Corporation, Tokyo, Japan) and A30 (Sumitomo Electric Cemented Carbide Co., Ltd., Itami, Japan), and coated carbide tools of UE6105 (Mitsubishi Materials Corporation, Tokyo, Japan) and CA5535 (Kyocera Corporation, Kyoto, Japan) were selected with mechanical properties listed in Table 2. The geometric parameters of clamped tools were: rake angle of −6°, relief angle of 6°, inclination angle of −6° and cutting edge angle of 75°.

Table 2. Mechanical properties of tool materials.

Tools	Hardness (HRA)	Transverse Rupture Strength (MPa)
NX2525	92.2	2000
TN620	91.5	2500
UTi20T	90.5	2000
A30	91.3	2100
UE6105	90.8	1800
CA5535	89.4	2970

Figure 1 shows the photographic view of a turning experiment in which a dynamometer (Model 9272, Kistler Group, Winterthur, Switzerland), a thermal infrared imager (Model A325SC, Teledyne FLIR, Wilson Ville, OR, USA) and a roughness meter (Model 3200, TIME Group Inc., Beijing, China) were used to obtain the average values of initial cutting force, cutting temperature and surface roughness through five tests, respectively. The sampling frequency of the dynamometer was set as 30,000 Hz/s, and the resultant cutting force was obtained by the three components. The thermal emissivity of the workpiece was set as 0.35. After the cutting process lasted for 41 min at the cutting speed of 40 m/min and 15 min at the cutting speed of 80 m/min, a tool microscope (Model AM413ZT, VIDY Optical Co., Ltd., Wuxi, China) was used to analyze the worn tools and measure the tool flank wear value. In the roughness measurement, the Gaussian filter was used with an evaluation length of 4.0 mm and a cutoff value of 0.8 mm for the uniform surface ($Ra \geq 0.10$–2.00), and with an evaluation length of 12.5 mm and a cutoff value of 2.5 mm for the rough surface ($Ra \geq 2.00$–10.0).

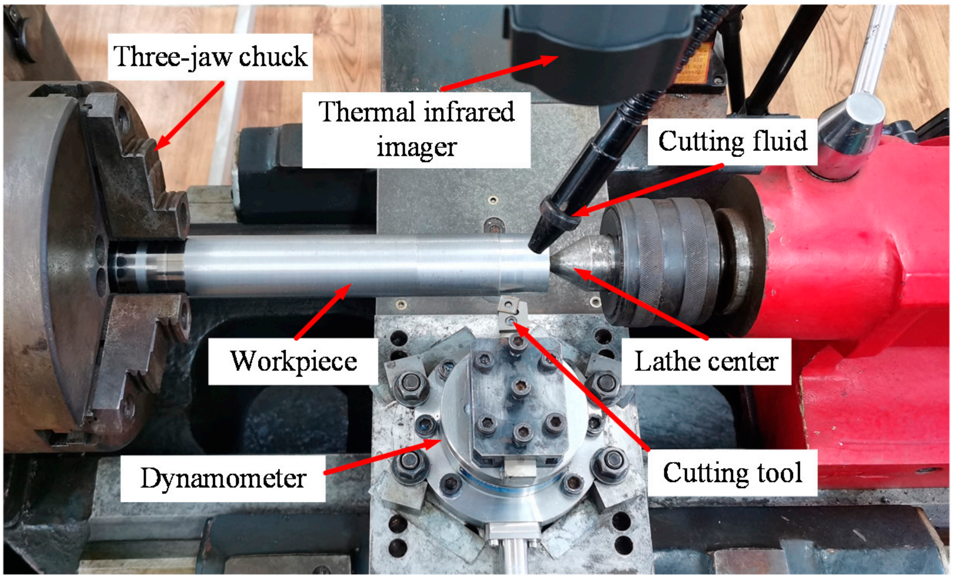

Figure 1. Photographic view of turning experiment.

3. Cutting Performances of Tool Materials

3.1. Cutting Force and Cutting Temperature

The cutting force and cutting temperature for each tool at both cutting speeds are shown in Figures 2 and 3, respectively. It can be shown that for all the cutting tools, the cutting force decreased with the increased cutting speed, while the cutting temperature presented the opposite trend. The smaller cutting force at the high cutting speed can be ascribed to the thermal softening effect on workpieces under the higher cutting temperature. Moreover, at the high cutting speed, the deterioration of friction condition between tools and workpieces, and the difficult heat dissipation, resulted in the higher cutting temperatures of cutting tools.

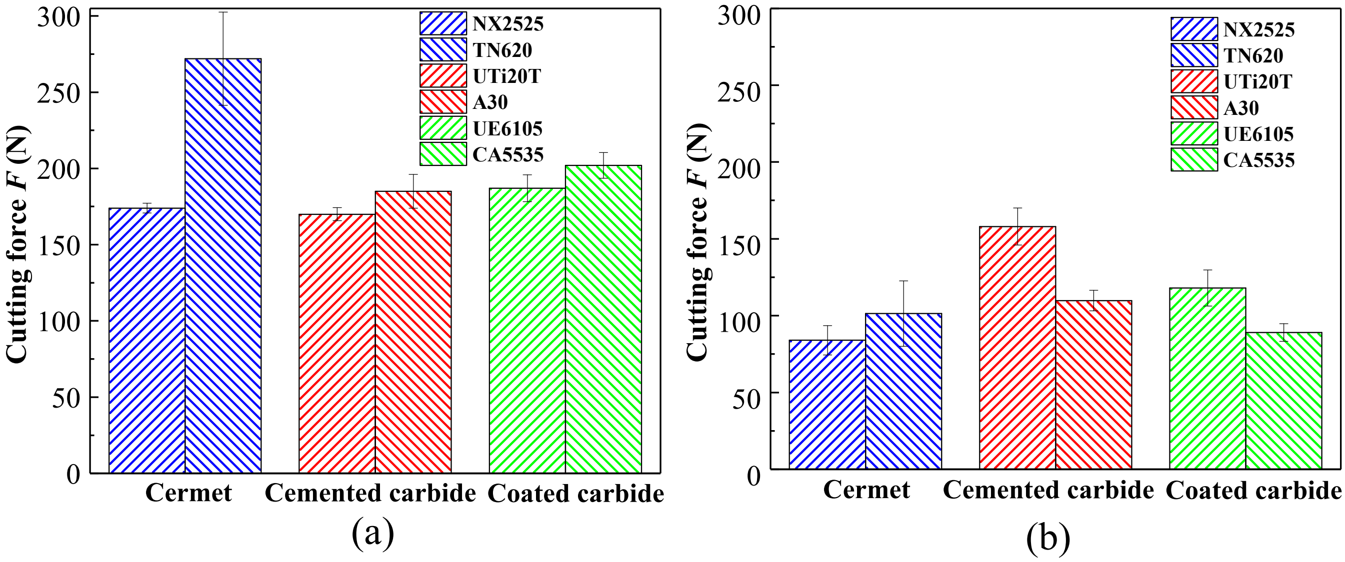

Figure 2. Cutting force for each tool at both cutting speeds: (**a**) 40 m/min and (**b**) 80 m/min.

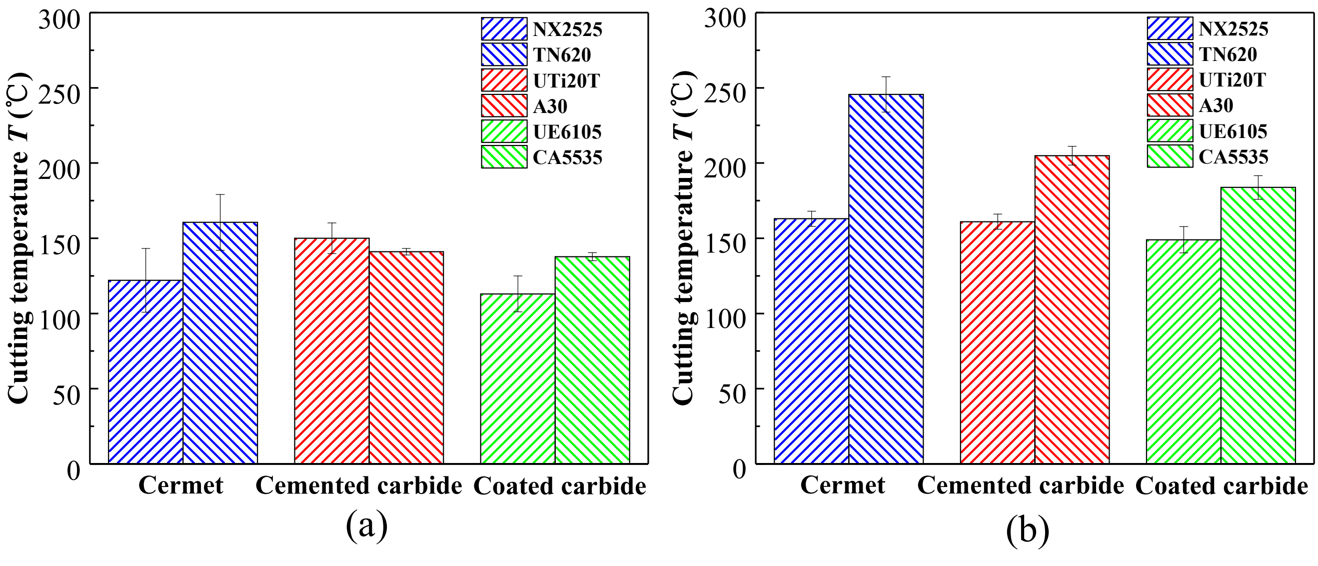

Figure 3. Cutting temperature for each tool at both cutting speeds: (**a**) 40 m/min and (**b**) 80 m/min.

Furthermore, at the low cutting speed, the cutting forces of cemented carbide tools were smaller than those of the other tools, and the TN620 cermet tool had the highest cutting force. Figures 4–6 illustrate the wear morphologies of cutting tools at both cutting speeds, respectively. As shown in Figure 5, the cemented carbide tools had a built-up edge, which can decrease the cutting force by increasing the actual rake angle. Thus, in virtue of the built-up edge and anti-friction coating, the cemented carbide tools and coated carbide tools presented smaller cutting forces than those of cermet tools at the low cutting speed, respectively. At the high cutting speed, owing to the smaller friction coefficient with steel workpieces, the cutting forces of cermet tools and coated carbide tools were smaller than those of the cemented carbide tools.

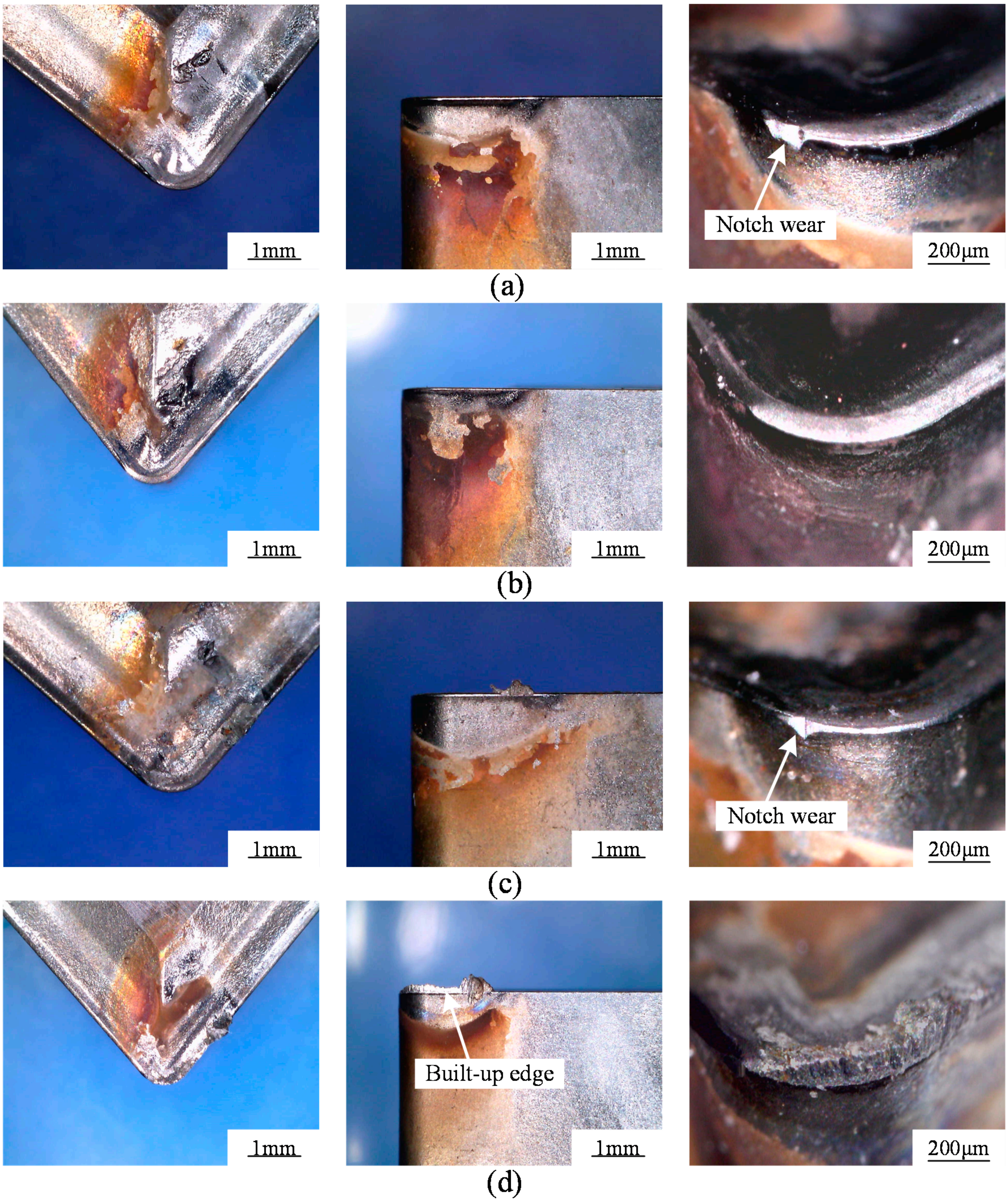

Figure 4. Wear morphologies of cermet tools at both cutting speeds: (**a**) NX2525 and (**b**) TN620 at 40 m/min for 41 min, and (**c**) NX2525 and (**d**) TN620 at 80 m/min for 15 min.

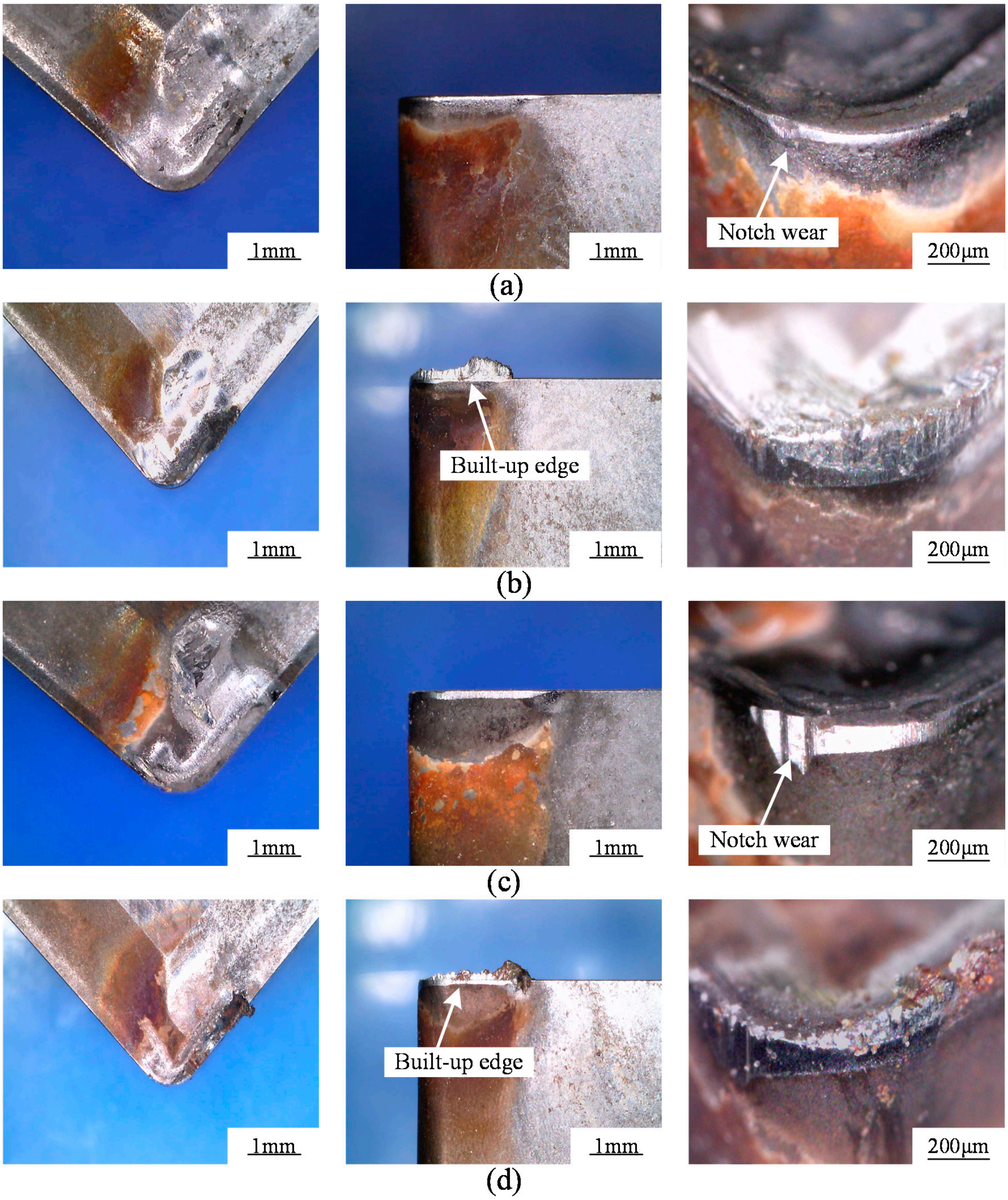

Figure 5. Wear morphologies of cemented carbide tools at both cutting speeds: (**a**) UTi20T and (**b**) A30 at 40 m/min for 41 min, and (**c**) UTi20T and (**d**) A30 at 80 m/min for 15 min.

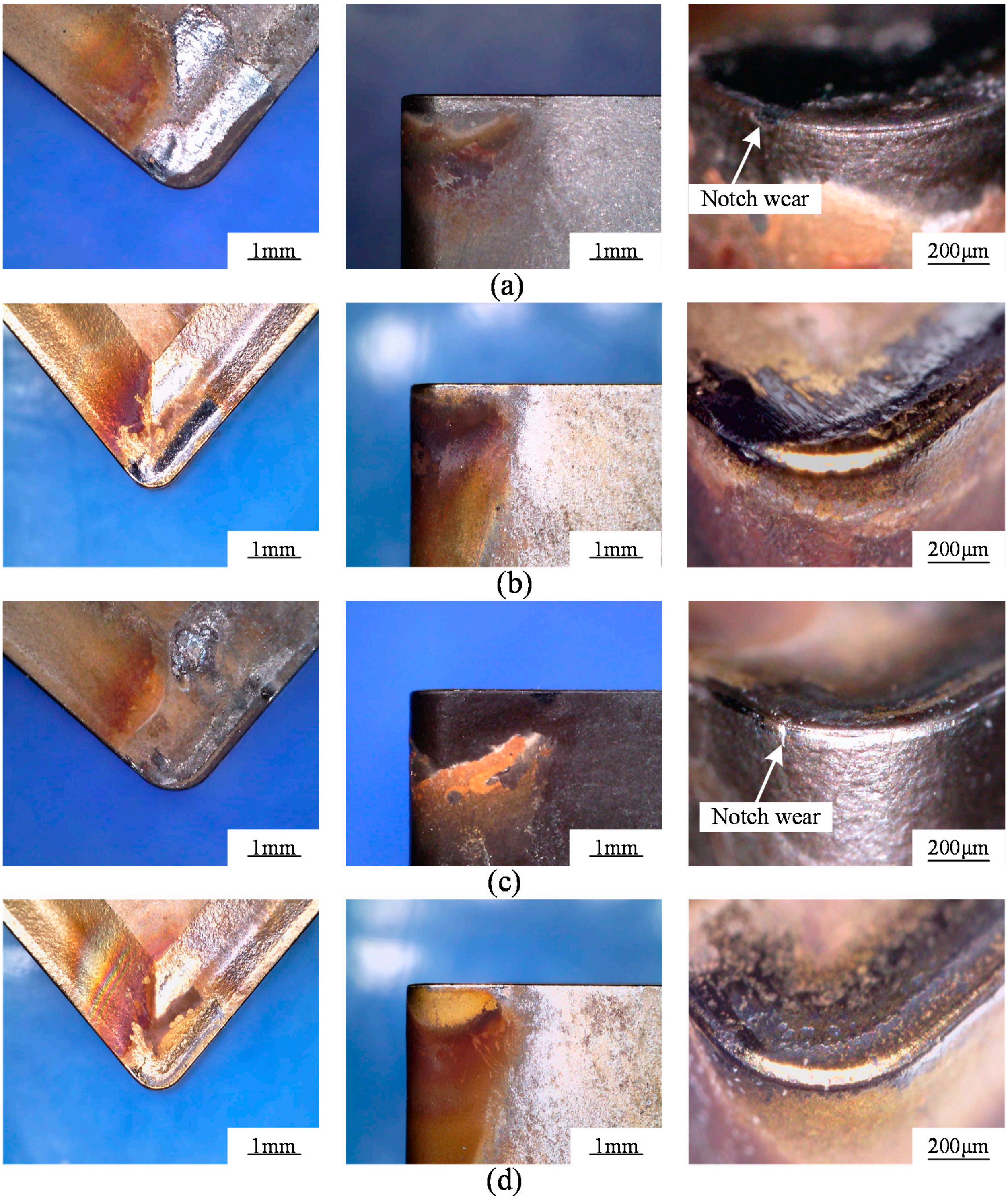

Figure 6. Wear morphologies of coated carbide tools at both cutting speeds: (**a**) UE6105 and (**b**) CA5535 at 40 m/min for 41 min, and (**c**) UE6105 and (**d**) CA5535 at 80 m/min for 15 min.

On the whole, at both cutting speeds, as a result of the smaller thermal conductivity, the cutting temperature of cermet tools were higher than those of other tools. Meanwhile, due to the better anti-adhesion and smaller friction coefficient with steel workpieces, the coated carbide tools presented the lower cutting temperatures.

3.2. Tool Wear Characteristics and Surface Roughness

From Figures 4–6 it can be seen that for each tool material the wear degree sequence was cemented carbide > coated carbide > cermet at both cutting speeds, and the wear degree increased with the increased cutting speed due to the subsequent increased cutting temperatures (as shown in Figure 3b), respectively.

As illustrated in Figure 4, the cermet tools had mild abrasive wear on the tool corners by virtue of the better wear resistance with the higher hardness (as shown in Table 2). Meanwhile, as illustrated in Figure 4a,c, the NX2525 tool presented flank notch wear as a result of the lower transverse rupture strength (as shown in Table 2). For the TN620 tool, the built-up edge (as illustrated in Figure 4d) indicated the high affinity between the tool and marine steel under high cutting temperature (as illustrated in Figure 3b).

As illustrated in Figure 5, the cemented carbide tools presented serious adhesive wear morphologies with flank notch wear and a built-up edge, as a result of the strong affinity between the Co element in cemented carbide materials and the Fe element in steel materials. Meanwhile, the lower transverse rupture strength of UTi20T tool (as shown in Table 2) were responsible for the flank notch wear under the work hardening effect of the workpiece material. The high tool wear value indicated the poor wear resistances of cemented carbide tools when cutting marine steels.

As illustrated in Figure 6, benefiting from the anti-adhesion and anti-friction effects of coatings, the coated carbide tools exhibited abrasive wear on the cutting edge with coating wear on the rake face, notch wear on the flank face, and without a built-up edge. Thus, the coated carbide tools had relatively small cutting forces and cutting temperatures when cutting marine steels. In addition, due to the work hardening effect of the workpiece material and the lower transverse rupture strength of UE6105 tool (as shown in Table 2), the notch wear occurred on the flank face.

Based on the above analyses of tool wear characteristics, it can be concluded that the wear mechanisms of cermet tools were abrasive wear in low-speed cutting, while mainly abrasive wear with adhesive wear in high-speed cutting. The wear mechanisms of cemented carbide tools were mainly adhesive wear, accompanied by abrasive wear. The wear mechanisms of coated carbide tools were abrasive wear.

Figure 7 illustrates the surface roughness of machined workpieces obtained by each tool at both cutting speeds. It indicates that the surface roughness of machined workpieces decreased much with the increased cutting speed as a result of the small plastic deformation on surface layer metal. Owing to the better wear resistance and lower friction coefficient, the cermet tools with sharp cutting edge obtained the smaller surface roughness of machined workpieces, while the cemented carbide tools with adhesive wear presented the bigger surface roughness of machined workpieces. Meanwhile, compared with the same kind of tools, the NX2525 tool, UTi20T tool and UE6105 tool obtained the bigger surface roughness of machined workpieces, respectively, and this can be attributed to the flank notch wear (as illustrated in Figure 4a,c, Figure 5a,c and Figure 6a,c, respectively).

Based on the above experimental results and discussion, the tool cutting performance was diverse and difficult to evaluate with a single evaluation index. Therefore, the fuzzy evaluation method was used to evaluate the tool materials as follows.

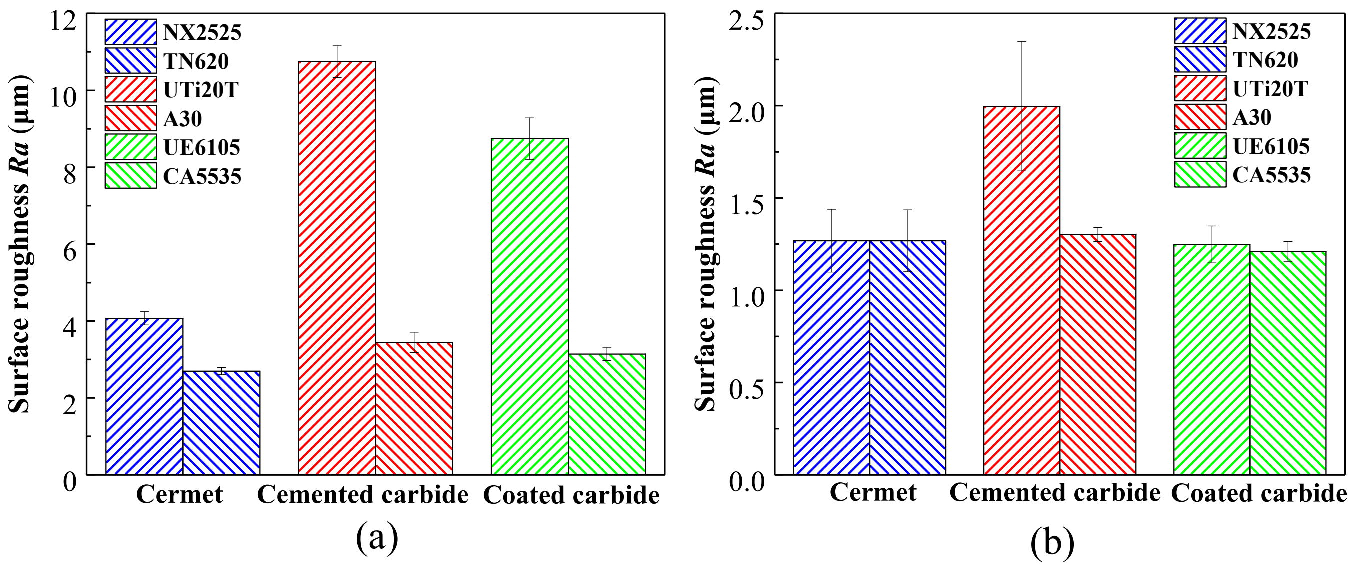

Figure 7. Surface roughness of machined workpieces obtained by each tool at both cutting speeds: (**a**) 40 m/min and (**b**) 80 m/min.

4. Fuzzy Evaluations of Tool Materials

4.1. Factor Set and Evaluation Set

For the evaluation objects of tool materials, the cutting force (*F*), cutting temperature (*T*), surface roughness (*Ra*) and tool flank wear value (*VB*) were used as evaluation indexes. The factor set was determined as U = {*F*, *T*, *Ra*, *VB*}, and the evaluation object set was determined as V = {cermet, cemented carbide, coated carbide}, respectively. The results of turning experiments with different tool materials at both cutting speeds are shown in Tables 3 and 4, respectively.

Table 3. Results of turning experiments at the cutting speed of 40 m/min.

Tool Grades	*F* (N)	*T* (°C)	*Ra* (μm)	*VB* (mm)
NX2525	174	123	4.070	0.024
TN620	272	160	2.696	0.012
UTi20T	170	150	10.751	0.056
A30	185	141	3.442	0.024
UE6105	187	113	8.742	0.024
CA5535	202	138	3.138	0.018

Table 4. Results of turning experiments at the cutting speed of 80 m/min.

Tool Grades	*F* (N)	*T* (°C)	*Ra* (μm)	*VB* (mm)
NX2525	84	163	1.268	0.032
TN620	101	245	1.267	0.032
UTi20T	158	161	1.997	0.111
A30	109	204	1.302	0.061
UE6105	118	149	1.248	0.048
CA5535	88	183	1.211	0.049

4.2. Fuzzy Judgment Relation Matrix

For each tool material, the mean values of evaluation indexes at both cutting speeds were calculated based on the data of Tables 3 and 4, and are shown in Tables 5 and 6, respectively. Depending on the principle of merit, for the four smaller-the-better evaluation indexes in this study, the mean values of indexes were fuzzified by the following formula:

$$r_{ij} = \frac{a_{max} - a_{ij}}{a_{max} - a_{min}}(i = 1,2,3,4; j = 1,2,3) \quad (1)$$

where r_{ij} is the optimal membership of the evaluation index u_i for the evaluation object v_j, a_{ij} is the mean values of the evaluation index u_i for the evaluation object v_j, and a_{max} and a_{min} are the maximum and minimum mean values of each evaluation index, respectively. The fuzzy memberships of evaluation indexes obtained for each evaluation object at both cutting speeds are listed in Tables 7 and 8, respectively. Then, the fuzzy evaluation relationship matrix R_1 and R_2 were drawn from the data of Tables 7 and 8 as follows, respectively.

$$R_1 = (r_{ij})_{4\times3} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0.626 \\ 0.020 & 0 & 1 \\ 1 & 0 & 0.312 \\ 1 & 0 & 0.864 \end{pmatrix}$$

$$R_2 = (r_{ij})_{4\times3} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0.744 \\ 0 & 0.566 & 1 \\ 0.910 & 0 & 1 \\ 1 & 0 & 0.685 \end{pmatrix}$$

Table 5. Mean values of evaluation indexes at the cutting speed of 40 m/min.

Evaluation Objects	*F* (N)	*T* (°C)	*Ra* (μm)	*VB* (mm)
Cermet	223.0	141.5	3.383	0.018
Cemented carbide	177.5	145.5	7.097	0.040
Coated carbide	194.5	125.5	5.940	0.021

Table 6. Mean values of evaluation indexes at the cutting speed of 80 m/min.

Evaluation Objects	*F* (N)	*T* (°C)	*Ra* (μm)	*VB* (mm)
Cermet	92.5	204.0	1.268	0.032
Cemented carbide	133.5	182.5	1.650	0.086
Coated carbide	103.0	166.0	1.230	0.049

Table 7. Fuzzy membership of evaluation indexes at the cutting speed of 40 m/min.

Evaluation Objects	Optimal Membership of *F*	Optimal Membership of *T*	Optimal Membership of *Ra*	Optimal Membership of *VB*
Cermet	0	0.020	1	1
Cemented carbide	1	0	0	0
Coated carbide	0.626	1	0.312	0.864

Table 8. Fuzzy membership of evaluation indexes at the cutting speed of 80 m/min.

Evaluation Objects	Optimal Membership of *F*	Optimal Membership of *T*	Optimal Membership of *Ra*	Optimal Membership of *VB*
Cermet	1	0	0.910	1
Cemented carbide	0	0.566	0	0
Coated carbide	0.744	1	1	0.685

4.3. Weight Vector

In this study, the coefficient of variation method was adopted to obtain the weight vector for the four evaluation indexes of tool materials. The coefficient of variation V_i for each evaluation index was obtained by the following formula:

$$V_i = \frac{\sigma_i}{\overline{X}_i}(i = 1, 2, 3, 4) \quad (2)$$

where σ_i is the standard deviation of evaluation index u_i, and $\overline{X}_i$ was the arithmetic mean of evaluation index u_i. Then the weight W_i of each evaluation index can be obtained as follows:

$$W_i = \frac{V_i}{\sum_{i=1}^{4} V_i}(i = 1, 2, 3, 4) \quad (3)$$

Based on the weight values of evaluation indexes obtained from data of Tables 5 and 6, the weight vector of evaluation indexes can be expressed as A = (a_1, a_2, a_3) = (W_1, W_2, W_3). Then, the obtained weight vectors of evaluation indexes at both cutting speeds were A_1 = (0.117, 0.077, 0.350, 0.456) and A_2 = (0.202, 0.107, 0.175, 0.516), respectively.

4.4. Evaluation

The fuzzy evaluation vector B was calculated by the weight vector A and fuzzy evaluation relationship matrix R according to the following formula:

$$B = A \circ R = (b_1, b_2, b_3) \quad (4)$$

where "∘" symbol represents the operation mode, b_j reflects the optimal membership of evaluation object v_j in the fuzzy evaluation of tool materials, and is calculated using the weighted averaging operator by the following formula:

$$b_j = \sum_{i=1}^{4} (a_i \cdot r_{ij}), \ (i = 1, 2, 3, 4; \ j = 1, 2, 3) \quad (5)$$

Thus, the fuzzy evaluation results at both cutting speeds were calculated as follows, respectively:

$$\begin{aligned} B_1 &= A_1 \circ R_1 = \begin{pmatrix} 0.117, & 0.077, & 0.350, & 0.456 \end{pmatrix} \circ \begin{pmatrix} 0 & 1 & 0.626 \\ 0.020 & 0 & 1 \\ 1 & 0 & 0.312 \\ 1 & 0 & 0.864 \end{pmatrix} \\ &= \begin{pmatrix} 0.808, & 0.117, & 0.653 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} B_2 &= A_2 \circ R_2 = \begin{pmatrix} 0.202, & 0.107, & 0.175, & 0.516 \end{pmatrix} \circ \begin{pmatrix} 1 & 0 & 0.744 \\ 0 & 0.566 & 1 \\ 0.910 & 0 & 1 \\ 1 & 0 & 0.685 \end{pmatrix} \\ &= \begin{pmatrix} 0.877, & 0.061, & 0.786 \end{pmatrix} \end{aligned}$$

The above results at both cutting speeds showed $b_1 > b_3 > b_2$. Thus, based on the maximum membership principle, for the turning of marine steels at low and high cutting speeds, the sequence of cutting performance of different tool materials was cermet > coated carbide > cemented carbide. The result indicates that cermet tools can be recommended to cut marine steels.

5. Discussion

The result of fuzzy evaluation demonstrates that the cermet tools presented the best cutting performance, followed by the coated carbide tools, and then the cemented carbide tools. This is also consistent with the experimental results. According to the above analyses of cutting performances of tool materials, it can be concluded that the cemented carbide tools presented poor cutting performance with severe wear and bad surface quality, and this can be ascribed to the serious adhesive wear caused by the strong affinity between the tool material and marine steel. Compared with the cemented carbide tools, the cermet tools showed excellent wear resistance with about 60.3% smaller tool flank wear value and good surface quality with about 46.8% smaller surface roughness, as a result of the good wear resistance and small friction coefficient. By virtue of the anti-adhesion and anti-friction effects of coatings, the coated carbide tools presented low cutting temperatures about 15.6% smaller than those of the cermet tools.

Based on the fuzzy evaluation method, quantitative evaluations for the cutting performances of tool materials were accomplished, and the cutting performances of recommended cermet tools meet the requirements for emergency rescues of capsized steel ships.

6. Conclusions

This work conducted a fuzzy evaluation of tool materials for the cutting of marine steels in emergency rescues of capsized steel ships. The conclusions drawn from this study are as follows:

(1) In the cutting of marine steels, the tool cutting performance was diverse and difficult to evaluate with a single evaluation index. On the whole, the cermet tools showed good wear resistance and surface quality, and the coated carbide tools had low cutting temperatures, while the cemented carbide tools presented bad cutting performance with severe wear.

(2) According to the fuzzy evaluation concerning cutting force, cutting temperature, surface roughness and tool wear, the cutting performance of cermet tools was the best, followed by the coated carbide tools, and then the cemented carbide tools.

(3) The cermet tools are recommended to cut marine steels in emergency rescues of capsized steel ships.

For the cutting of marine steels under special conditions and requirements in emergency rescues of capsized steel ships, this work can be used as a reference for tool materials selection, and the results obtained can be applied for future research on cutting parameter optimization and tool development.

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