Experimental Research on Milling Temperature of New Cold Saw Blade Milling Cutter

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Abstract: Based on the orthogonal test method and comparative study, the effects of workpiece material, workpiece diameter, milling cutter rotational speed and feed per tooth on milling temperature are investigated when cutting metal bars with new cold saw blade milling cutter. Then this paper reveals the change rule of new cold saw blade milling cutter milling temperature and the essential difference from the traditional hot saw blade milling cutter. Construction of sawing metal bar experiment system at production site, four-factor and three-level orthogonal test method is used to cut 45 steel, 40Cr and Q235B metal materials. The influence curves of workpiece material, workpiece diameter, milling cutter rotational speed and feed per tooth on milling temperature are obtained. By normalizing the experimental data, this paper uses the multiple linear regression method to fit the mathematical model of milling temperature. According to simulation analysis and experimental research, the milling temperature change rule of new cold saw blade milling cutter is obtained. Compared with the traditional hot saw blade milling cutter, the results show that under the same or similar conditions, the highest milling temperature center of new cold saw blade milling cutter is located at the bottom of the chip at a certain distance from the tip and the interface of the corresponding cutting layer adjacent to the bottom layer of the chip. The maximum milling temperature is around 300 °C, which is about 175 °C lower than the maximum milling temperature of traditional hot saw blade milling cutter. Further, it demonstrates that most of the heat generated by cold sawing is discharged from the cutting area along with chips, which keeps the milling cutter and workpiece at a relatively low temperature.

1. Introduction
In order to adapt to the rapid development of manufacturing industry, circular saw blade milling cutters are developing in the direction of high hardness, high efficiency and low loss. Traditional high-speed steel milling cutter has a hardness of 60~70HRC, the hardness of the carbide milling cutter is 76~82HRC, and new cold saw blade milling cutter (NCSBMC) uses Ti(C, N)-based cermet material...
and its hardness can reach 92HRC. Compared with traditional hot saw blade milling cutter (THSBMC), NCSBMC has lower milling temperature (MT), better sawing surface quality, higher precision and efficiency, so it is widely used in new profile production \cite{1,2}. NCSBMC is used in various types of rolling mills, cold-formed steel and high-frequency welded pipe enterprises. It cuts the head, tail and fixed size of various profiles, pipes and solid bars that produced by hot rolling and cold bending \cite{3}. THSBMC material is mainly composed of high speed steel and cemented carbide, the maximum MT in the milling process is usually about 800 °C, and the workpiece temperature is about 100 °C \cite{4}, higher MT not only affect tool wear and service life, but also produce machining errors \cite{5}. Compared with THSBMC, lower MT is the most obvious feature of NCSBMC. Workpiece temperature of cold sawing is generally maintained at 40-70 °C, workpiece will not change its material properties because of the high temperature caused by friction. The highest and average temperatures in the cutting area of NCSBMC are also lower, despite the external force and thermal stress, NCSBMC doesn’t distorts. Therefore, workpiece has a high section quality.

MT test is the most important and direct method to reveal the mechanism of milling cutter. Meanwhile, MT is also an important basis for evaluating the life and accuracy of milling cutter. Contact and non-contact methods are usually used to study MT. Liu Zhanqiang, Aixing, etc. \cite{6} summarized the commonly used cutting temperature measurement methods, and elaborated the basic principles, advantages and disadvantages and application scope of various temperature measurement methods in detail. McFeron et al. \cite{7} developed a technique which includes a two-color pyrometer and two optical fibers, one is rotating with tool insert and the other is stationary located in tool spindle to measure the tool temperature. Kerrigan et al. \cite{8} used a wireless telemetric system, which is designed with tool holder to measure the cutting temperatures during milling of CFRP composites by a coupled thermocouple. Karaguzel, U \cite{9} presented a novel experimental technique to measure transient tool temperatures in dry milling operation with a K type thermocouple, and proposed a Green’s functions analytical model to solve the 3D transient heat conduction problem. Zhang Kai et al. \cite{10} simultaneously measured the temperature change at a certain point on the saw blade using a K-type thermocouple and an infrared thermometer. It is available from the experiment that when the emissivity of the saw blade is 0.3, the temperature change curves measured by the infrared thermometer and the thermocouple is consistent. Dong Huiyue et al. \cite{11} proposed a dynamic artificial thermocouple temperature measurement method, which has the advantages of artificial thermocouple method and semi-artificial thermocouple method. Kwon et al. \cite{12} obtained the instantaneous temperature of the contact surface between the tool and the chip through infrared photography, and then calculated the average temperature of the steady state of the contact surface between the tool and the chip according to the heat transfer principle. Gu Lizhi, Yuan Zhejun et al. \cite{13} measured the temperature distribution of the surface of the tool and the workpiece by infrared radiation pyrometer, and obtained the temperature value of the corresponding region through signal conversion and processing.

NCSBMC has been applied in Germany and Japan, but it is seldom used in China. The research on MT of NCSBMC has rarely been reported. Since NCSBMC thickness is usually less than 3 mm, milling area structure and geometry are small, and NCSBMC is in a combined motion state of the rotary motion and the feed motion during the machining. Therefore, it is not suitable to use the way of thermocouple embedding to test. In this paper, MT is measured and tested by high-precision and high-speed infrared thermal imager.

2. Orthogonal experimental study on MT

2.1 Establishment of material, method and test system

MT tests are performed on a P-150B intelligent circular sawing machine. Workpiece are placed in a self-made fixture with positioned and clamped, and fixture is rigidly fixed to the three-component cutting force dynamometer via four M8 socket head cap screws. The dynamometer-workpiece combination is bolted to the machine tool’s tombstone via a surface ground steel plate approximately
20 mm in thickness. NCSBMC and workpiece materials are shown in Fig. 1 and Fig. 2, respectively. The specifications of NCSBMC and the milling process parameters used in the test are shown in Tab. 1. A high-speed thermal imaging camera ImageIR5325 with the measurement accuracy of ±1°C and the resolution of 15 μm is used to measure temperature field distribution as shown in Fig. 3.

![Fig.1 NCSBMC](image1)

![Fig.2 Workpiece material and diameter](image2)

### Tab.1 Basic information and process parameters

| Project                              | Parameters                               |
|--------------------------------------|------------------------------------------|
| Milling cutter specification         | φ460 × 2.7 × 50 × 60Z                    |
| Milling cutter material              | Ti(C,N)-based cermet                     |
| Milling cutter rotational speed      | 90RPM, 108RPM, 110RPM                   |
| Feed per tooth                      | 0.020mm, 0.025mm, 0.030mm                |
| Workpiece material                   | 45#, 40Cr, Q235B                         |
| Workpiece diameter                   | φ32mm, φ36mm, φ38mm                      |

The factors of affecting the MT in machining include workpiece material, workpiece diameter, milling cutter rotation speed, feed per tooth, cutting fluid and vibration. In this paper, the four main influencing factors of workpiece material, workpiece diameter, milling cutter rotation speed and feed per tooth are studied. Each factor takes three levels, and the inspection index is MT. Four-factor and three-level orthogonal test design is shown in Tab. 2.

### Tab.2 Four-factor and three-level test design

| Factors Levels | Workpiece material (M) | Workpiece diameter (D) (mm) | Milling cutter rotation speed (R) (RPM) | Feed per tooth (W) (mm) |
|----------------|------------------------|-----------------------------|----------------------------------------|------------------------|
| 1              | 45steel                | 32                          | 96                                     | 0.020                  |
| 2              | 40Cr                   | 36                          | 110                                    | 0.025                  |
| 3              | Q235B                  | 38                          | 115                                    | 0.030                  |

2.2 Experiment results and data processing
L9 (3^4) is selected to design the experiment, and each number is repeated three times. The measured maximum MT sampling points are divided into five groups at equal intervals according to the time sequence. The average values of each group are taken, and the individual data with large deviations are eliminated. Then the average values are taken, and the MT values are obtained as shown in Tab. 3.

| Number | M   | D   | R   | W   | Maximum MT (°C) |
|--------|-----|-----|-----|-----|-----------------|
| 1      | 45 steel | 32   | 96  | 0.020 | 272.5           |
| 2      | 45 steel | 36   | 110 | 0.025 | 293.3           |
| 3      | 45 steel | 38   | 115 | 0.030 | 322.4           |
| 4      | 40Cr    | 32   | 110 | 0.030 | 394.4           |
| 5      | 40Cr    | 36   | 115 | 0.020 | 408.4           |
| 6      | 40Cr    | 38   | 96  | 0.025 | 395.9           |
| 7      | Q235    | 32   | 115 | 0.025 | 338.8           |
| 8      | Q235    | 36   | 96  | 0.030 | 347.1           |
| 9      | Q235    | 38   | 110 | 0.020 | 312.1           |

As shown in Tab. 3, the highest MT that occurs in test is 408.4 °C, the minimum MT in test is 272.5 °C, and overall MT are between 300 °C and 400 °C. Generally, machining performance of the workpiece material, workpiece diameter, milling cutter speed and feed per tooth have a positive correlation with the maximum MT.

According to the principle of orthogonal experiment, the $K$ value and the average $K$ value of the maximum MT measurement data in Tab. 3 are calculated and a decimal number is retained. Using the numerical values of $\bar{k_1}$, $\bar{k_2}$ and $\bar{k_3}$, the relationship between the four factors and the highest MT is obtained, as shown in Fig. 4.

![Fig. 4 The relationship between four factors and the maximum MT](image)

It can be obtained from Fig. 4, four influencing factors are analyzed based on the fluctuation of the highest MT value. Among them, workpiece material and feed per tooth have the greatest influence on MT, and milling cutter speed and workpiece diameter have little effect on MT. For workpiece material, MT measured during the cutting process from high to low is 40Cr>Q235B>45 steel. 40Cr is difficult to process with high hardness and poor processing performance; Q235B has lower hardness and poor processing performance; in contrast, 45 steel has the best processing performance, so workpiece material processing performance has a positive correlation with MT.

According to the orthogonal test results, in order to reduce MT and machining errors of the workpiece in the actual production. For the same workpiece material, the process parameters should give priority to the combination of smaller single-tooth feed and higher rotational speed; for low-carbon steel materials such as 20 steel and Q235B, we can use larger single-tooth feed and lower rotational speed; for medium carbon steel materials such as 45 steel, large single tooth feed and medium rotational speed can be used; for workpiece materials such as 40Cr, stainless steel, die steel, etc., which are difficult to machine and have large diameters, process parameters should use small
single tooth feed and higher speed.

2.3 Mathematical model fitting of MT

According to metal cutting research conclusions, there is a complex exponential relationship between cutting temperature and cutting parameters. The main factors affecting MT include workpiece material, workpiece diameter, milling cutter speed and feed per tooth, since there are large differences in the values among the parameters corresponding to each factor. Therefore, normalized processing of each group of data in Tab. 3 can improve the accuracy of fitting. The mathematical model of MT is put forward as shown in equation (1).

\[
T_{max}^{i} = K \left( \frac{M_i}{\sum_{i=1}^{n} M_i} \right)^{a} \left( \frac{D_i}{\sum_{i=1}^{n} D_i} \right)^{b} \left( \frac{R_i}{\sum_{i=1}^{n} R_i} \right)^{c} \left( \frac{W_i}{\sum_{i=1}^{n} W_i} \right)^{d}
\]

where \( T_{max}^{i} \) represents the maximum MT value obtained in \( i \)-th group test; \( K \) is a comprehensive correction coefficient that determines milling conditions, friction coefficient, etc., and \( a, b, c, \) and \( d \) are unknown coefficients to be solved, \( i \) is a positive integer, and \( n \) is the number of tests.

Take the logarithm of two sides of equation (1), equation (2) may be obtained:

\[
\log \left( \frac{T_{max}^{i}}{\sum_{i=1}^{n} T_i} \right) = \log K + a \log \left( \frac{M_i}{\sum_{i=1}^{n} M_i} \right) + b \log \left( \frac{D_i}{\sum_{i=1}^{n} D_i} \right) + c \log \left( \frac{R_i}{\sum_{i=1}^{n} R_i} \right) + d \log \left( \frac{W_i}{\sum_{i=1}^{n} W_i} \right)
\]

Suppose that

\[
E = \log \left( \frac{T_{max}^{i}}{\sum_{i=1}^{n} T_i} \right), \quad X_0 = \log K, \quad X_1 = \log \left( \frac{M_i}{\sum_{i=1}^{n} M_i} \right), \quad X_2 = \log \left( \frac{D_i}{\sum_{i=1}^{n} D_i} \right), \quad X_3 = \log \left( \frac{R_i}{\sum_{i=1}^{n} R_i} \right), \quad X_4 = \log \left( \frac{W_i}{\sum_{i=1}^{n} W_i} \right),
\]

and all of these are substituted into equation (2) to obtain equation (3):

\[
E = X_0 + aX_1 + bX_2 + cX_3 + dX_4
\]

After normalizing the orthogonal test data in Tab. 3, the multiple linear regression method is adopted to fit experimental data on the Matlab software platform. The test values of 45 steel, 40Cr, and Q235B are based on the corresponding Rockwell hardness of 28HRC, 32HRC, and 15HRC as fitting parameters. After fitting the solution to the values of coefficients in the mathematical expression, we have equation (4):

\[
T_{max}^{i} = 0.0364 \left( \frac{M_i}{\sum_{i=1}^{n} M_i} \right)^{0.19} \left( \frac{D_i}{\sum_{i=1}^{n} D_i} \right)^{0.07} \left( \frac{R_i}{\sum_{i=1}^{n} R_i} \right)^{0.16} \left( \frac{W_i}{\sum_{i=1}^{n} W_i} \right)^{0.21}
\]

Equation (4) can be further simplified, and then the equation (5) may be obtained.

\[
T_{max} = 0.0364 \frac{\sum_{i=1}^{n} T_i}{\left( \sum_{i=1}^{n} M_i \right)^{0.19} \left( \sum_{i=1}^{n} D_i \right)^{0.07} \left( \sum_{i=1}^{n} R_i \right)^{0.16} \left( \sum_{i=1}^{n} W_i \right)^{0.21}} M^{0.19} D^{0.07} R^{0.16} W^{0.21}
\]

where \( T_{max} \) is the fitting value of the maximum MT,

\[
\frac{\sum_{i=1}^{n} T_i}{\left( \sum_{i=1}^{n} M_i \right)^{0.19} \left( \sum_{i=1}^{n} D_i \right)^{0.07} \left( \sum_{i=1}^{n} R_i \right)^{0.16} \left( \sum_{i=1}^{n} W_i \right)^{0.21}}
\]

is a constant, so the mathematical model between NCSBMC maximum MT and four factors is calculated as shown in equation (6):

\[
T_{max} = 12.083 M^{0.19} D^{0.07} R^{0.16} W^{0.21}
\]

From equation (6), the degree of influence of each factor on the MT can be quantified. Compared with milling cutter speed and workpiece diameter, feed per tooth and workpiece material have great influences on the MT. It is consistent with the conclusions obtained from the orthogonal experiment, which shows that the MT mathematical model has certain accuracy. In order to further verify the accuracy of MT mathematical model, the residual rationality analysis of equation (6) is shown in Fig. 5.
According to Fig. 7, the residuals are evenly distributed around the zero line and the zero point is within the confidence interval. It is also indicated that the mathematical model conforms original data. In the mathematical model of calculation, the fitting degree of MT sample data is $R^2=0.2492$, which indicates that MT mathematical model is well fitted; and the overall significance test value of all variables of MT is $F= 0.3319>0$, which meets the requirements. According to the residual analysis, the MT mathematical model of NCSBMC can be applied into the theoretical research and actual production.

3. Research on the variation laws of MT
Under the same or similar conditions, for the commonly used 45 steel workpiece material, comparative test results and corresponding simulation results are used to further research the MT variation laws with NCSBMC. The simulation and test parameters of NCSBMC are shown in Tab. 4.

### Tab. 4 Simulation and test parameters

| Project                  | Simulation parameters | Test parameters     |
|--------------------------|-----------------------|---------------------|
| Milling cutter specification | φ460×2.7×50×60Z       | φ460×2.7×50×60Z     |
| Saw tooth material       | Ti(C,N)-based cermet  | Ti(C,N)-based cermet|
| Workpiece material       | AISI 1045             | 45 steel            |
| Workpiece diameter       | φ32mm                 | φ32mm               |
| Feed per tooth           | 0.020mm               | 0.020mm             |
| Milling cutter speed     | 96RPM                 | 96RPM               |
| friction coefficient     | 0.3                   | -                   |
| Cutting fluid            | -                     | Water-insoluble cutting oil |

(Note: the mechanical properties of AISI1045 material are equivalent to 45 steel)

3.1 MT from 3-D simulation
3-D simulation of MT is carried out in the FEM physical simulation software of AdvantEdge. In order to improve simulation efficiency and accuracy, simplify and optimize the structure of NCSBMC with the overall number of meshes, 3-D simulation model and milling cutter mesh model are given in Fig. 6. The mesh density of milling cutter base and saw tooth cutting area is different, and the cutting area is refined to improve simulation accuracy and efficiency.
Simulation results of MT obtained by polynomial fitting are shown in Figs. 7 and 8 with the temperature field distribution of two adjacent saw teeth and that of the fresh chip respectively. Fig. 7 (a) shows the temperature distribution on the first tooth of a pair of the two adjacent saw teeth, and Fig. 7 (b) gives the temperature distributions of the second tooth. Figure 8 shows the temperature distribution of the milling area where the chip has just been discharged.

3.2 Experimental study on MT

The high-speed infrared camera ImageIR5325 is used to collect and filter the infrared radiation energy in milling area. The infrared thermal image monitored in milling area is shown in Fig. 9. Fig. 9 (a) is an overall thermal image of the initial cutting state of milling cutter; Fig. 9 (b) is a partial enlarged thermal image of NCSBMC while participating in the maximum number of milling teeth; Fig. 9 (c) is a partial enlarged thermal image of chips discharged. Filtering the infrared radiation energy signal in milling area, the MT process curve is shown in Fig. 10.
3.3 MT simulation and test comparison analysis

For the solid bar with diameter of $\phi 32$ mm and workpiece material of 45 steel, the temperature field monitoring results obtained by simulation and test under the same or similar conditions are shown in Fig. 9-12. In the simulation process, when the workpiece is cut by cold sawing from Fig. 9(a) and Fig. 9(b), two adjacent saw teeth are cut into one set, and the chips are divided into two parts by the chip groove. The first saw tooth cuts off one layer on workpiece, and the second saw tooth cuts off the remaining part of the layer (the part corresponding to the chip groove). Fig. 10 shows the temperature field distribution of the chip as it exits the milling area, the temperature field of the chip obtained from Fig. 10 is roughly divided into three regions. The highest temperature measured in the area where the milling cutter is milling and the chip groove is in contact, as shown in the red part of the I area in Fig. 10; the temperature measured in the middle area of the chip is second, as shown in the orange part of the II area in Fig. 10; The chip area that is first separated from the workpiece measured the lowest temperature, as shown in the yellow and blue parts of the III area in Fig. 10. The formation, breaking and discharge of each chip has experienced an excessive transition from I region to III region, reflecting the diffusion process of chip temperature, it shows that the chips carry a lot of heat. By combining Fig. 9 and Fig. 10, it can be concluded that the highest MT center of cold sawing is located at the interface between the bottom layer of the chip at a certain distance from the tool tip and the portion of the cutting layer adjacent to the bottom layer of the chip. The highest MT is about 300-320 °C, and the milling area temperature is about 270-290 °C, but the part is small; the measured temperature of workpiece and the base part of milling cutter is around 50 °C.

During the test, it can be seen from Fig. 11 that the heat generated by cold sawing is concentrated on a minute area of two packs: a tiny region of the milling layer, and an infinitesimal zone of the chip bottom layer. Other areas have coarse heat distribution with lower temperature. It can be seen from Fig. 11(b) that when the number of the saw teeth participating the sawing simultaneously is the most, the milling area produces the heat most. However, the change in the maximum MT value is not obvious.
Also available in Fig. 12, as the sawing time of cold sawing increases, the maximum MT is almost constant. By combining Fig. 11(b) and Fig. 12, at the same time, the number of saw teeth involved in milling has less influence on the maximum MT, which is consistent with the mathematical model fitted by equation(6). It can also be seen from Fig. 11(c), chips are divided into two parts under the action of the chip groove. The heat generated by the cold sawing is mainly transferred to the chips by the saw teeth and carried away by chips, so workpiece and the base part of milling cutter remain relatively cool. By combining Fig. 11 and Fig. 12, it can be concluded that, the highest MT generated during the test is 290 °C-300 °C, workpiece temperature is maintained at around 50 °C.

Through the comparison of simulation results and test gains, we can see that, for the solid bar with diameter of φ32mm of 45 steel, the maximum MT of the NCSBMC measured by simulation and test is about 300 °C, workpiece temperature is kept at around 50 °C. The simulation and test results are not completely consistent with the friction coefficient set in the simulation process and whether the cutting fluid is used or not. Under the action of the chip groove, the chip is divided into two parts. The heat generated during the milling process is mainly concentrated on the chips and the tiny areas of the milling section. The highest milling temperature center is located at the interface between the bottom layer of the chip at a certain distance from the tool tip and the portion of the cutting layer adjacent to the bottom layer of the chip. Most of the heat is removed from the cutting zone along with chips, which keeps milling cutter and workpiece at a relatively low temperature.

4. Comparative experimental study

Milling tests are carried out on the P-150B intelligent circular saw machine with NCSBMC and THSBMC. According to the test results and machine tool display parameters, the comparison parameters of NCSBMC and THSBMC are shown in Tab. 5.

| Comparison item          | NCSBMC          | THSBMC          |
|--------------------------|-----------------|-----------------|
| Milling cutter specification | φ460×2.7×50×60Z | φ460×3.0×50×60Z |
| Saw teeth material       | Ti(C,N)-based cermet | Cemented carbide |
| Workpiece material       | 45 steel        | 45 steel        |
| Workpiece diameter       | φ32mm           | φ32mm           |
| Feed per tooth           | 0.020mm         | 0.020mm         |
| Milling cutter speed     | 96 RPM          | 96 RPM          |
| Maximum MT               | 300 °C          | 475 °C          |
| Total machine power      | 3.7 KW          | 6.2 KW          |

According to Tab. 6, under the same conditions, the maximum MT and total machine power of the THSBMC are 1.6 times and 1.7 times those of the NCSBMC respectively. Compared with THSBMC, NCSBMC has the characteristics of lower MT and lower energy consumption.

Through comparative experimental research, the reasons for the lower MT and lower energy consumption of NCSBMC can be summarized into two points. First, because NCSBMC saw teeth material is Ti (C, N)-based cermet, its Rockwell hardness is 2.5-5 times the Rockwell hardness of the workpiece material. However, THSBMC saw teeth use cemented carbide, its Rockwell hardness is about 1.5-2 times the Rockwell hardness of workpiece material. Compared with cemented carbide, cermet has lower affinity with carbon steel and less friction coefficient. Second, due to the special setting of NCSBMC chip groove, chips are easily formed, broken and discharged during milling. Most of the heat is removed from the milling zone with the chips, which keeps the milling cutter and workpiece at a relatively low temperature.

5. Conclusion

In the current study, the NCSBMC is tested at the production site for the milling temperature law.
Based on the orthogonal test method and comparative study, combined with simulation analysis, the test has been done with the main conclusions as follows.

(1) Using the four-factor and three-level orthogonal test method, the influence curves are obtained of workpiece material, workpiece diameter, milling cutter speed, and feed per tooth on MT. These curves indicate that feed per tooth and workpiece material have a greater influence on MT. By normalizing the experimental data and using the multiple linear regression method to fit the mathematical model of MT containing these four main influencing factors, the influence degree of each factor on MT is quantitatively determined, and the accuracy of the mathematical model is verified by residual analysis.

(2) Simulation analysis and experimental study of cold sawing milling process are carried out, with workpiece material is the 45 steel solid bar with diameter of φ32mm. Under the action of the chip groove, chips are divided into two parts, the highest MT center of NCSBMC is located at the bottom of the chip at a certain distance from the tip and the interface of the corresponding cutting layer adjacent to the bottom layer of the chip. In the sawing progress, most of the heat is removed from the milling zone with the chips, which keeps the milling cutter and workpiece at a relatively low temperature. The maximum MT measured during sawing is around 300 °C, and workpiece temperature is maintained at around 50 °C.

(3) In the same or similar cases, through experimental comparison, the maximum MT and total machine power of the THSBMC are 1.6 times and 1.7 times that of the NCSBMC, respectively. The maximum MT of NCSBMC is about 175 ° C lower than the maximum MT of the THSBMC. The saw teeth material and the chip groove setting are the two main reasons for the lower MT of NCSBMC.

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