The investigation of the optimization scheme of the low-cycle fatigue cropping based on the acoustic emission technique

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Abstract
Low-cycle fatigue cropping (LCFC) is a new metal bar separation method which utilizes the material fracture under cyclic load. To achieve good and fast separation of metal bars, a control scheme based on characteristics of whole cropping process is necessary. Three kinds of materials, such as 16Mn, 1045 and Al 6061, have been operated in this study and found that the kurtosis is more suitable as a monitoring parameter in control method, because it has a better stability in the complicated industrial environment. In addition, crack instability stage formed the most uneven region on the section and the best time when change the frequency is before crack instability stage. According to the above results, an optimal control scheme which by reducing the loading frequency before the crack instability stage based on the acoustic emission kurtosis is proposed. Moreover, four control strategies’ results for three kinds of materials are compared, and find the section quality increases with the decrease of loading frequency, but the effect of this increase decreases with the decrease of loading frequency. To evaluate the advantages and disadvantages of the control strategy, a parameter combining efficiency and section quality is proposed, and according to this parameter, the most suitable control strategy for three materials is obtained.

Keywords Low-cycle fatigue cropping · Acoustic emission · Ring-down counts · Kurtosis · Section quality · Optimal control method

Abbreviations
LCFC  Low-cycle fatigue cropping
AE  Acoustic emission
MES  Maximum equivalent stress
SEM  Scanning electron microscope
FEM  Finite element method
RA  Ratio of rise time to amplitude
ASL  The average value of the amplitude of AE signal
PLC  Programmable logic controller
OM  Optical microscope
$K_{th}$  Threshold stress intensity factor
$K_{IC}$  Fracture toughness
$T$  Transient time, s
$h$  The height between the highest point and the lowest point on the section
$S$  The area of the fracture zone
$W$  The evaluation parameter of section quality and efficiency

1 Introduction
The separation of metal is the first step of industrial production. There are some common deficiencies in traditional separation method, such as the high active load, low energy efficiency and a large number of sectional defects exits. Hua et al. [1] proposed the low-cycle fatigue cropping (LCFC) method, which could solve the above problem. In this method, a metal bar is applied on the cyclic loading, and a
V-shaped groove is prefabricated on the surface of the bar to produce the stress concentration effect. Dong et al. [2] investigate the evolution of the LCFC by using SEM, find cracks initiate at the root of V-shaped groove, and propagate throughout the V-shaped groove until fracture. Wang et al. [3] used the analytical, numerical and experimental methods to investigate the kinetic properties of the LCFC; the results showed LCFC an advanced green manufacturing method, which overcomes the problem of high active load in the traditional cropping method.

In addition to reducing active load, improving section quality is another key problem of low-cycle fatigue blanking process. To eliminate the defect of the section, numerous research efforts have been devoted. Some studies focus on the processing parameters of the LCFC system. Zhong et al. [4] investigated the effect of the interstice and the notch-sensitivity in the LCFC process, and pointed out the ductile damage initiation was affected by the interstice (C1) between the bar and the clamping device, and the interstice (C2) between the bar and crevice significantly; for metal bars with a diameter of 40 mm, the optimal geometric parameters are C1 = 0.1 mm, and C2 = 0.1 mm. By investigating the effect of the bottom corner of the groove on the metal bar surface and the impact of clamping position, Zhang et al. [5] found the crack initiate at the MES (maximum equivalent stress) gradient point and obtained the proper clamping position: the rate of distance \( L1 \) (distance between groove and clamping position) to the bar diameter is 0.3, and the rate of distance \( L2 \) (distance between groove and cropping die) to the bar diameter is 0.25. Besides, Zhao et al. [6] established a FEM (finite element method) model to investigate the temperature versus stress, and found that the cropping time was reduced by a prefabricating crack at the notch bottom with the heat stress. Other researchers design different control curves during the cropping process. Zhao et al. [7] designed two control curves, and found that constantly increasing displacement and reducing striking frequency can obtain stable crack propagation and fracture. Hua et al. [1] designed five types of control curves to study the influence of loading mode on section quality. The results showed that the linear decrement control curve had a good performance in producing high-quality section. However, the above control strategies are based on experience rather than the characteristics of the crack growth process, which leads to the efficiency and the section quality, have not been improved to the maximum extent. Therefore, the primary work of this research is to find a suitable method to get the characteristics of low-cycle fatigue cropping process and propose an optimal control method for LCFC.

Carolan et al. [8] pointed out AE technique is effective to measure the changing process of metal materials with non-contact, and can get change rule of fatigue process. Fang and Berkovits [9] carried out fatigue tests on Incoloy 901 material specimens by using the AE method. He found AE signal generates when plastic deformation, crack initiation and crack propagation occur, and characteristics of the fatigue process can be obtained via analysis of the AE signal. One analysis method is parameter analysis which is based on the properties of the signal. Many parameters, such as amplitude, ring-down counts, kurtosis and energy, can be used to analyze fatigue crack propagation process. Roberts and Talebzadeh [10] set up an AE system to monitor the steel and welded steel fatigue propagation, and obtained the reasonable relevance between the rates of AE counts and the rates of crack propagation. Elforjani and Mba [11] used energy, counts, amplitude and ASL (the average value of the amplitude of AE signal) in a shaft run to failure tests, and prove these parameters that detect the crack and damage in low-speed shaft are effective. Han et al. [12] established the relationship among the counts, cycles and crack length by studying the characteristics of fatigue crack propagation stage in the base metal and weld of Q345 steel. According to the results, Han divided the fracture process into 3 stages: crack initiation stage, crack growth stage and final fracture. Yu et al. [13] found the absolute energy could be used to warn the unstable growth because of the absolute energy less depended on the threshold value. Aggelis et al. [14] come up with a new parameter RA value (ratio of rise time to amplitude) and used it do a damage assessment for metal plates. He found the RA value could indicate the predominant cracking model from tensile to shear. Chai et al. [15] came up with a new parameter: AE entropy to investigate the fatigue process of 316LN stainless steel, and found it can be used to assess the damage of fatigue process under high noise loading environment accurately.

Based on the application progress of AE technology in high-cycle fatigue, more and more scholars begin to pay attention to the application of AE technology in the field of low-cycle fatigue. Li et al. [16] found amplitude; ring-down counts and kurtosis are able to as monitoring parameters to study the LCFC process. Ren et al. [17] studied the effect of notch eccentric ratio during process of the LCFC by using counts and kurtosis, and found these parameters could offer valuable information to get the affection of the factors during the LCFC process. Since AE technology can obtain the characteristics of low-cycle fatigue cropping process, it may be feasible to use AE technology to achieve optimal control of the process. The goal of this paper is to come up with an optimal control method based on the AE technology and realize the high efficiency and good section quality simultaneously.

2 Principle of LCFC method

The schematic diagram of the principle of the LCFC is shown in Fig. 1. The fixed sleeve supports the left end of the bar, and the cropping die shove on the right end of
the bar. Due to the eccentricity between the axis $O_1-O_1$ and the axis $O_2-O_2$, the Eccentric sleeve die and spindle applied cyclic loading on the bar’s surface. Due to the pre-fabricated V-shaped groove, which generates stress concentration, the fatigue cracks occurred at the tip of notch and propagated until the metal bar fracture.

3 Materials and methods

A new type of LCFC experiment system is set up which includes three parts: LCFC machine, control system and monitoring system. A brief description of the composition and the principle of these three parts are given in the following content.

3.1 The new type of LCFC machine and experiment materials

The new LCFC machine is shown in Fig. 2. The left end of the metal bar is connected with the sleeve, which is fixed in the three jaw chuck 1. The servo motor 1 drives the ball screw to rotate, and the three jaw chuck 1 moves along the X-axis, at the same time the sleeve which fixed on the three jaw chuck 1 is contact and apply displacement load to the metal bar. The sleeve is a sliding bearing, and the diameter of the sliding bearing is larger than the diameter of the metal bar. When the axes of two three jaw chucks are at the same line, sliding bearing does not contact metal bar. Only when the metal bar is bent will one side of the bar and the sliding bearing contact each other. Besides, the material of the sliding bearing is ZCuZn25Al6Fe3Mn3, which has better wear resistance. The right side of the metal bar is fixed at the
prefabricated groove in the three jaw chuck 2, and it is driven by servo motor 2 to rotate along the Y-axis which applying a cyclic displacement load to the metal bar. Three jaw chuck 2, bearing pedestal, coupler and servo motor 2 make up the whole drive loading devices. The support seat 2 is installed on the t-shaped slot of the baseplate, which can slide on the baseplate and adjust the distance, and the whole drive loading device is installed on the supporting seat 2, so when the supporting seat 2 slides, it will drive the whole drive device to move, to adjust the distance between the two three jaw chucks, to adapt to the metal bar of different lengths. The experimental device is shown in Fig. 2b; the clamping position of the metal bar also can be seen. The sleeve is a sliding bearing. The diameter of the sliding bearing is larger than the diameter of the metal bar. When the axes of two three jaw chucks are at the same line, sliding bearing does not contact metal bar. Only when the metal bar is bent will one side of the bar and the sliding bearing contact each other. Besides, the material of the sliding bearing is ZCuZn25Al6Fe3Mn3, which has better wear resistance. Servo motor power is 2.6 Kw and the speed range is from -3000r/min to 3000r/min. The two servo motors controlled by two drivers, respectively, and the model of the driver is SBF-AL301.

Three metal materials are presented in this experiment: 1045, 16Mn and Al 6061. The materials properties are presented in Table 1. The geometric parameters of metal bar are presented in Fig. 3a. The length of the metal bar L1 is 75 mm, and the diameter of metal bar D is 12 mm. The width of the V-shaped notch C is 0.2 mm, and the angle of the V-shaped notch $\phi$ is 90°. The depth of V-shaped notch d is 1 mm, and the corner radius of the V-shaped notch is 0.1 mm. Three types of metal bars are shown in Fig. 3b. Forty samples of each type material have been experimented in this study. They have been set as 4 groups which under different control strategies.

### 3.2 The control system for LCFC

The diagram of the control system is shown in Fig. 4a. The computer sends pulse commands to the s7-200 programmable logic controller (PLC). Two servo motors are controlled by PLC, and provide a rotating load and eccentric displacement, respectively. The PLC program logic control schemes for servo motor 1 and servo motor 2 are shown in Tables 2 and 3, respectively. As shown in Fig. 4b, the rotation control program realizes high- and low-speed conversion through the PLC transmission pulse signal to switch the internal speed of the driver to achieve the conversion of high and low speed, the internal speed of the driver can be adjusted through the driver operation interface. The eccentric displacement control program realizes the displacement loading and unloading, and the flow chart is shown in Fig. 4c. In this study, high frequency is 20 Hz (1200 r/min), and low

### Table 1 Mechanical properties of the specimens [17–19]

| Parameters                          | 16Mn   | 1045   | Al 6061 |
|-------------------------------------|--------|--------|---------|
| Elastic Modulus ($E$)               | 206 GPa| 210 GPa| 71 GPa  |
| Poisson’s ratio ($\mu$)             | 0.3    | 0.3    | 0.33    |
| Yield strength ($\sigma_s$)         | 345 MPa| 355 MPa| 55.2 MPa|
| Tensile strength ($\sigma_b$)       | 470~630 MPa| 600 MPa| 124 MPa |
| Threshold stress intensity factor ($\Delta K_{th}$) | 183.41 MPa $\times$ mm$^{1/2}$ | 252.98 MPa $\times$ mm$^{1/2}$ | 3.47 MPa $\times$ mm$^{1/2}$ |
| Fracture toughness ($K_{IC}$)       | 443.64 MPa $\times$ mm$^{1/2}$ | 1675 ~ 1920 MP $\times$ mm$^{1/2}$ | 10.5 MPa $\times$ mm$^{1/2}$ |
frequency is set as 10 Hz (600 r/min), 8.33 Hz (500 r/min) and 6.67 Hz (400 r/min), respectively.

### 3.3 The monitoring system for LCFC

As shown in Fig. 5, the monitoring system includes a computer, a sensor (AE sensor) and an acquisition card (PCI-1714). The AE sensor model is Nano30 which peak frequency is 293 kHz, and the bandwidth is 125–750 kHz (Physical Acoustics Corporation, USA), and attached to the sleeve with a magnetic seat. The ultrasonic couplants are coated on the surface of sensor to ensure the intensity of the signal. During the experiment, signal are obtained by AE sensor, amplified by an operational amplifier, and stored in the computer through the acquisition card which sampling rate can attain 30 M/s. In this experiment, the sampling frequency is set as 2 MHz, the threshold value of the event is set as 0.2 V, which is about twice over the background noise to avoid noise signal interference. The gain amplifier is set as 20 dB. To preprocess the AE signal, the frequency range of the bandpass filter is set as 25 to 800 kHz. In addition, the kurtosis is calculated over a duration of 200 ms which not only ensure the enough number of signals in an interval of interval length which lead to the average results are more reliable, but also the processed signal interval length is not too long to reflect the change process.

### 4 Results and discussion

#### 4.1 AE results

To select a reasonable parameter as optimal control method parameter, two AE parameters: ring-down counts and kurtosis are compared in this section. Ring-down counts representing the number of events per duration, and are suitable to describe the crack propagation stage. Kurtosis representing an outlier-prone distribution related to the fourth
standardized moment about the mean of the data [20]; it can be used to characterize the sudden variation of material and describe the abrupt change between various stages. The ring-down counts during the LCFC process are used to compare with AE kurtosis to select a more suitable parameter as the critical parameter to optimize the control strategy.

Figure 6a, c, e shows the variation in ring-down counts vs. loading time for different kinds of metal bar materials. It can be seen, a sudden rise of ring-down counts ranged from 0 to 8000, 8453 and 3973 for 16Mn, 1045 and Al 6061 at the beginning of the LCFC process, respectively. This sudden increase is mainly related to the crack initiation stage. In this stage, cyclic loading will lead to cyclic slip and micro-crack produce at the adjacent region because of the stress concentrate effect. At this time, the plastic zone size is smaller than several grains diameter range, the crack growth rate is low and the average crack extension corresponding to each cycle is smaller than lattice spacing, the AE signal intensity is too low to detected. As the loading cycles increased, the micro-crack grows up to the size of several crystal lattice, macro cracks appear, and acoustic emission signal intensity is greatly enhanced which led the above phenomenon. Subsequently, as shown in Fig. 6a, c, the ring-down counts maintain a stable range, for 16Mn, from 1.3 to 9.7 s, the values of ring-down counts remain steady between 7000 to 10,000; for 1045, from 7.5 to 16.7 s, the value of ring-down counts remain steady between 7500 to 8500. This stage is mainly related to crack propagation. In this stage, the size of the plastic zone increased which reaches the level of multiple grain sizes and the intensity of the AE signal exceeds the threshold value. According to the previous studies, there is a good linear relationship between \( \log (da/dN) \) and \( \log \Delta K \). With the increase of the \( \Delta K \), the crack growth rate \( (da/dN) \) increased stably. However, Fig. 6e shows a different pattern of change that there is no stable stage of ring-down counts. This phenomenon can be described as follows: according to the study of RO Ritchie [21], the fracture toughness \( K_{IC} \) has a great influence on the crack propagation stage. If the \( K_{IC} \) of the material is too small, the exponent of crack growth rate increased immediately which led the crack growth increased rapidly and shorten the crack propagation duration. The range of \( K_{IC} \) of Al 6061 is 10.5 MPa m\(^{1/2}\) is smaller than other materials, hence the crack ratio of Al 6061 is extremely quick and the crack propagation stage shorten greatly which led the stable stage disappeared. At the last stage, the value of the ring-down counts decreases rapidly from 8320 to 0, 7860 to 0 and 3885 to 0 for 16Mn, 1045 and Al 6061, respectively. At this time, \( \Delta K = K_{IC} \) the crack growth rate \( (da/dN) \) reach a high value. At this stage, the crack expands rapidly, and the fracture form is mainly brittle fracture, with almost no plastic deformation. The energy of the acoustic emission signal decreases rapidly (the acoustic emission signal is proportional to the degree of plastic deformation), and the number of events that can be detected decreases rapidly.

Figure 6b, d, f shows the variation in ring-down counts vs. loading time for different metal bar materials. As can be seen from the parts of b, d, the peak of kurtosis concentrated in two areas. For 16Mn, the first peak of kurtosis emerged from 0.3 to 0.7 s; the maximum value of the kurtosis is 39. The second peak of kurtosis emerged from 9.7 to 10.5 s; the maximum value of the kurtosis is 156. For 1045, the first peak of kurtosis emerged from 3.1 to 4.3 s; the maximum value of the kurtosis is 83. The second peak of kurtosis emerged from 16.7 to 18.7 s; the maximum value of the kurtosis is 279. Ruiz-Carcel et al. [22] pointed out the kurtosis representing a distribution of outlier-prone, which can be defined as:

\[
\beta = \frac{E(x - \mu)^4}{\sigma^4}
\]  

where \( \mu \) is the mean of \( x \), \( \sigma \) is the standard deviation of \( x \) and \( E \) represents the expected value of quantity. \( x \) is equal to the amplitude of acoustic emission signal. According to Formula (1), kurtosis indicates the waveform’s smoothness, and the peak kurtosis value indicates a dramatic change of

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Fig. 5 Photograph and diagram of the monitoring system

![Monitoring System Diagram](image)
the material. The above results showed there are two time points in low-cycle blanking in which the signal changes dramatically. These two time points are defined as transition point 1 and transition point 2, respectively. As shown in Fig. 6f, for Al 6061, from 2.2 to 4.4 s, the value of kurtosis changes dramatically, which showed there is no stable stage from the crack propagation to the fracture. In other words, there is no significant boundary between crack propagation stage and fracture stage for Al 6061. This result consistent with the result of the ring-down counts which caused by the rapid crack grow during the crack propagation stage.

According to the above analyses, it can be known that ring-down counts and kurtosis can be used to monitor whole process of LCFC. However, above results are built in a relative quiet environment of the lab; the background noise is stable and low. In actual industrial production, background noise changes all the time. Hence, a parameter which is not affected by the threshold value of event will be more suitable for monitor the process of LCFC. According to the definition of ring-down counts and kurtosis, ring-down counts depend on the threshold value but kurtosis does not. When the threshold value of the event is change to 0.3 V, compare with Figs. 6c and 7a, it can be seen the maximum value of the ring-down counts and the duration of the rising and stable phases had changed when the threshold value changed. Compare with Figs. 6d and 7b, the variation in kurtosis as a function of fatigue loading time has not been changed. This result shows that kurtosis has better anti-interference ability and it is more stabilized and suited for monitoring the process of LCFC in a noisy factory environment.
4.2 Fatigue propagation mechanism

To determine the reasonable point for optimal control strategy, the evolution of fatigue propagation needs to be investigated and find when the most uneven fracture area produced. The macroscopic sections of metal bars and microscopic sections of metal bars are shown in Figs. 8 and 9, respectively.

As shown in Fig. 8a–c for 16Mn and 1045, there are three different zones which related to three stages of fatigue process: crack initiation stage, crack propagation stage and fracture stage for Al 6061, there are only two different zones which there is no obvious boundary between the crack propagation stage and the fracture stage. The positions marked by red dots in the Fig. 8 are scanned by SEM. As shown in Fig. 9a, d, g, the microscopic view of crack initiation stage of 16Mn, 1045 and Al 6061 revealed the fatigue striations predominant the zone 1. At zone II, the materials go through slight plastic deformation near the V-shaped notch and form the fatigue striations. In this stage, the materials crack along the direction of the red arrow which perpendicular to the fatigue band and the crack growth rate (da/dN) is less than 0.1 μm/cycle. The damage accumulates slowly, which leads to the signal strength are less than the threshold value. Hence, the ring-down counts and kurtosis are close to 0 in this stage. Figure 9b, e, h show the microscopic view of crack propagation stage; it can be seen for 16Mn and 1045, dimples and fatigue striations are predominant in crack surfaces; for Al 6061, there are almost no fatigue striations. The results of macro-picture and the microstructure of Al 6061 section also showed the small KIC led the crack growth rate great and the area of crack propagation stage disappeared. Compare with the crack initiation stage, the crack growth rate (da/dN) increased, which leads to the signal strength increase. Moreover, the formations of the dimples also generate intense AE signals. Hence, the value of ring-down counts in the crack propagation stage is much larger which in crack initiation stage. Figure 9c, f, i displays the microscopic image of the center area of the metal bar. Equiaxed dimples predominant the crack surface and the depth of the dimples are larger than which in the crack propagation stage. The above phenomenon shows that the tensile fracture is the primary damage model during the fracture stage. In this stage, metal bars go through unstable crack growth until fracture, large area of uneven fracture zone produced and the section quality reduced.

According to the study of [17], higher frequency can accelerate crack growth in the plastic zone and make the cropping

![Fig. 7 Ring-down counts vs. time a and kurtosis vs. time b with 1045 specimens when the threshold value of peak event is 0.3](image)

![Fig. 8 Macroscopic cross sections of metal bars. a 16Mn, b 1045, and c Al 6061](image)
efficiency improve, but it will lead to insufficient plastic deformation during the crack propagation, and the uneven area of fracture zone increased. Combine with the above microscopic evolution of the crack propagation, reduce the load frequency before crack unstable growth stage will reduce the uneven area of fracture, which is beneficial to improve the section quality and also ensure the cropping efficiency. The specific control methods will be discussed below.

4.3 The optimize control method and the assessment of section quality

According to the analyses of the above sections, the kurtosis is set as the critical parameter to monitor the process of LCFC and the best time to reduce the load frequency is before unstable crack propagation. As shown in Fig. 10, there is a rise edge before unstable crack propagation stage, which can be set as control point. It can be seen there are two rise edges during the whole process for 16Mn and 1045, and only one rise edge for Al 6061. Hence, for 16Mn and 1045, the time of second rise edge occurred is set as control point; for Al 6061, the time of first rise edge occurred is set as control point. To know the accurate time when rise edge occurred, derivative of kurtosis with time is calculated and the slope of kurtosis is named as C. After 10 groups of experiments for each material, for 16Mn, 1045 and Al 6061, the value of C is determined as 100, 300 and 20, respectively. T is a transient time that is used to avoid the interference.
of the first rise edge. After 10 groups of experiments for each material, T values of 16Mn, 1045 and Al 6061 is determined as 5 s, 10 s and 1 s, respectively. The control method scheme is illustrated in Fig. 11: first, metal bar is applied under high-frequency load, when load time over T and the slope of kurtosis exceed C, the computer gives a command to PLC to change the rotate speed of the servo motor from high frequency to low frequency and maintain low frequency until metal bar fracture. The whole process is monitored and controlled in real time.

To further study the influence of different load frequency after the control point on the section, 4 control strategies are come up with. As shown in Table 4, high frequency is set as 20 Hz, and three load frequencies, i.e., 8.33 Hz, 6.67 Hz, 5 Hz, are set in low-frequency region.

To compare the section quality before and after optimization, two evaluation indexes are presented, in which h represents the height difference of surface (the height between the highest point and the lowest point on the section), and S represents the area of the fracture zone. The OM system, OLYMPUS DSX1000, is used to observe the roughness of the section. The ×42 objective is selected and 3D information of the section surface is obtained through automatic image splicing.

The section information of metal bars with different control strategies is presented in Fig. 12. It can be seen from Fig. 12a that the roughness measuring part can be used to obtain the height (h). Each sample is measured 10 times, and the average height value of different materials under four control strategies are shown in Fig. 12b, c and d. When the frequency change at the control point, h reduces obviously. For 16Mn, the height value drops from 1836 to 1182 μm by 35.62%; for 1045, the height value goes from 721.3 to 368.2 μm by 48.95%; and for Al 6061, the height value goes from 52.35 to 35.21 μm by 32.74%. Furthermore, the area of the

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**Fig. 10** Rise edge of kurtosis and the slope of kurtosis of metal bars a 16Mn b 1045 c Al 6061

**Fig. 11** Logic of optimize control method

**Table 4** Four control strategies

| Strategy 1 | Strategy 2 | Strategy 3 | Strategy 4 |
|------------|------------|------------|------------|
| High-frequency region | 20 Hz | 20 Hz | 20 Hz | 20 Hz |
| Low-frequency region | 8.33 Hz | 6.67 Hz | 5 Hz |
fracture zone reduces significantly. For 16Mn, the area of fracture zone drops from 16.74 to 13.61 mm² by 18.70%; for 1045, the area of fracture zone drops from 7.630 to 3.650 mm² by 52.16%; and for Al 6061, the area of fracture zone drops from 1.25 to 1.15 mm² by 0.08%. The above results show that after the loading frequency changes from high frequency to low frequency, the section quality is significantly improved, and both the height difference of surface topography and the area of fracture area are decreased. At the same time, the sections of the three materials all show this change rule, which reflects that reducing the frequency after the transition point has universal applicability for improving the section quality of different materials. The optimize control method has a significant effect on section quality improving.

The change of bar section quality under lower loading frequency (6.67 Hz and 5 Hz) control strategy was further compared. According to Fig. 12b, c and d, the lower the loading frequency after the transition point, the smaller the height difference of surface and the fracture area of the section. The results indicate that the lower the loading frequency is, the better the section quality is. However, the reduction of loading frequency after the transition point will lead to the decrease of shear efficiency, so it is necessary to study the change law of section quality with the reduction of loading frequency. According to Fig. 12b, when the loading frequency drops from 20 to 8.33 Hz, from 8.33 to 6.67 Hz and from 6.67 to 5 Hz, height difference of surface of 16Mn section decreases by 35.62%, 16.84% and 11.45%, respectively. The area of fracture area decreased by 18.70%, 10.52% and 0.022% respectively. It can be found that with the decrease of loading frequency, the improvement effect of section quality decreases. The same conclusion can be obtained by studying the variation rule of section mass of 1045 and Al 6061 under different loading frequencies. This shows that the effect of loading frequency on section quality decreases with the decrease of loading frequency.

On the basis of overall consideration of cropping efficiency and section quality, which control strategy is better is a virtical problem. In this study, cropping time, height value of section and area of fracture zone considered equally important. Hence, a new parameter $W$ is proposed to measure the effect of different strategies which is expressed as:

$$W = h \times S \times t$$  \hspace{1cm} (2)

$t$ represents the cropping time. The trend of $W$ reveals the improvement effect of different control strategies on the efficiency and section quality, and the smaller value of $W$ indicates the better improvement effect under this strategy. Figure 13 shows the normalized $W$ of different materials with 4 strategies. It can be seen the value of normalized $W$ steepest decrease from strategy 1 to strategy 2, and it reaches the minimum value under strategy 3 for 16Mn, 1045 and Al 6061. Hence, the strategy 3 is the most suitable control strategy for Al 6061, 1045 and 16Mn.

Fig. 12  a Software interface of OLYMPUS DSX1000. b Height value and the area of fracture zone for 16Mn under four control strategies. c Height value and the area of fracture zone for 1045 under four control strategies. d Height value and the area of fracture zone for Al 6061 under four control strategies.
5 Conclusion

To achieve good and fast separation of metal bars, a process analysis and control scheme based on acoustic emission technology are proposed in this study. Through the experimental study on three kinds of materials, the fatigue cropping process characteristics of three kinds of materials and the key process parameters of the control scheme based on acoustic emission technology are obtained, and the optimization effect of the control scheme is evaluated. The detailed conclusions of this study are as follows:

(1) Ring-down counts and kurtosis are able to describe the whole LCFC process. However, the kurtosis is not affected by the threshold value of events. Hence, it is more suitable for monitoring the whole process of LCFC and as a critical parameter to optimize the control method in a noisy factory environment.

(2) Combining macro image, microstructure and acoustic emission results can be obtained for 16 Mn and 1045, the LCFC process is divided into three stages. The third stage is the fracture stage when metal bar is in a state of unstable crack, and lots tensile fracture occurred at this stage which produced the most uneven region of the section. For Al 6061, due to the fracture toughness is small, the unstable crack occurred earlier from the beginning of the crack propagation stage and last till fracture.

(3) An optimal control method has come up which used kurtosis described as follows: first, the metal bar applied a high-frequency cyclic loading and when the load time is over the T and the slope of kurtosis is bigger than C, the computer gives commands to a PLC to change the state of the serve motor from high frequency to low frequency until the metal bar fracture. Two control parameters, transient time T and the critical value of the slope of kurtosis C are determined. For 16Mn, 1045 and Al 6061, the T is 5 s, 10 s, and 1 s, respectively. For 16Mn, 1045 and Al 6061, the C is 100, 300, and 20, respectively.

(4) The section quality increases with the decrease of loading frequency, but the effect of this increase decreases with the decrease of loading frequency. In this study, a new parameter is proposed to measure the comprehensive effect of cropping efficiency and section quality improvement of different control strategies, and four different control strategies are analyzed and compared. It is concluded that control strategy 3 is optimal for 16Mn, 1045 and Al 6061.

Declarations

Conflict of interest There is no conflict of interest in this manuscript.

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