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# Roughness and micro pit defects on surface of SUS 430 stainless steel strip in cold rolling process

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**Abstract.** Experiment on roughness and micro pit defects of SUS 430 ferrite stainless steel was investigated in laboratory. The relation between roughness and glossiness with reduction in height, roll surface roughness, emulsion parameters was analyzed. The surface morphology of micro pit defects was observed by SEM, and the effects of micro pit defects on rolling reduction, roll surface roughness, emulsion parameters, lubrication oil in deformation zone and work roll diameter were discussed. With the increasing of reduction ratio strip surface roughness Ra(s), Rp(s) and Rv(s) were decreasing along rolling and width direction, the drop value in rolling direction was faster than that in width direction. The roughness and glossiness were obtained under emulsion concentration 3% and 6%, temperature 55°C and 63°C, roll surface roughness Ra(*r*)=0.5 $\mu$m, Ra(*r*)=0.7 $\mu$m and Ra(*r*)=1.0 $\mu$m. The glossiness was declined rapidly when the micro defects ratio was above 23%. With the pass number increasing, the micro pit defects were reduced, uneven peak was decreased and gently along rolling direction. The micro pit defects were increased with the roll surface roughness increase. The defects ratio was declined with larger gradient at pass number 1 to 3, but gentle slope at pass number 4 to 5. When work roll diameter was small, bite angle was increasing, lubrication oil in micro pit of deformation zone was decreased, micro defects were decreased, and glossiness value on the surface of strip was increased.

**Keywords:** stainless steel; cold rolling; lubrication; roughness; micro pit defects

## 1. Introduction

Cold rolled stainless steel strips had been widely used in various fields due to their excellent corrosion resistance, heat resistance, moderate strength and ductility, long life and recycling. In order to meet the requirement of application, chemical composition and degree of purity were controlled in stainless steel making. With the stainless steel making technology development of VD, VOD, AOD, GOR and SS-VOD, the control level of specific element in stainless steel, including oxide and sulfide was increasing gradually, internal quality of stainless steel was guaranteed.

Producing the stainless steel strips more efficiently had been attempted recently by tandem cold

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mill which had large diameter and high speed work rolls. The technology of rolling stainless steel strips with a tandem mill had become a hot spot because of the high efficiency. It had been reported by AK-Rockport steel factory, JFE Chiba steel factory, Nippon steel, and Sumitomo metal Ludao factory in recent years. Two critical technical issues should be solved in the technology of stainless steel tandem rolling. The first one was how to meet the high rolling force requirement because of the large diameter work roll used in tandem mill. Surface glossiness was reduced by high speed rolling, the surface brightness of stainless steel strip rolled by large diameter work rolls got worse than that rolled by small diameter work rolls. How to get good surface quality was the other critical technical issue in stainless steel tandem rolling.

Surface defects and roughness of steel strips in cold rolling were investigated by researchers. Kenmochi *et al*. (1997) researched the effect of micro defects on the surface brightness of cold rolled stainless strip. The surface brightness of the strip was deteriorated by high speed rolling, and the surface brightness of a strip rolled by large diameter work rolls became worse than that of a strip rolled by small diameter work rolls. Micro defects could be reduced to four types. The first was micro pit originating from the surface roughness of the mother sheet. The second was oil pit formed during cold rolling. The third was grooves formed by inter granular corrosion during pickling. The last one was scratches due to the surface roughness of the rolls. The micro pits remaining on the surface of cold rolled sheet were affected by the diameter of the work rolls, the surface roughness of the mother sheet, and the rolling reduction. Ahmed and Sutcliffe (2000) had an experimental investigation of the mechanisms of pit elimination in strip drawing and rolling of stainless steel strips. A comparison of strip drawn and cold-rolled stainless steel samples show that the change in pit area and Rq roughness varies with overall reduction in a remarkably similar way. Sun *et al*. (2000) investigated the roughness of SUS 304 stainless strip and viscosity of rolling oil. The thickness of oil film in deformation zone was related to roughness of work rolls, excessive oil generated by high viscosity would result in coarse plasticity on the surface of steel strips. The surface quality could be improved by high reduction in height and lower viscosity of rolling oil. Ma *et al*. (2002) carried out an experimental investigation of surface transfer in cold rolling of carbon steel strip and the influence of rolling parameters. The roughness analysis indicates that low reduction rolling could improve strip surface quality. The results of calculation showed that the strip surface did not follow a Gaussian distribution and symmetry of surface roughness had been observed at high-speed rolling. The wavelength components are revealed from power spectral density (PSD) and the height distribution of asperity is obtained by a bearing analysis. Jin and Ren (2011) investigated the heat scratch on strip surface in a 6 high tandem cold rolling mill. The results showed that roll bite lubrication and quenching may indeed play a large role in mill chatter. The main factors of the heat scratch included the film forming properties in a high temperature and high pressure rolling contact, boundary lubrication properties under high temperature, emulsion quenching properties, etc. It is shown that heat scratch can be significantly reduced or even eliminated by improving and optimizing these properties of the rolling lubricants.

In order to make wear mechanism clear, research works about friction and lubrication had been carried out in steel cold working. Dick and Lenard (2005) researched the tribological mechanisms with three kinds of lubrication oil during cold rolling of low carbon steel strips. The independent variables in the study were the viscosity of the oil in the emulsions, the roll roughness, the roll velocity and reduction. The roll roughness played an integral role affecting the dependent rolling parameters during cold rolling of steel strips. An increased roughness leads to an increase in the loads on the rolling mill. The viscosity of the oil did not have a major effect on the loads. Increasing speeds caused a reduction of the loads at higher roll roughness but with the smoother rolls no speed effect was observed. At higher roll roughness almost hydrodynamic conditions were observed. The dynamic concentration theory appeared to fit the observations well. Jiang and Tieu (2007) simulated the contact mechanics and work roll wear in cold rolling of thin strip using a developed modified influence function method. Surface roughness of the rolled strip on a cold rolling mill was characterized by a surface profile meter. The focus of this work on cold rolling of thin strip was to justify the roll bite contact mechanics and to analyze the friction in the roll bite and the effect of the friction on the strip profile and the surface finish. The lubrication film thickness had a significant influence on the surface quality of the cold rolled strip. Lo and Wilson (1999) established a theoretical model of micro-pool lubrication in metal forming. It showed that with sufficiently high viscosity and sliding speed, the lubricant trapped in the micropools between the tool and work piece can be drawn into the interface. The friction force is either increased or decreased, depending on the viscosity and sliding speed. Lu *et al*. (2003) developed the modeling of the lubrication in the mixed lubrication situation of cold strip rolling. The mixed film lubrication model was adopted to describe the behavior of the lubricant and asperity deformation. The elastic Von Karman equation was used to describe the elastic deformation of strip in the inlet zone. The length and lubricant film thickness of the inlet zone can be obtained by a numerical method. Saito *et al*. (1996) investigated the sliding wear tests of stainless steel couples in water at high temperature and load. The research was focused on the effects of load and water temperature on the wear rate, the mechanical behavior of the stainless steel surface and the water chemistry changes caused by continuous severe wear at elevated temperature. The wear rate increased exponentially with increasing load, and was two times great at 260°C than at room temperature. The ratio of wear rate of the rotating specimen to the stationary specimen decreased exponentially with increasing load. The wear particle sizes were distributed widely up to 4 mm, and most wear debris consisted of thin flakes with scratch marks on the surface. The bare surface of the stainless steel, created continuous by severe wear, was oxidized in high temperature water and caused the chemistry change such as the consumption of dissolved oxygen and the evolution of dissolved hydrogen. Saxena *et al*. (1996) proposed a model of cold strip rolling under hydrodynamic lubrication which combines the finite element analysis of strip with the refined analysis of the lubricant film. The viscosity of the lubricant is assumed to depend on both the pressure and the strain rate, while the strip is modeled as rigid plastic material. The thickness of the lubricant film is assumed to vary parabolically from inlet to exit. In the proposed model the roll force remains virtually unaffected by both the lubricant viscosity and the roll velocity and thus remains insensitive to lubrication. At high reduction or for a low value of the roll radius to strip thickness ratio, the film thickness becomes very small, requiring the use of high viscosity lubricant or a large roll speed to maintain hydrodynamic lubrication. Singh *et al*. (2008) developed a model to predict the oil film thickness at the deformation zone in terms of operating parameters particularly at the elevated roll speeds. The performance parameters in the lubricated domain have been evaluated for rolling speeds (up to 20.0 m/s), reduction ratios (0.05-0.20), and slip values varying up to 20%. Significant reduction in minimum film thickness has been observed with the increase in the rolling speed and slip. Empirical relations are developed for the prediction of minimum film thicknesses at the contact. A relation for evaluation of maximum film temperature rise in the inlet zone has been also developed. Wang *et al*. (2011) reported the friction behavior of SUS 304 austenitic stainless steel sheet under the condition of friction coupling plastic deformation. The results indicated that the friction coefficients between SUS 304 sheet strip and DC 53 forming tool firstly descended rapidly in the initial stage, which is followed by approaching an almost stable state. In addition, friction coefficients under high sliding speed and large pressure head extension tend to

Table 1 Inlet thickness, exit thickness, reduction, rolling speed, roll surface roughness and conditions of emulsion parameters for different rolling pass

| Pass number | Inlet thickness [mm] | Exit thickness [mm] | Reduction [%] | Rolling speed [m/s] | Ra(*r*) [$\mu$m] | Ce [%] | Te [°C] |
|---|---|---|---|---|---|---|---|
| 1 | 3.0 | 2.26 | 24.7 | 0.2 | 0.5, 0.7, 1.0 | 3, 6 | 55, 63 |
| 2 | 2.26 | 1.53 | 32.3 | 0.5 | 0.5, 0.7, 1.0 | 3, 6 | 55, 63 |
| 3 | 1.53 | 1.08 | 29.4 | 0.6 | 0.5, 0.7, 1.0 | 3, 6 | 55, 63 |
| 4 | 1.08 | 0.76 | 29.6 | 0.8 | 0.5, 0.7, 1.0 | 3, 6 | 55, 63 |
| 5 | 0.76 | 0.60 | 21.0 | 1.0 | 0.5, 0.7, 1.0 | 3, 6 | 55, 63 |

decrease with the increasing of external weight loading.

The surface brightness and micro pit defects was evaluated by visual evaluation, a surface gloss and micro meter. How surface roughness depends on surface glossiness and micro-defects been studied but no quantitative relationship had been advanced in previous studies. In this paper, experimental research on roughness, glossiness and micro pit defects of SUS 430 ferrite stainless steel was investigated in laboratory. The relation between roughness and glossiness with reduction in height, roll surface roughness, emulsion parameters was investigated. The surface morphology of micro pit defects was observed by SEM, and the effects of micro pit defects on rolling reduction, roll surface roughness, emulsion parameters, lubrication oil in deformation zone and work roll diameter were also analyzed.

## 2. Experimental materials and method

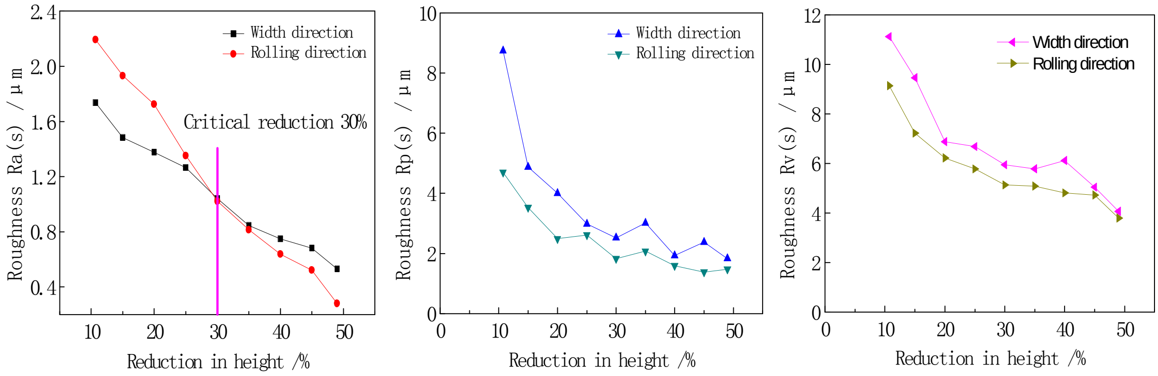
The chemical composition (wt. %) of the experimental material (SUS430 ferrite stainless steel) contained 0.039 C, 0.35 Si, 0.25 Mn, 0.014 P, 0.002 S, 16.01 Cr, 0.23 Ti, 0.0427 N and bal. Fe. Before cold rolling, the hot rolled stainless steel strips was treated by annealing in Bell type furnace and pickling in sequence. Dimensions of the sample were 3.0 mm in thickness and 120 mm in width.

The rolling oil was supplied by a chemical company. Viscosity value of the oil at 40°C was 61 $mm^2/s$, saponification value was 181 mgKOH/g, and acid value was 10.0 mgKOH/g. The emulsion was composed by mixed rolling oil (3%-7%) and deionized water (93%-97%). It was then used as lubricants at 55°C and 63°C in the cold rolling experiment. According to the processing requirements, the concentration and temperature of the emulsion could be adjusted.

Single sheet cold rolling with 9 passes was proposed to investigate the sheet surface roughness and micro pit defects. The thickness after cold rolling was 2.7-2.3-1.8-1.4-1.0-0.6-0.4-0.2-0.1. The reduction in height was 10.7%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 49% respectively.

The coiled strip cold rolling with 5 passes was used to test the strip surface roughness, glossiness and micro defects with roll surface and emulsion parameters. The target thickness was 0.6 mm and total reduction ratio in height was 80%. Inlet thickness and exit thickness of the tested strips, reduction distribution, rolling speed, roll surface roughness and conditions of the emulsion for 5 rolling passes were shown in Table 1.

It was noted that in Table 1, rolls surface roughness of arithmetic average deviation was presented by Ra(*r*) ($\mu$m), the letter r in parentheses represented rolls. Ce represented concentration




(a) Ra(s) (b) Rp(s) (c) Rv(s)

Fig. 1 Strip surface roughness along rolling and width direction at different reduction in height

of the emulsion (%) and Te represented temperature of the emulsion (°C).

A 4 high cold rolling mill (Φ110/Φ325×300 mm, maximum rolling force was 1000 kN, rolling velocity was 0-7 m/s, main motor power was 400 kW) was employed in the experiment. The material of work rolls was 9Cr2Mo steel. The emulsion system of the cold rolling mill had function of temperature control, flow control, mixing and iron power filter.

Surface roughness was measured by TR300 desktop roughness meter. Surface glossiness was measured by PicoGloss503 meter. Temperature was measured by portable Mxm1310 digital thermometer. In order to observe and analyze surface morphology, the strip samples were also scanned by Quanta600 SEM (Scanning electron microscopy). The micro defects ratio was calculated by measuring the ratio of the defect area observed through SEM to the whole observed area of the strips.

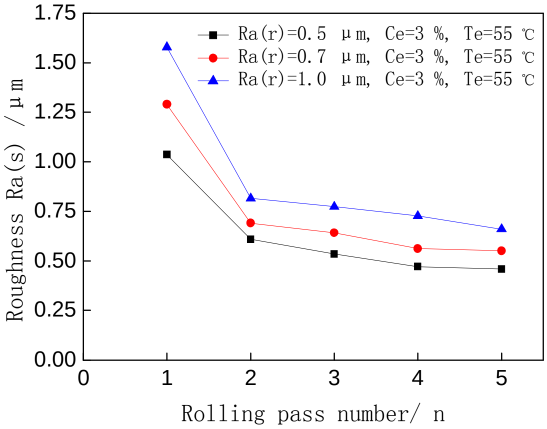
## 3. Results and discussion

### *3.1 Strip surface roughness with reduction in height*

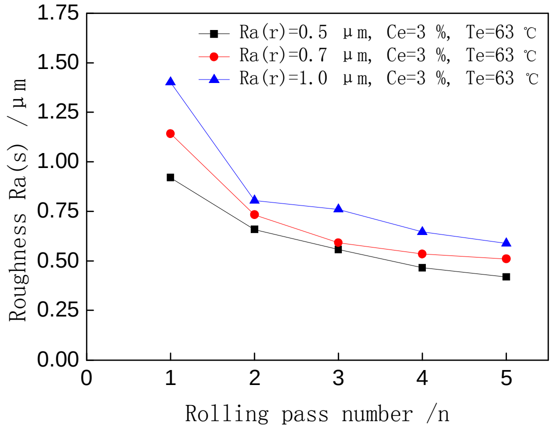
Strip surface roughness along rolling and width direction was measured at different reduction in height, including arithmetic average deviation Ra(s), maximum height of profile peak Rp(s), maximum profile deep valley Rv(s). The results were shown in Fig. 1. It is noted that the letter s in parentheses represented strip.

It was shown from Fig. 1, with the increasing of reduction the roughness value Ra(s), Rp(s) and Rv(s) of the strip was decreased along rolling and width direction. The drop of Ra(s) value in rolling direction was faster than that in width direction. The critical value of reduction was 30%. When the reduction was less than or equal to critical value, Ra(s) value in width direction was less than or equal to Ra(s) value in rolling direction. When the reduction was greater than critical value, Ra(s) value in width direction was great than Ra(s) value in rolling direction. While Rp(s) and Rv(s) value in width direction was throughout greater than that in rolling direction during deformation zone.

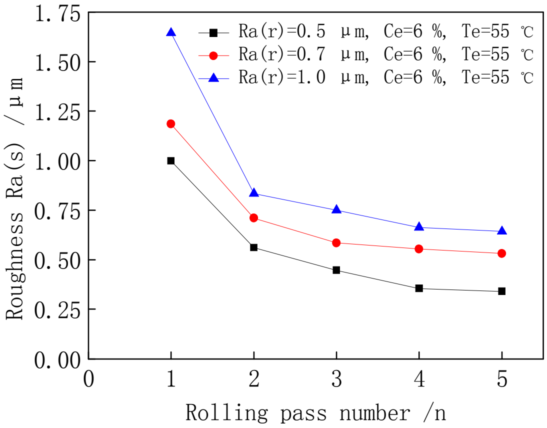
### *3.2 Strip surface roughness with roll surface roughness and emulsion parameters*



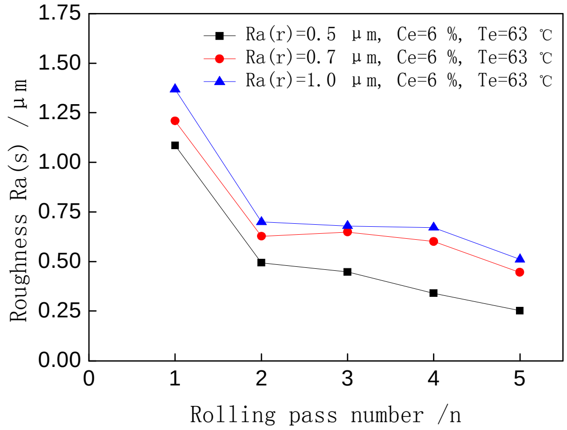

(a) Ce=3%, Te=55°C




(b) Ce=3%, Te=63°C




(c) Ce=6%, Te=55°C




(d) Ce=6%, Te=63°C

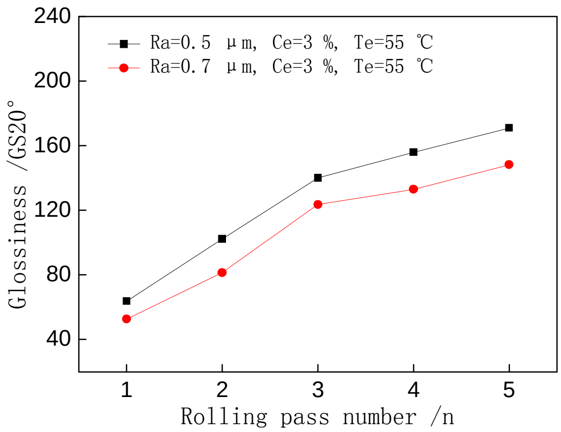
Fig. 2 The roughness value Ra(s) of the sample under the condition of emulsion parameters with roll roughness Ra(r)=0.5 $\mu$m, Ra(r)=0.7 $\mu$m and Ra(r)=1.0 $\mu$m

The roughness value Ra(s) of the sample was measured under different rolling pass with the emulsion parameters of Ce=3% and 6%, Te=55°C and 63°C, roll surface roughness Ra(r)=0.5 $\mu$m, Ra(r)=0.7 $\mu$m and Ra(r)=1.0 $\mu$m. The effects of strip roughness on roll surface roughness and emulsion parameters were shown in Fig. 2.

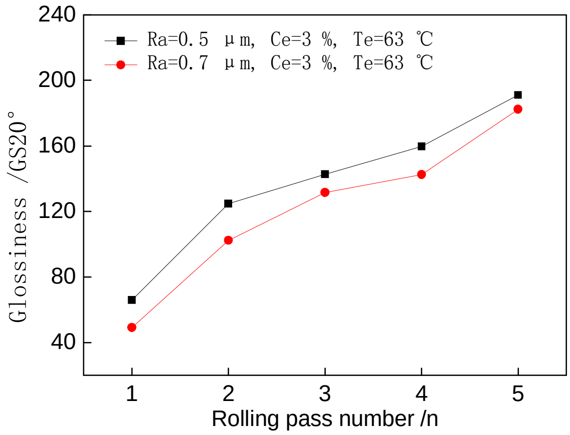
With the increasing of pass number, roughness of strip Ra(s) was slightly decreased under roll surface roughness Ra(r)=0.5 $\mu$m, Ra(r)=0.7 $\mu$m and Ra(r)=1.0 $\mu$m. At different rolling pass roughness of the strip Ra(s) was increased with the increasing of roll surface roughness Ra(r). In the same concentration of emulsion, roughness of strip Ra(s) was decreased when temperature of emulsion varied from 55°C to 63°C. In the same temperature of emulsion, roughness of strip Ra(s) was decreased when concentration of emulsion varied from 3 % to 6 %.

### *3.3 Strip surface glossiness with roll surface roughness and emulsion parameters*

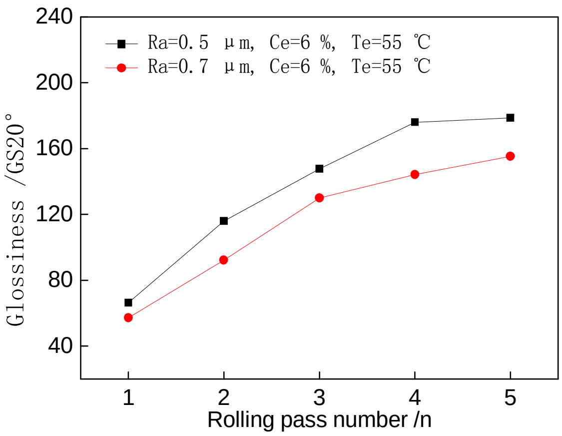
The glossiness GS20°, GS60° and GS85° value of strip surface was measured under Ce=3%



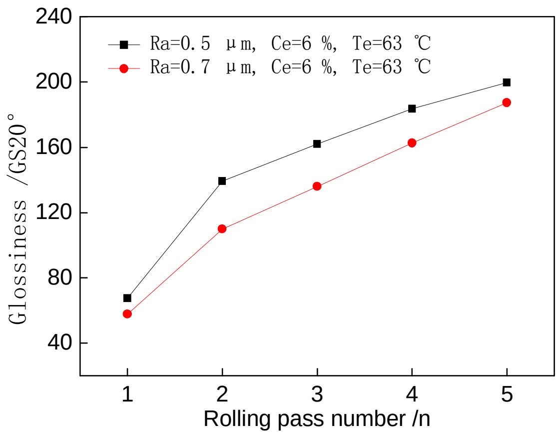

(a) Ce=3 %, Te=55°C




(b) Ce=3 %, Te=63°C




(c) Ce=6 %, Te=55°C




(d) Ce=6 %, Te=63°C

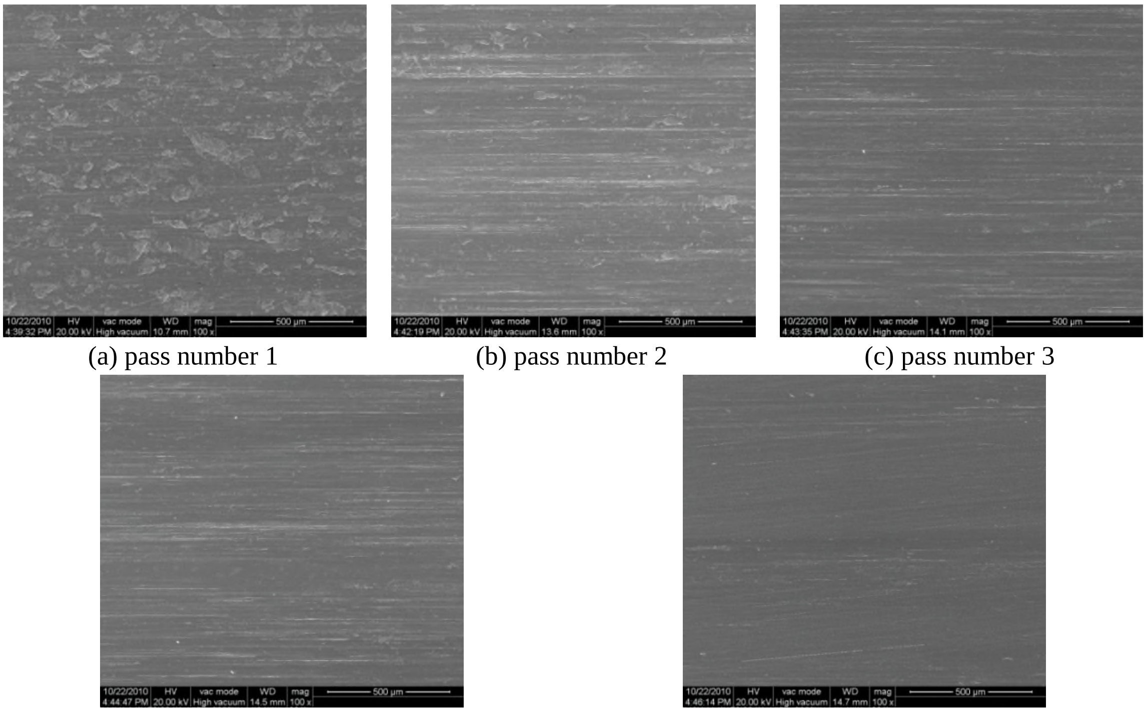
Fig. 3 Effects of strip glossiness value GS20° on roll surface roughness Ra(r)=0.5 $\mu$m, Ra(r)=0.7 $\mu$m and emulsion parameters

and 6%, Te=55°C and 63°C, roll surface roughness Ra(r)=0.5 $\mu$m and Ra(r)=0.7 $\mu$m. Because the regular variation of GS20°, GS60° and GS85° were the same, effects of glossiness value GS20° on roll surface roughness and emulsion parameters was shown in Fig. 3.

As it can be seen from Fig. 3, under the experimental conditions strip glossiness value GS20° was increased with the increasing of roll surface roughness at different rolling pass numbers. In the same concentration of emulsion, when temperature of emulsion varied from 55°C to 63°C glossiness of strip value GS20° was increased. In the same temperature of emulsion, when concentration of emulsion varied from 3% to 6%, glossiness of strip value GS20° was increased. The effect of temperature is evident, while the effect of emulsion on glossiness is very small.

### *3.4 Strip surface glossiness with micro defects*

The glossiness was affected by micro defects on the strip surface. The micro defects of the strip were observed by Quanta600 SEM at different pass numbers as shown in Fig. 4.



(a) pass number 1 (b) pass number 2 (c) pass number 3

(d) pass number 4 (e) pass number 5

Fig. 4 Morphology of micro defects were observed by Quanta600 SEM at rolling process

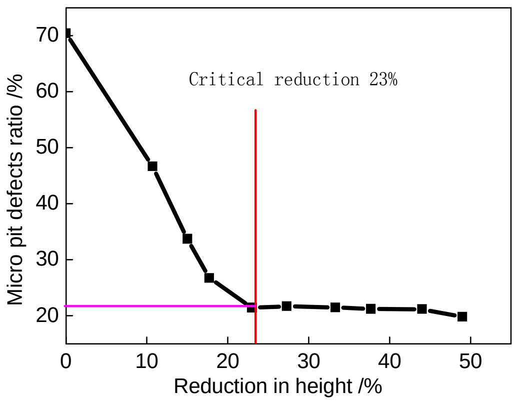



Fig. 5 The relation between surface micro pit defects with reduction

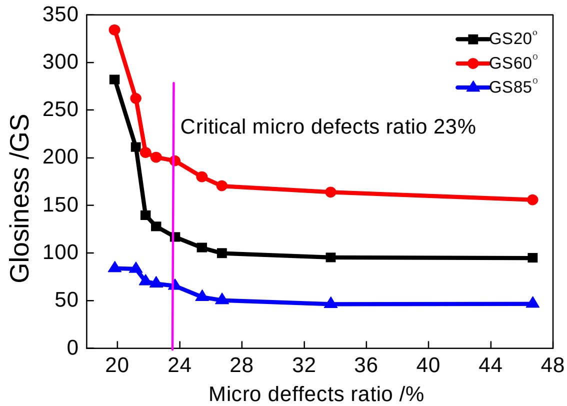
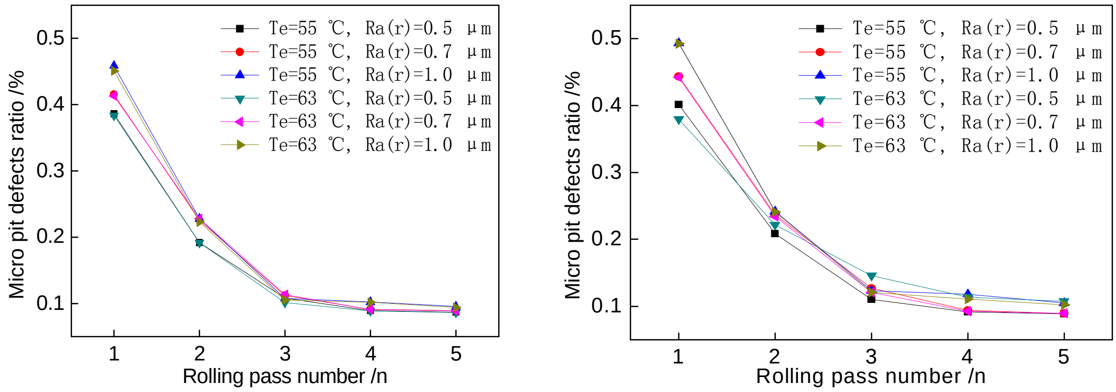



Fig. 6 The relation between glossiness value with micro defects ratio

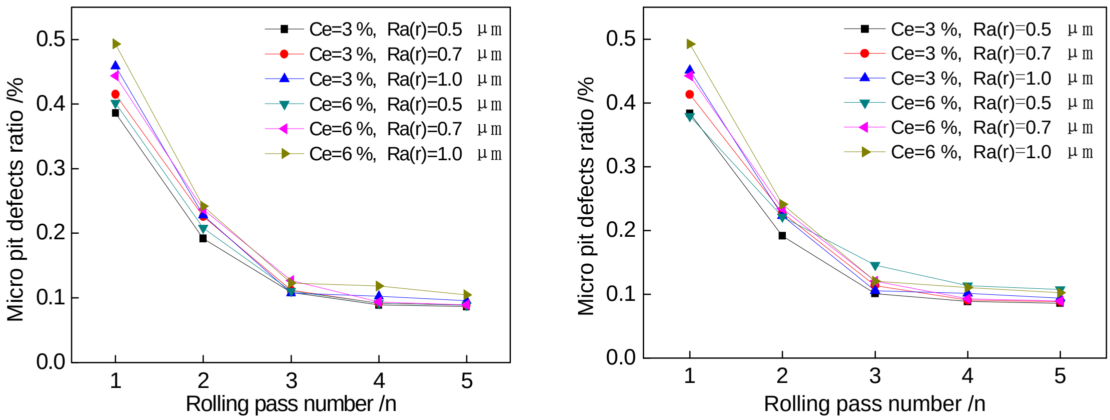
It was shown in Fig. 4(a), at the first rolling pass morphology of micro defects were polygon appearance, average length of long side was about 130 μm. At the rolling pass number 2, morphology of micro defects were deformed to elongated appearance as shown in Fig. 4(b). From Figs. 4(a)-(e), with the increasing of pass number, the micro defects was decreased, mechanical wear between rolls and strip along rolling direction was clearly occurred.

The reduction in height had effects on the surface defects in cold rolling. The relation between




(a) Ce=3% (b) Ce=6%

Fig. 7 Micro pit defects with Ra(r)=0.5 $\mu$m, 0.7 $\mu$m and 1.0 $\mu$m of rolls for different rolling pass




(a) Te=55°C (b) Te=63°C

Fig. 8 Micro pit defects under Ce=3% and 6% concentration of emulsion for different rolling pass

surface micro pit defects with reduction was shown in Fig. 5. It can be seen that the micro pit defects ratio was reduced from 70.5% to 19.8% with the increasing of reduction from 0 to 49%.

The glossiness value on degree of 20, 60 and 85 was also measured. The relation of micro pit defects and glossiness was shown in Fig. 6. It was seen from this figure, with the decreasing of the micro defects the glossiness of the strip was increased, while micro defects ratio was less than 23% the glossiness of the strip grew abruptly. So for the sake of less micro defects reduction in height must be large enough. It was interesting that the critical reduction and defects ratio were both about 23%, to guarantee the enough high glossiness the reduction in height must be greater than 23%.

### *3.5 Micro pit defects with roll roughness, temperature and concentration of emulsion*

Micro pit defects with Ce=3% and 6% under Te=55°C, 63°C, Ra(r)=0.5 $\mu$m, 0.7 $\mu$m and 1.0 μm for different rolling pass were measured and calculated. The result was shown in Fig. 7. It was seen from Fig. 7, when the concentration of emulsion was 3% and 6%, with the increasing of

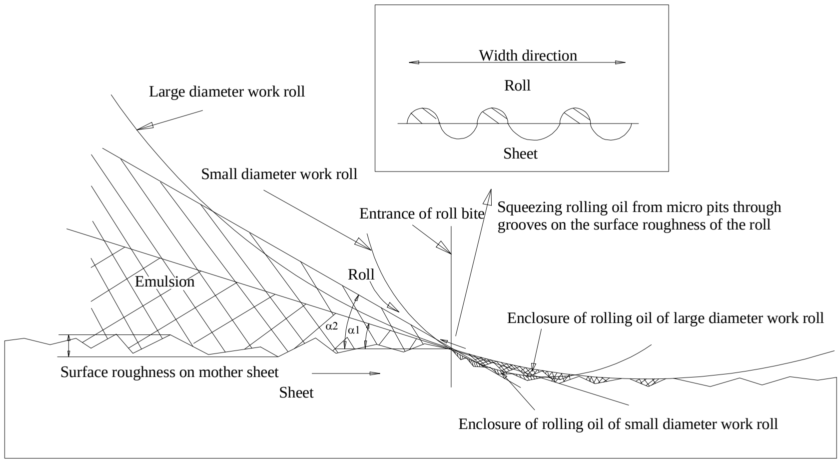



Fig. 9 Effect of micro defects on rolling oil nearby the deformation zone

rolling pass number micro pit defects ratio was reduced. The defects ratio was declined with larger gradient at pass number 1, 2 and 3, but gentle slope at pass number 4 and 5. The effects of temperature 55°C and 63°C on micro pit effects had not obvious difference. Roll surface roughness had great effect on micro pit defects. For the sake of minimum micro pit defects roll surface roughness should be 0.5 $\mu$m at pass number 1, 2 and 3, 0.7 $\mu$m at pass number 4 and 5.

Micro pit defects with Te=55°C and 63°C under Ce=3%, 6%, Ra(r)=0.5 $\mu$m, 0.7 $\mu$m, 1.0 $\mu$m for different rolling pass were measured and calculated. The result was shown in Fig. 8. It was seen from Fig. 8, when Te=55°C and 63°C, with the increasing of rolling pass number micro pit defects ratio was reduced. The defects ratio was declined with larger gradient at pass number 1, 2 and 3, but gentle slope at pass number 4 and 5. At pass number 1 to 3, when roll surface roughness Ra(r)=0.5 $\mu$m, less micro pit defects had effects on the surface with 3% concentration compared with 6% concentration of emulsion. At pass number 4 to 5, when the roll surface roughness Ra(r)=0.7 $\mu$m, effects of concentration 3% and 6% of emulsion on micro pit effects had not obvious difference.

In the same concentration and temperature of emulsion, the micro pit defects were increased with the roll surface roughness increase. This was because maintain of micro pit was effected by rolling oil or air in the micro pit, the quality of oil was much more than the air in the micro pit in lubrication rolling. The coefficient of volume compressibility of the air was $7\times10^{-6}$ $Pa^{-1}$, while that of rolling oil was 5-$10\times10^{-10}$ $Pa^{-1}$. The oil was so difficult to deform in lubrication rolling as to the micro pit was maintained. Effect of micro defects on rolling oil nearby the deformation zone was shown in Fig. 9 (Kenmochi *et al*. 1997). In the figure work roll diameter had effects on micro defects, $\alpha 1$ was bite angle of a big work roll diameter, $\alpha 2$ was bite angle of a small work roll diameter.

It was seen from the Fig. 9 that if the work roll diameter was small, rolling oil was less in micro pit which resulted in lower micro defects and higher glossiness of strip. This is due to the fact that more rolling oil on the strip surface in the deformation zone would result in more surface micro defects. Therefore, less roll oil would result in lower micro defects and higher glossiness of strip.

Quantity of oil in entrance deformation zone was affected by mechanical entrapment intensively, because the roughness of the mother strip was larger than oil film thickness in entrance. Roughness of the mother strip had more intensive effects on micro defects of strip than that of roll surface roughness, concentration and temperature of emulsion.

Micro defects ratio was decreased after bite point in deformation zone. If the rolling force was increased from bite point to neutral point, squeezing oil was increasing so that oil film thickness was thin. With the increased reduction in height, micro defects were less, and glossiness value of the strip was increased.

## 4. Conclusions

The relation between roughness and glossiness with reduction in height, roll surface roughness, emulsion parameters of SUS 430 stainless steel strip in cold rolling process was investigated in this study.

- With the increasing of reduction in height, along rolling and width direction roughness value Ra(s), Rp(s) and Rv(s) was decreased, the drop of Ra(s) value in rolling direction was faster than that in width direction.
- In the same concentration of emulsion, roughness of strip Ra(s) was decreased when temperature of emulsion varied from 55°C to 63°C. In the same temperature of emulsion, roughness of strip Ra(s) was decreased when concentration of emulsion varied from 3% to 6%. With the pass number increasing, the quantity and surface of micro pit defects was reduced, uneven peak was decreased and gently along rolling direction, micro pit defects had equally distributed tendency along width direction.
- To guarantee the enough high glossiness the reduction in height must be great than 23%. The defects ratio was declined with larger gradient at pass number 1, 2 and 3, but gentle slope at pass number 4 and 5.
- The micro pit defects were increased with the roll surface roughness increase, this was because maintain of micro pit was effected by rolling oil or air in the micro pit, the quality of oil was much more than the air in the micro pit in lubrication rolling. If the work roll diameter was small, rolling oil was less in micro pit which resulted in lower micro defects and higher glossiness.

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