A new suction-roll shell material for the highly aggressive paper mill white water environment

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ABSTRACT: A new suction-roll material has been developed to withstand the increasingly harsh paper machine environment. Alloy 1 is an extra-low-carbon, duplex stainless steel. Various kinds of corrosion data, as well as its high pitting resistance equivalent number (PRE_N = Cr + 3.3Mo + 16N) (1, 2), indicate that Alloy 1 possesses superior pitting corrosion resistance in harsh white waters.

KEYWORDS: Alloy, alloy steel, corrosion, corrosion mechanisms, corrosion resistance, cracks, heat treatment, pitting, rolls, shells, stainless steel, steel, stresses, vacuum rolls, waste waters, white water.

We have been working together since the late 1960s developing various kinds of suction-roll shell materials for the paper industry. Those materials include Alloy 4 (martensitic stainless steel), Alloy 3 (duplex stainless steel), and Alloy 2 (precipitation hardened stainless steel).

More than 600 Alloy 2 shells have been produced and installed worldwide since 1980. Alloy 2 has been established as an excellent material for suction-roll shells because of its good corrosion fatigue properties and its low residual stress.

Paper machine white water and other operating conditions have become more and more aggressive. For instance, significant chloride ion concentrations exceeding 180 ppm are not unusual in the West Coast paper mills of the United States because of ocean transport and storage of logs. Also, increased recycling of white water is raising its temperature and lowering its pH value (*3*).

The white water temperature has reached levels as high as 60°C (140°F) in some Scandinavian paper mills. In addition, significant thiosulfate ($S_2O_3^{2-}$) concentrations are often analyzed in some paper mills as a result of bleaching using sodium hydrosulfite. Thiosulfate ions are one cause of pitting corrosion in chloride-containing white waters (*4–6*).

Due to this increasing severity of the corrosion environment and increasing machine speeds and widths, better materials are always needed. In response to these demands, we have developed Alloy 1, a new duplex stainless steel. In this paper, characteristics of Alloy 1—such as mechanical and metallurgical properties, corrosion resistance, corrosion fatigue strength, residual stress, and corrosion fatigue crack propagation—are described in comparison to other suction-roll materials. Field performance results of Alloy 1 shells also are introduced.

Chemical composition

Table I shows the chemical composition of Alloy 1 and other suction-roll shell materials. Alloy 1 is an extra-low-carbon stainless steel grade. Molybdenum and copper are added to obtain resistance to localized corrosion. Nitrogen in Alloy 1 affects the partitioning of chromium and molybdenum between the austenite and ferrite phases of the duplex stainless steel by distributing the chromium and molybdenum more evenly between the two phases, thus improving the resistance to localized corrosion (*7, 8*).

Table II shows the effect of nitrogen on the degree of partitioning of chromium, molybdenum, and nickel between the two phases as measured by an electron-probe microanalyzer. Alloy 1 has a pitting resistance equivalent number (PRE_N = Cr + 3.3Mo + 16N) of more than 30, which is the highest among suction-roll shell materials currently available. The higher this number, the more resistance the material has to pitting and crevice corrosion.

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Microstructure

Microstructures taken from actual suction-roll shells are shown in **Fig. 1**. Alloy 1 has a microstructure consisting of 40–60% pools of austenite in a ferrite matrix. Homogeneous microstructures are observed throughout the wall thickness of the shells. No intermetallic compounds such as σ phase or χ phase are observed.

Heat treatment

The heat treatment of a suction roll is a very important factor in obtaining low residual stresses within the shell as well as in obtaining good corrosion resistance and toughness.

In general, slow cooling of duplex stainless steels, such as furnace cooling, results in low residual stresses. However, toughness and corrosion resistance of the shell deteriorate due to precipitates along, as well as within, the ferrite phase of the duplex microstructure. On the other hand, rapid cooling, such as water quenching, achieves good toughness and corrosion resistance, but it causes high residual tensile stresses within the shell.

To overcome these adverse characteristics of duplex stainless steel shells, a computer-aided, air cooling, heat treatment process was developed. After being heated and held at a minimum temperature of 1050°C (1922°F) for a specific length of time, the Alloy 1 shell is air cooled, while rotating, under temperature-controlled conditions. The control of this procedure is important because temperature gradients through the thickness of the shell wall during cooling determines the degree and profile of residual stresses.

To obtain uniform cooling rates on the outside and inside surfaces, the inside surface of the shell is preferentially cooled by blowing it with misty air. The amount of air and mist are controlled by a computer and based on thermal gradient measurements taken on the inside and outside surfaces during cooling. The influence of the cooling method on the properties of duplex stainless steel having the same chemi-

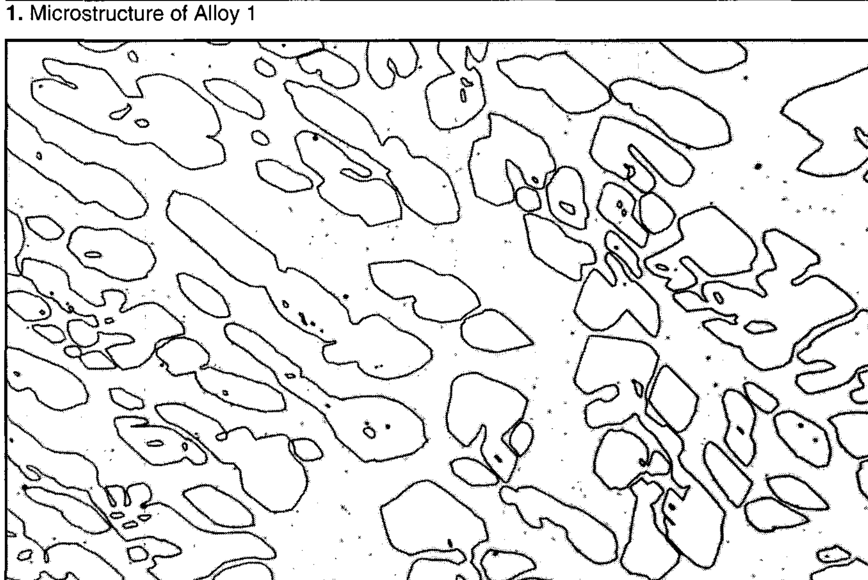
I. Chemical composition (wt%, typical)

Alloy	*C*	*Cr*	*Ni*	*Mo*	*N*	*Others*
Alloy 1	0.02	24.0	5.7	2.4	0.18	Cu, others
Alloy 2	0.05	20.0	5.0	2.0	...	Cu, others
Alloy 3	0.05	23.0	8.3	1.1	...	...
Alloy 8	0.02	18.5	5.0	2.8	0.10	...
Alloy 5	0.02	26.0	6.8	...	...	Cu

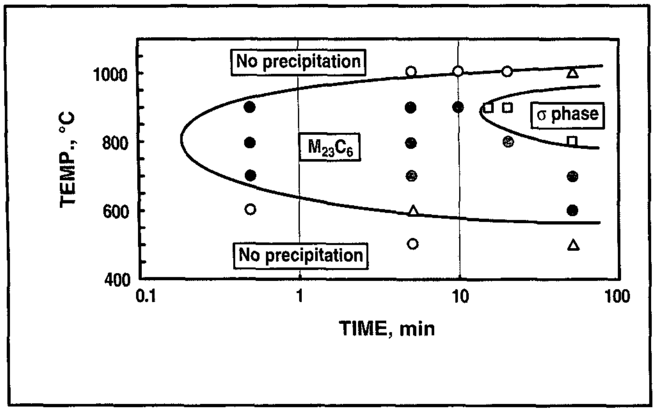
II. The effect of nitrogen on the degree of partitioning of chromium, molybdenum, and nickel

	Alloy 1 without nitrogen		*Alloy 1 with nitrogen*	
Element	*Ferrite*	*Austenite*	*Ferrite*	*Austenite*
Cr	23.23	21.17	26.51	22.78
Mo	2.69	1.58	2.66	1.62
Ni	4.52	7.65	4.12	6.25

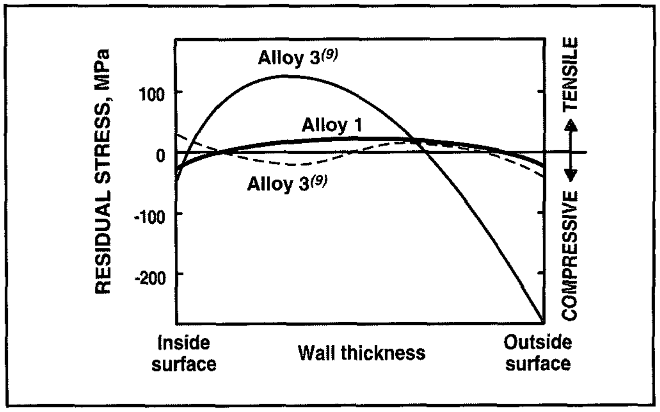
1. Microstructure of Alloy 1



2. T.T.T. curve of Alloy 1



3. Residual stress profiles (Sachs method)



III. Influence of cooling method on various properties (room temperature)

Cooling method	*Yield strength, MPa*	*Tensile strength, MPa*	*Elongation, %*	*Impact toughness, J*	*Hardness, BHN*	*Weight loss,* g/m²/h*
Furnace cooled	530	820	27	12	255	10.5
Controlled air cooled	545	700	31	156	229	2.0
Water quenched	540	700	41	242	208	0.8

*ASTM G48-76 $FeCl_3$ solution, 50°C, 72 hours

IV. Mechanical properties (room temp.)

Alloy	*Yield strength, MPa*	*Tensile strength, MPa*	*Elongation, %*	*Impact toughness, J*
Alloy 1	510	700	30	150
Alloy 2	480	730	26	100
Alloy 3	410	640	37	160

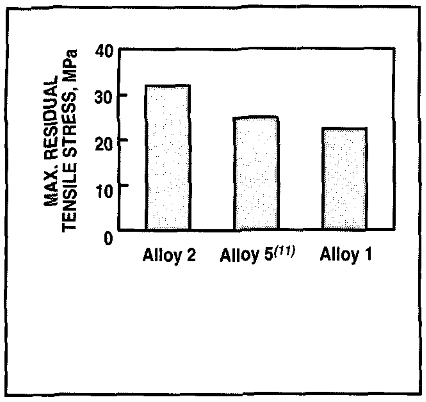
cal composition as Alloy 1 is summarized in **Table III**.

Furnace cooling, which gives the slowest cooling rate, makes the material brittle and yields a toughness of only 12 Joules in a Charpy impact test. Furnace cooling also reduces the pitting corrosion resistance of the material. Water quenching, on the other hand, gives excellent toughness and an exceptionally high pitting corrosion resistance. However, water quenching imparts higher residual tensile stresses within the shell.

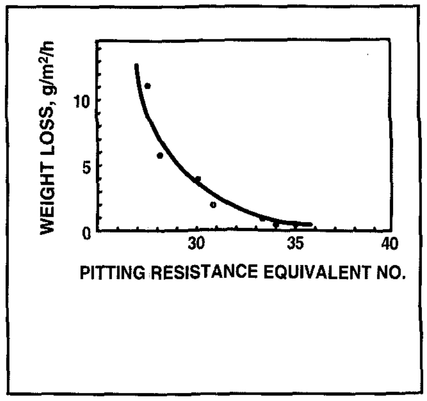
Optimum materials properties are obtained by controlled air cooling, as shown in Table III. The controlled air cooling technique developed for Alloy 1 results in low residual tensile stresses as well as good mechanical and corrosion resistance properties, all of which are very desirable for duplex, stainless steel, suction-roll shells.

Figure 2 shows the T.T.T. (Time-Temperature-Transformation) curve for Alloy 1. When duplex stainless steel is used for suction-roll-shell applications, the precipitation of a σ phase should be avoided because of deterioration of toughness and corrosion resistance. Precipitation of σ phase is avoided for Alloy 1 during controlled air cooling. Although chromium carbide precipitation will occur, Alloy 1 is able to keep optimal corrosion resistance because of its low carbon content, and effective elements such as chromium, molybdenum, and nitrogen still remain in the matrix due to the material's high PRE_N of more than 30.

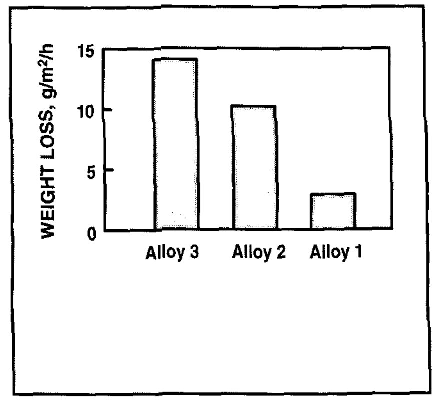
4. Maximum residual tensile stress



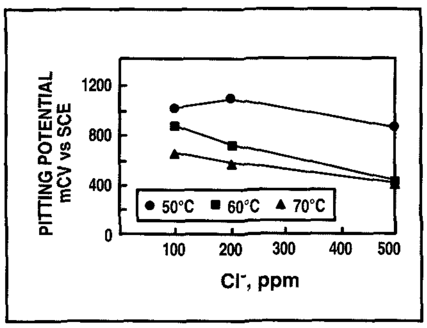
5. Influence of PRE_N on pitting corrosion resistance



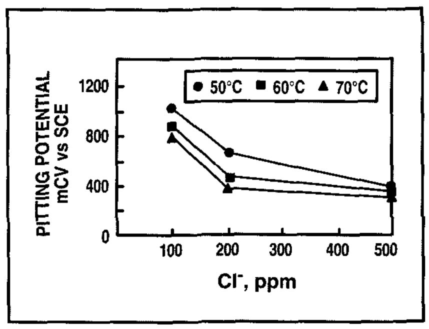
6. Corrosion resistance of products in $FeCl_3$ solution



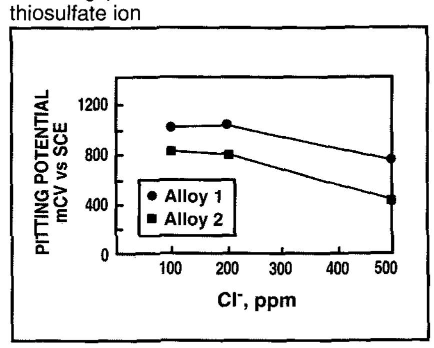
7. Pitting potential of Alloy 1



8. Pitting potential of Alloy 2



9. Pitting potential in a solution containing thiosulfate ion



Residual stress

We used the Sachs method to check the level of residual stress of Alloy 1. The Sachs method is the best procedure to accurately evaluate the residual stress profile through the wall thickness of a cylinder, although this method is expensive, time consuming, and requires great care and skill.

Strain gauges were mounted on the outside surface of an actual Alloy 1 shell. The changes in strain from each strain gauge were measured as 4-mm increments of wall thickness and were machined from the inside of the shell. To avoid the influence of temperature on the change of strain, strict attention was paid to the machining so as not to increase the temperature of the shell. Measurements of strain were taken under constant ambient temperature. Results are shown in **Fig. 3**.

You can see that Alloy 1 shells possess very beneficial residual stress profiles. The value of residual tensile stress at mid-wall is as low as 21 MPa. The residual stress profile also shows compressive stresses at the inside and outside surfaces. Compressive stresses are desirable since they help reduce the chances of corrosion fatigue and stress corrosion cracking (*10*).

Among currently used suction-roll shell materials, Alloy 1 has the lowest residual tensile stress, as shown in **Fig. 4**. The controlled air cooling developed contributes the beneficial residual stress profile of Alloy 1.

Mechanical properties

Mechanical properties of Alloy 1 are summarized in **Table IV** together with those of other suction-roll materials. Alloy 1 has higher yield strength than Alloy 2 and Alloy 3. Alloy 1 also has a good ductility of 30% in elongation and an average toughness of 150 Joules in impact-absorbed energy as a result of the controlled air cooling. When duplex stainless steels are subjected to slow furnace cooling, elongation does not deteriorate significantly, but toughness decreases drastically. The toughness level of a given shell material can be used as an index to determine whether or not the shell has been properly heat treated.

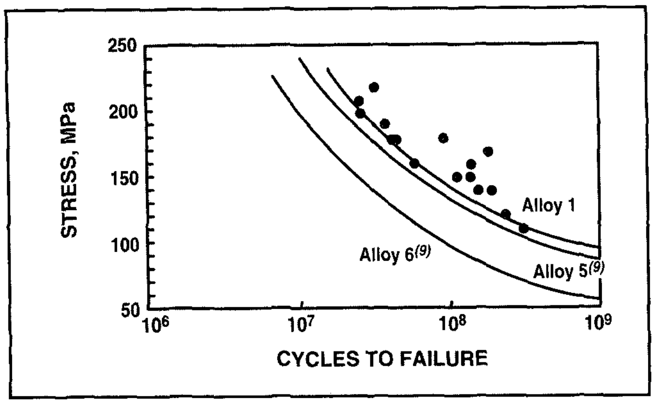
Corrosion properties

Pitting corrosion test using 6% $FeCl_3$ solution

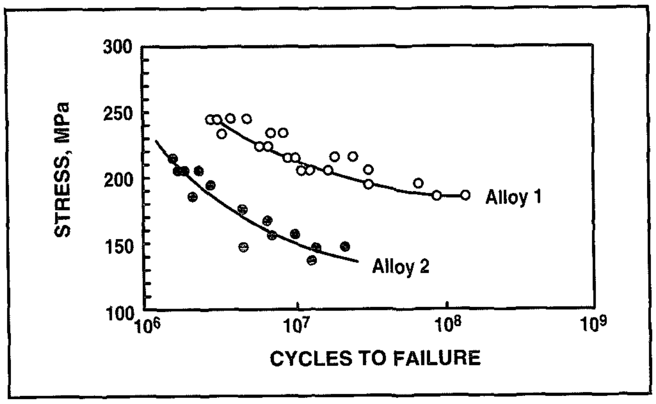
Pitting corrosion tests were performed using a 6% $FeCl_3$ solution at 50°C for 72 hours. Test coupons having different PRE_N numbers were prepared. The results are summarized in **Fig. 5**.

As PRE_N is increased, weight loss is drastically decreased. Also, the effect of decreased pitting corrosion by increasing PRE_N seems to level off at about 30. On average, Alloy 1 has a PRE_N of 34. Figure 5 indicates that Alloy 1 has excellent pitting resistance in severe chloride-containing environments. Furthermore, as shown in **Fig. 6**, in 6% $FeCl_3$ solution, Alloy 1 has excellent pitting corrosion resistance

10. Corrosion fatigue strength in white water containing thiosulfate ion



11. Corrosion fatigue strength in TAPPI II solution



among several currently used suction-roll shell materials.

Electrochemical pitting corrosion test

Using Alloy 2 for comparison, the pitting corrosion resistance of Alloy 1 was evaluated using anodic potentiodynamic polarization measurements.

The effects of the amount of chloride ion (Cl^-), thiosulfate ion ($S_2O_3^{2-}$), and temperature on pitting potential were investigated. The pitting potential was determined at a current density of 100 μA/cm^2 (Vc'_{100}) in accordance with JIS (The Japanese Industrial Standard) G0577. The concentration of sulfate ion (SO_4^{2-}) and pH were held constant at a level of 100 ppm and 3.5, respectively. The potentiodynamic scan sweep rate was 20 mV/min.

Figures 7 and 8 show the influence of chloride ion content and temperature on the pitting potentials of Alloy 1 and Alloy 2, respectively. As temperature or Cl^- content, or both, increase, pitting potentials for both materials decrease. However, Alloy 2 clearly is more susceptible to the increase in temperature or Cl^- than Alloy 1. In actual severe white water environments having 200 ppm Cl^- and a temperature of 70°C, Alloy 1 maintains a pitting potential of 600 mV versus saturated calomel reference electrode (SCE).

Figure 9 shows test results in white water containing 10 ppm thiosulfate ion ($S_2O_3^{2-}$) with Cl^- ion contents varying from 100 ppm to 500 ppm at a temperature of 50°C. Over the range of Cl^- contents, Alloy 1 has higher pitting potentials than Alloy 2. Figure 9 also indicates that the pitting potential of Alloy 1 is more than 700 mV versus SCE at 500 ppm Cl^- with 10 ppm $S_2O_3^{2}$. This shows that Alloy 1 is suitable for mills using sodium hydrosulfite bleaching, where white waters may contain thiosulfate ion as well as high levels of Cl^- ion.

Corrosion fatigue property

Corrosion fatigue properties of Alloy 1 were evaluated using an ONO-type, rotating, bending fatigue machine. Smooth, round bar specimens were taken from an actual Alloy 1 shell. The rotational speed was 1750 rpm, and the specimens were exposed to simulated white water having 1000 ppm Cl^-, 40 ppm $S_2O_3^{2-}$, 800 ppm SO_4^{2-}, and a pH of 3.5. The tests were conducted at a constant room temperature of 25°C.

As shown in **Fig. 10**, Alloy 1 has a higher corrosion fatigue strength than both Alloy 5 and Alloy 6 (*11, 12*). Corrosion fatigue results for specimens taken from actual Alloy 1 suction shells delivered to Scandinavian paper mills also are included in Fig. 10. Shown on or above the determined corrosion fatigue curve, these dots confirm the high corrosion fatigue strength of Alloy 1 in aggressive white water.

Corrosion fatigue properties for Alloy 1 were also determined for another simulated white water environment having 1000 ppm of Cl^-, 1000 ppm of SO_4^{2-}, and a pH of 3.5. Specimens were rotated at 3000 rpm at ambient temperature. As shown in **Fig. 11**, the corrosion fatigue strength of Alloy 1 is higher than Alloy 2 in severely corrosive environments due to the superior corrosion resistance of Alloy 1.

Crack growth rate measurement

Recently, studies have been focused on corrosion fatigue crack propagation rates, since it is well known that, although it can measure the number of cycles to the initiation of a crack (*13*), a smooth-bar rotating corrosion-fatigue test cannot predict the life of a suction roll.

In the future, studies of corrosion-fatigue crack propagation will be extensively performed, since the data produced will be useful in predicting shell life as well as determining inspection intervals and critical flaw sizes for suction-roll shells (*14*).

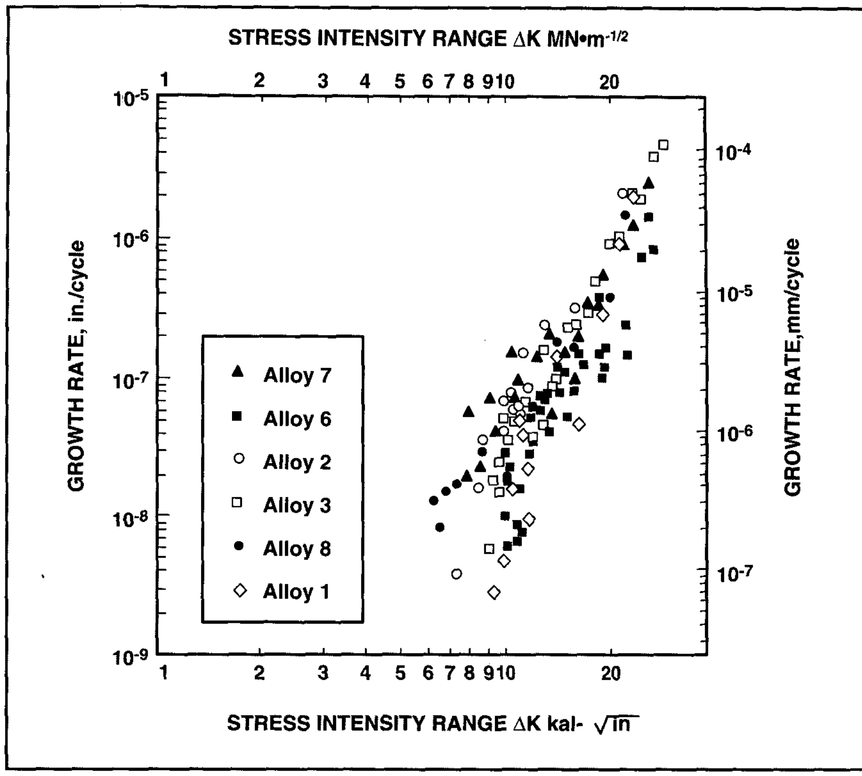
Studies of corrosion fatigue crack propagation were performed for Alloy 1. The experimental procedures followed American Society for Testing and Materials Standard Method E647 (*15*). One-inch compact tension specimens were prepared from an actual Alloy 1 suction-roll shell with crack growth arranged to be in the circumferential direction of the shell. After being precracked, the specimens were subjected to fatigue loading in simulated white water.

Average crack growth rates were calculated using periodic measurements of the crack length. Threshold stress intensities (ΔK_{th}) for crack growth were determined by a load-shedding technique. The test specimens were subjected to pulsating tension loading with a sinuous wave form and a frequency of 25 Hz.

Tests were conducted with several mean stresses corresponding to an R ratio of 0.1. The white water contained 1000 ppm Cl^-, and a pH of 3 and a temperature of 50°C were maintained. The results are shown in **Fig. 12**. The data are plotted in a format similar to that presented in a previous investigation by Yeske (*16*).

Although it is not entirely possible to directly compare the results of Fig. 12 with those of Yeske (because of somewhat different conditions and specimen size), Fig. 12 clearly shows that Alloy 1 has satisfactory resistance to crack initiation.

12. Crack growth rate of Alloy 1



Field performance

After determining and evaluating the material properties of Alloy 1, more than 35 Alloy 1 shells have been produced and installed in Northern European, Scandinavian, and North American paper mills since 1989. Alloy 1 shells have been used mainly in suction-press-roll applications in aggressively corrosive white waters having high chloride and thiosulfate ion contents brought about by sodium hydrosulfite bleaching practices. All shells installed today are performing extremely well and continue to establish an excellent reputation for Alloy 1.

Conclusion

Alloy 1 is a new suction-roll shell material that has been developed for aggressive paper machine white waters.

Computer-aided, controlled air cooling makes it possible for Alloy 1 to have low residual stress, excellent corrosion resistance, and superior corrosion fatigue strength.

Electrochemical corrosion studies indicate that Alloy 1 is able to maintain high pitting potentials in severely aggressive high-temperature white waters containing high levels of thiosulfate and chloride ions.

Alloy 1 has a greater corrosion fatigue strength than Alloy 2 and other suction-roll shell materials in high-chloride and thiosulfate-ion-containing white water.

Alloy 1 has an impact toughness of 150 Joules on average, based on the Charpy impact test at room temperature.

Alloy 1 has low tensile residual stresses at mid-wall and beneficial residual compressive stresses at the inside and outside surfaces of actual production suction-roll shells.

Service experience to date is very encouraging, and we believe that Alloy 1 should give excellent service in the more aggressive environments now being found in the paper industry. TJ

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