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FRACTURE RESISTANCE OF THE DEPOSITED METAL UNDER DYNAMIC AND CYCLIC LOADING

OTPORNOST NA LOM METALNE PREVLAKE OPTEREĆENE DINAMIČKI I CIKLIČNO

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Keywords

- fracture resistance
- deposited metal
- dynamic load
- impact strength
- fatigue crack

Abstract

Analyses of experimental data are presented that enable the fracture resistance assessment of dynamically and cyclically loaded materials used for the manufacture and surfacing of rollers in continuous casting machines for beam blanks and crimping mill rollers. It has been noted that steels for manufacturing and surfacing of crimping rolls with different carbon content and alloying elements, differ in the determination fraction of the crack nucleation work in the integral value of the impact strength. The value of that fraction is much higher for corrosion-resistant steels of the Cr13 type which are also distinguished by high fracture resistance to cyclic loading. It is shown that the properties of these steels make it possible, along with the use of CCM rollers for surfacing, to recommend them for hardening the rollers in crimping mills. The possibility of an additional increase in the efficiency of the crimping rolls by eliminating uneven wear along the length of the barrel by surfacing a layer of Cr13 steel with a variable carbon content (0.10-0.25 %) is considered.

Ključne reči

- otpornost na lom
- metalne prevlake
- dinamičko opterećenje
- otpornost na udar
- zamorna prslina

Izvod

Predstavljene su analize eksperimentalnih podataka, kojima se omogućava procena otpornosti na lom dinamički i ciklično opterećenih materijala koji se koriste u proizvodnji i prevlačenju valjaka mašina za kontinualno livenje profilisanih nosača i valjaka mlinova i krunjača. Uočavaju se razlike u određivanju udela rada za nukleaciju prsline u integralnoj vrednosti udarne čvrstoće čelika koji se koriste za izradu i prevlačenje valjaka krunjača, sa različitim sadržajem ugljenika i legirajućih elemenata. Veličina ovog udela je mnogo veća kod nerđajućih čelika tipa Cr13, koji se takođe prepoznaju po velikoj otpornosti prema lomu usled cikličnog zamornog opterećenja. Pokazuje se da su osobine ovih čelika takve da se mogu preporučiti za nanošenje tvrdih prevlaka na valjcima u mašinama za kontinualno livenje, tako i kod valjaka u krunjačima. Takođe se razmatra mogućnost dodatnog povećanja efikasnosti valjaka krunjača, eliminisanjem neravnomernog podužnog trošenja alata, nanošenjem sloja prevlake čelika Cr13 promenljivog sadržaja ugljenika (0,10-0,25 %).

INTRODUCTION

Rollers of continuous casting machines (CCM) for workpieces and rolls of crimping rolling mills (crates), being a tool for deforming hot metal, are operated under the influence of cyclic heat changes, thermal fatigue, and dynamic load. Despite the fact that the loading mode and aggressiveness of the environment are different for the casters and hot rolling rolls, their operation with cracks during most of the resource is common. Therefore, when choosing a material for surfacing rolls and rollers, the most important role is played by the characteristics of resistance to nucleation and propagation of the crack, evaluated during tests by dynamic and cyclic loading. Generalization and analysis of the results of such tests make it possible to choose the composition of the deposited metal, the properties of which most correspond to the operating conditions of both the casters and the crimping rolls.

Analysis of recent research and publications

Materials for surfacing rolls of hot rolling mills were developed and used in the metallurgical industry much earlier than the creation of the CCM and the development of the continuous casting process. Therefore, at the initial stage, for the surfacing of rollers, the CCM sought to use materials used for surfacing rolls. Due to the unsatisfactory results of this approach, and due to the different load and operating environment, the prevailing point of view has become that use of other metal compositions is necessary for the surfacing of the caster rollers /1, 2/. The validity of this conclusion does not raise objections, however, it should be noted that even for the surfacing of the same type of rolls, the choice of material is sharply different, depending on the conditions of their operation in different rolling mills. As an example, we can compare compositions and properties of metals for hardening the rolls of crimping mills (stands), the surfacing of which is used much more widely than on other hot rolling rolls. As can be seen from Table 1, the composition of the deposited metal varies from low-alloy steel 30CrMnSi with a structure of granular pearlite and ferrite, and heat-resistant steel 35W9Cr3VSi, in the structure of which large-needle martensite, residual austenite, carbide eutectic, to corrosion-resistant heat-resistant austenitic steel 08Cr21Ni10Mn6. The hardness of these metal compositions varies in the range of 215-590 HV, and the impact strength is from 0.12 to 0.45 MJ/m^2.

Table 1. Composition and properties of the metal used for surfacing rolls of crimping mills and stands.

Vintage composition of deposited metal	Hardness, HV at temperature		Impact strength, MJ/m^2	Heat resistance of deposited metal*)
	20 °C	500 °C		
18Cr3MnMoV	350	310	0.43	1720
18Cr6MnMoVSi	405	355	0.42	1690
30CrMnSi	215	–	0.28	–
25Cr5VMoSi	420	365	0.33	1480
35W9Cr3VSi	590	450	0.12	510
35Cr7Mo2VNT	575	430	0.22	1700
15Cr4MnMoV	340	310	0.45	1780
08Cr21Ni10Mn6	160	110	–	680

*) number of heating-cooling cycles until a visible crack appears in the heating zone.

At the same time, the primary cause of wear of the caster rollers depends on the location on one of the sections of the filling stream: from thermal shocks and corrosion under the action of fluorine-containing cooling water, high-temperature oxidation and significant mechanical stresses to metal-on-metal friction wear /1/. Therefore, high requirements for the corrosion resistance of the surface layer of caster rollers are justified as well as the use of corrosion-resistant steels 17Cr 12MoV, 20Cr25Ni19Si2, 20Cr13 /3/ for their manufacture, and for surfacing - compositions of the Cr13 - Cr17 type. At the same time, rollers are operated at metallurgical plants, the working layer of which is much less corrosion resistant than steel Cr13 for which arc surfacing with cored wire 25Cr 5VMoSi and laser powder surfacing (additive type 30Cr 5Mn2WMoVNi) is used /4, 5/.

Table 2. Hardness and toughness of steels for the manufacture of rolling rolls and casters of CCM.

Steel grade	Hardness (HV)	Impact strength *KC* (MJ/m^2)	KC_n (MJ/m^2)	KC_p (MJ/m^2)	$K_{1c}{}^d$ (MPa·m$^{1/2}$)
45	180	0.36	0.33	0.03	18.2
50CrNi	210	0.51	0.37	0.14	15.4
90CrV	260	0.11	0.09	0.02	14.6
25Cr1Mo1V	250	0.65	–	–	–
20Cr1Mo1V	240	0.70	–	–	–
20Cr13	225	0.55	–	–	–

Unlike the rollers of the CCM, the rolls in crimping mills experience intense shock and contact loads in combination with cyclic heat changes. At the same time the impact strength, as an indicator of the resistance to dynamic fracture of steels used in the manufacture and surfacing of caster rollers, is significantly higher than the corresponding values for roll steels (Table 2). Analysing the above, it is impossible not to note a rather conditional separation of materials intended for surfacing hot rolling rolls and CCM rollers. Moreover, if we limit the assessment of deposited metal properties based on the characteristic operating condition of the surface layer of rolling rolls in crimping mills and rollers of CCM, it is possible to choose the optimal composition that meets the requirements of both the first and the second.

In addition to matching the load, such a choice should take into account the cast nature of the weld. During the operation of rolls in crimping mills and rollers of continuous casting machines, micro and macro fractures occur in the cast structure of the surface deposited layer under the influence of alternating thermomechanical load, /6/. Not removed while machining before surfacing, these defects can serve as foci of crack formation. However, much more often such foci are hot (crystallization) and cold cracks that occur during surfacing and heat treatment of the product /2/. To quantify the probability of hot cracks, an indicator of the deformation ability of the seam during welding is used. Such an indicator is the critical rate of deformation of the metal during crystallization, A_{cr}. The latter depends on the composition of the deposited metal, primarily on carbon content, the degree of complex deoxidation, and modification of the bath melt, grinding of the primary structure, reduction of microchemical heterogeneity, /7, 8/.

The high probability of the appearance of such defects affects the resistance to fracture nucleation in the metal deposited on crimping rolls /2/ under dynamic loading influence. At the same time, based on the main role of the cyclic load experienced in caster rollers, the use of a test method is justified, making it possible to quantify the rate of fatigue crack growth depending on the metal composition and on the stresses corresponding to those arising during the surfacing and operation of the rollers.

Presentation of the main material

The resistance of rolled steels and deposited metal to dynamic fracture depends, first of all, on the magnitude of nucleation of the main crack (Tables 2, 3). As follows from the data in Table 3, for heat-resistant deposited metal containing 4.0-6.0 % Cr, additionally alloyed with Mo and V, the work for crack nucleation depends on carbon content. With a decrease in its content from 0.25 to 0.15 %, impact strength increases from 0.33 MJ/m^2 for the composition of 25Cr5VMoSi to 0.45 MJ/m^2 for composition of 15Cr4MnSi MoV. This is due to a change in the microstructure from martensitic to ferrite-carbide, which determines the fracture nature by dynamic load (from transcrystalline cleavage to microviscous pit). The results of shock tests with oscillography of the fracture process /9, 10/ confirm the decisive role of energy expenditure on elastic and plastic deformation, which precedes crack initiation. The increase in impact strength of the composition of 18Cr6MnMoVSi compared to 25Cr5VMoSi is determined by the increase of the crack nucleation component KC_n, with equal values of its propagation work KC_p (Table 3). Crack nucleation resistance increases when the deposited metal is modified by introducing an optimal amount of REM (rare earth metals), leading to a change in shape, an increase in the dispersion of non-metallic inclusions, and grinding of the primary austenitic grain, /8/. The associated increase in the resistance of the metal against the formation of hot cracks is confirmed by an increase in the critical deformation rate, while KC_n increases, the integral value of the impact strength of the deposited metal 18Cr6MnMoVSi increases to 0.50 MJ/m^2 /7, 10/.

Table 3. Characteristics of dynamic fracture resistance of the deposited metal.

Metal composition	KC (MJ/m^2)	KC_n (MJ/m^2)	KC_p (MJ/m^2)	K_{1D} (MPa·m$^{1/2}$)
15	0.36	0.28	0.08	–
30CrMnSi	0.28	0.26	0.02	31.1
16Cr4MnMoVSi	0.44	–	–	28.8
18 Cr6MnMoVSi	0.42	0.33	0.09	28.2
25Cr5VMoSi	0.33	0.25	0.08	28.4

Metal compositions used for surfacing hot rolling rolls containing more than 0.30 % carbon: 30Cr2Mo2NiV, 30Cr 4W2Mo2VSi, 40Cr4Mo3W2VMnSiTi /11/, 30XCr3Mo3Ni 2Mn2V (ASM 4450), 30Cr5Mn2W1Mo1VNi (ASM 4603) /12/, used to harden the working rolls of roughing stands, are characterised by a toughness of less than 0.30 MJ/m^2. The low corrosion resistance of these steels is quite understandable from the standpoint of the electrochemical theory of corrosion, since the chromium concentration in them is lower than the first critical concentration (~ 6.5 mass %) /13/. At the same time, in the composition of 35Cr7Mo2Vni Ti2 used to harden the crimping rolls, as well as the working rolls of the roughing stands, the chromium content is not less than 6.5-7.0 %. Due to this, corrosion resistance increases, and the dispersed martensitic structure of the metal is characterised by high temperature resistance and heat resistance (Table 1). The 35Cr6Mo2V cored wire according to GOST 26101-84 that provides the composition of 35Cr7 Mo2VNTi, among similar wires used for surfacing rolled rolls under flux, stands out for high welding and technological properties, /2/.

With an increase in the chromium content to 12-13 %, when the second critical concentration (the Tamman limit) is reached, the steel becomes stainless, which meets the corrosion resistance requirements of the surface layer of caster rollers. Such properties are possessed by the deposited 12Cr 12Mn12SiV with an energy-intensive structure of metastable austenite, whose impact strength (0.62 MJ/m^2) is higher than its value for compositions presented in Table. 3. The surfacing of chromium-manganese metal is carried out with a cored wire 12Cr12Mn12SiV. Stainless deposited metal 10Cr13 with an equally high integral value of impact strength (0.60 MJ/m^2) differs from the composition of 12Cr12Mn12SiV by significantly higher resistance to crack nucleation. This is evidenced by the results of comparative operation of casters of 300 mm diameter with a deposited 7.5 mm thick layer. In rollers deposited with 12Cr13 wire according to GOST 2246-70 (0.12 C, 0.60 Si, 0.80 Mn, 12.0 Cr, 0.60 Ni, mass. %), the number of loading cycles before surface crack nucleation is much higher than average (~ 5000 cycles), and much higher than in rollers deposited with 12Cr12Mn12SiV steel, /1/.

Even greater is the specific work of crack nucleation and the integral value of impact strength for a metal of the type Cr13 with a very low carbon content, mass. %: 0.04 C, 1.3 Mn, 0.4 Si, 13.5 Cr, 3.3 Ni, 1.3 Mo, 0.1 Nb, 0.15 V, 0.08 N (42-44 HRC, KCV = 0.8 MJ/m^2, ψ = 68 %), deposited with a cored wire 742-SK /14/, and used for surfacing the most loaded rollers of the CCM /15/. In the structure of such a metal, the proportion of the carbide phase at grain boundaries is significantly lower, thereby reducing the weakening of their boundaries. The substitution of carbides with dispersed vanadium and niobium nitrides distributed evenly over the grain volume in combination with the fine-grained structure significantly increases the resistance to crack formation in the deposited metal 04Cr13Ni3Mo1MnVNiNb.

This is consistent with the high performance of the caster rollers deposited with ASM 4313 cored wire (0.06 C, 0.9 Si, 0.8 Mn, 13.5 Cr, 4.5 Ni, 1.0 Mo, 0.2 V, 0.1 N, mass. %) and especially, ASM 4155 (0.06 C, 0.9 Si, 0.8 Mn, 13.0 Cr, 4.0 Ni, 0.8 Mo, 0.4 V, mass. %), in the case of which additional elements are introduced, /12/. Solving of the problem of obtaining a surfacing material with an exceptionally low carbon content of 0.017 % made it possible to develop an alloy 12Cr6Ni2Mo with a ‘supermartensitic’ structure, /16/. Its properties provide not only heat resistance, but also corrosion resistance of the surface layer of the rollers installed directly behind the mould.

The most important characteristic of materials for manufacturing and hardening caster rollers is the resistance against cracking under the influence of cyclic loading, which is estimated by the rate of fatigue crack propagation. The kinetic diagram of fatigue failure (KDFF) reflects the dependence of crack growth rate dl/dN on the change in the stress intensity coefficient ΔK, /17/. To analyse and generalize the dependencies of dl/dN on ΔK, Fig. 1 presents the results of processing experimental data presented in /1/. This made it possible to compare the growth rate of the fatigue crack with the change in ΔK for the cast structure of the deposited and centrifugally cast metal, as well as the resulting plastic deformation (forging).

The linear nature of the KDFF indicates a constant rate of crack growth, typical for homogeneous (monolithic) materials. The cast needle-like structure of the deposited metal 35W9Cr3SiV in which twinned martensite and carbide eutectic (W_2C carbides are located along grain boundaries) are associated with a high crack propagation rate and a brittle-mixed nature of fracture (intergranular chipping and intragranular fracture) are shown in Fig. 2a. The fatigue crack rate in the deposited metal of 25Cr5VMoSi is lower in the structure with a martensite batch and partially of twinned martensite crystals. The crack rate in the unstable austenitic structure of the 12Cr12Mn12SiV composition is approximately the same as in 25Cr5VMoSi steel, despite the sharp differences in their structure.

For compositions 35W9Cr3SiV and 25Cr5VMoS, the values of dl/dN, depending on the ΔK, are in fairly good agreement with the data on impact strength (0.12 and 0.33 MJ/m^2, accordingly) and the results of the evaluation of the metal's resistance to thermal fatigue cracking, presented in Table 1. To a much lesser extent, this is inherent in the composition of 12Cr12Mn12SiV, which on the contrary has a much higher impact strength (0.65 MJ/m^2), but insufficient strength and plasticity. Among the high-chromium compositions, it is necessary to distinguish centrifugal cast steel 17Cr12MoV with a fine-grained structure of rack-and-pinion martensite, characterised by density and the absence of casting defects. Since 17Cr12MoV steel is used as the surface layer of caster rollers /3/, it is of interest to compare the propagation velocity of the fatigue crack in cast metal with the forged material of the rollers, 25Cr1Mo1V steel.

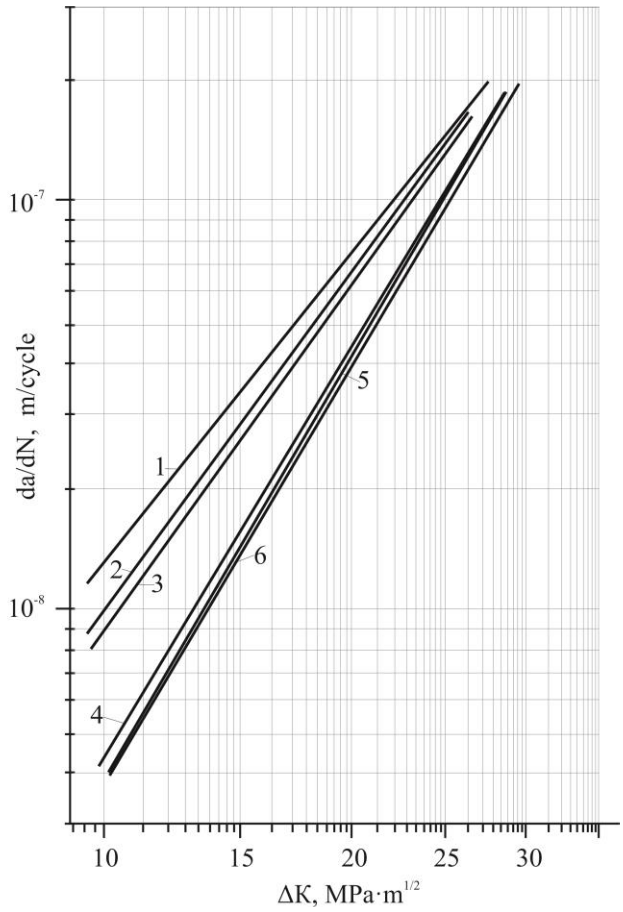
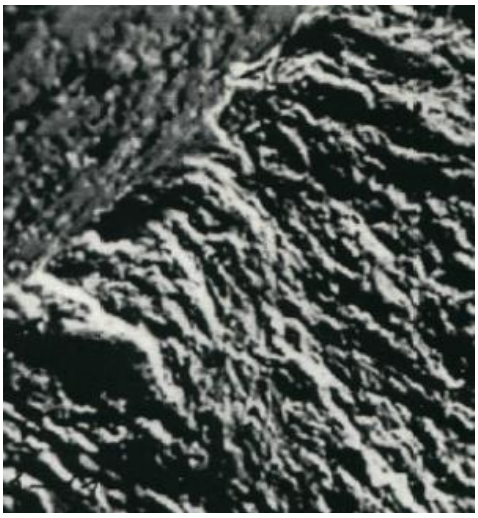


Figure 1. The kinetics of crack growth at an arbitrary fixed stress intensity coefficient span: 1 – 3Cr2W8; 2 – 25Cr5VMoSi; 3 – 12Cr12Mn12SiV; 4 – 25Cr1Mo1V; 5 –10Cr13; 6 – 17Cr12MoV.

(a)

(b)



(c)

Figure 2. The nature of fatigue failure: a) deposited metal 35V9H3FS; b) centrifugal cast layer of steel 17Cr12MoV; c) solid-forged roller (steel 25Cr1Mo1V), ×400.

As can be seen from Fig. 1, the crack propagation rate in cast metal is lower than in forged metal, and the energy-intensive fracture mechanism by cyclic loading of steel 17Cr 12MoV is confirmed by the formation of fatigue grooves on the fractogram (Fig. 2b). The nature of the fracture of steel 25Cr1Mo1V is an intra-grain chip and separate areas of viscous fracture (Fig. 2c). The martensitic-ferritic structure of the deposited metal 10Cr13 differs in almost as high resistance to fatigue cracking as in 17Cr12MoV steel.

The impact strength of deposited metal 10Cr13 is significantly higher than for the centrifugal cast steel 17Cr12MoV (0.60 MJ/m^2 vs. 0.35 MJ/m^2). At the same time, a lower carbon content in 10Cr13 steel is associated with an increase in heat resistance while reducing friction wear resistance at elevated temperatures. However, given the high wear resistance of rollers made of 17Cr12MoV steel, 3-4 times higher than the resistance of rollers made of 25Cr1Mo1V steel /3/, there is no concern about the failure of rollers with a deposited layer of 10Cr13 due to wear.

At the same time, the uneven wear along the length of the barrel is associated with the nature of the load distribution and the much greater wear intensity of the crimp rolls than the caster rollers. The technology of surfacing rolls with a variable composition layer along the length of the barrel that reduces the uneven wear and consumption of rolls, provides for the use of an independent feed rate control system for 2 electrodes of different composition /18, 19/. The choice of 10Cr13 steel as the base composition of the deposited layer and obtaining a hardness variable along the length of the crimp roll barrel allows a change in the carbon content in the range of 0.10-0.25 % by adjusting the feed rate of 12Cr13 and 20Cr13 types (GOST 4986-79, cold-rolled strip made of corrosion-resistant and heat-resistant steel). This ensures an increase in hardness within the limits of HV 380-440 (Table 4), in which a reliable grip of the metal is maintained during the rolling process, preventing the rolls from slipping.

Table 4. Effect of the ratio of feed rates of strip electrodes 12Cr13 and 20Cr13 on the carbon content and hardness of deposited metal.

Ratio of feed rates	Carbon content (mass. %)	Hardness (HV)
100/0	0,10	380
50/50	0,17	410
0/100	0,24	440

Surfacing of crimping rolls with a diameter above or equal to 650-700 mm is carried out using specialized equipment /20/ that provides control of the penetration depth /21, 22/. Two ribbon electrodes with a cross-section of 60×0.5 mm are used (the total cross-section is 60 mm^2). Surfacing is carried out on mode: constant current of reverse polarity 650-700 A, voltage 32-33 V, surfacing speed 4.69 m/s, total volumetric feed rate of two tapes 0.90 cm^3/s.

For welded joints of dissimilar steels, the type of dependence of the kinetic diagram of fatigue failure differs from the linear one. The variable rate of fatigue crack development (Fig. 3) was revealed in /23/ for the fusion zone of austenitic steel 12Cr18Ni10 with high-carbon (0.75 % C) rail steel. The fracture mechanism at macro and micro levels differs in areas with different structures and mechanical properties. The crack rate decreases in the plastic components of the microstructure, where fracture is quite energy-intensive, but increases markedly in the micro volumes of martensite, when the fracture mechanism is an intragrain chip with elements of viscous fracture.

Such structural heterogeneity, more clearly expressed and determined by the choice of materials and technology, is distinguished by layered heterogeneous deposited compositions with a given level of alloying of each layer and high contrast of composition and properties at the boundaries of the layers. Their development and application make it possible to increase crack resistance by inhibiting fracture at the layer boundaries by the mechanism of the formation of stratifications, /10/. Crack braking (fracture resistance) of heterogeneous compositions consisting of high strength layers and of high plasticity, largely depends on the nature of the residual stress diagram. The prospects for the use of such compositions obtained by surfacing, as well as by other methods /24/, are associated with economical alloying of layers, the reliability and technological stability of the composition formation process, and the use of an automated control system.

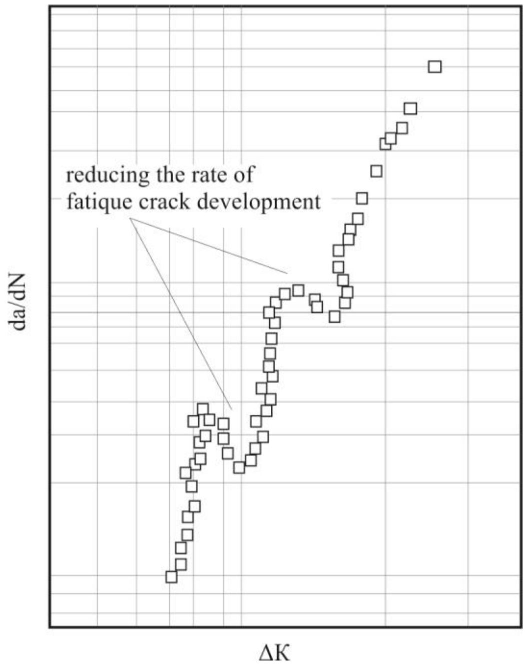


Fig. 3. Kinetics of crack growth in the weld of dissimilar steels, /23/.

CONCLUSIONS

Fracture resistance of steels for manufacturing and surfacing of crimping mill rolls and stands under dynamic loads is mainly influenced by the work of crack nucleation.

The corrosion-resistant steels of the Cr13 type used for the manufacture and surfacing of CCM rollers differ from the corresponding materials for crimping mill rolls by higher indicators of fracture resistance both by dynamic and cyclic loading.

Additionally, the performance of crimping mill rolls can be improved by eliminating uneven wear along the barrel length by surfacing a layer of type Cr13 with variable carbon content (0.10-0.25 %).

The variable rate of fatigue crack development in the fusion zone of dissimilar steels differs from the linear nature of the dependence of fatigue crack velocity on the change of stress intensity coefficient for homogeneous materials with the structures of electric arc surfacing, forging, and centrifugal casting.

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