Mechanism of Film Boiling Elimination during Quenching Probes in Mineral Oils Containing Oligomeric Additives

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Abstract:- It has been shown by authors that an addition of the special additive to mineral quench oils for example a polyisobutylene oligomer (PIB), creates an insulating layer on the surface of steel parts during quenching. This insulating layer eliminates the film boiling process on the part surface without affecting physical properties of the oil. The insulating layer decreases an initial heat flux density which becomes less than critical one. The paper presents results of the detailed investigations of the mechanism of the film boiling elimination or its cardinal decreasing due to a presence the small amount of the PIB in mineral oils. Experiments were conducted using an Inconel 600 probe of 10 mm in diameter and 30 mm long, which was quenched from 810°C in Industrial oils (I-8A, I-12A and I-20A). An effect of the oil viscosity and molecular weight of the PIB was investigated by authors. It was shown that by eliminating of the film boiling during quenching, it is possible to govern the intensity of cooling and to provide a uniformity of the hardening process. A phenomenon on eliminating of the film boiling process due to a presence of the small amount of the PIB in the mineral oil is called an EFB effect, which has an important practical use.

Key -Words:- PIB oligomeric additives, film boiling elimination, mechanism, uniformity, EFB effect.

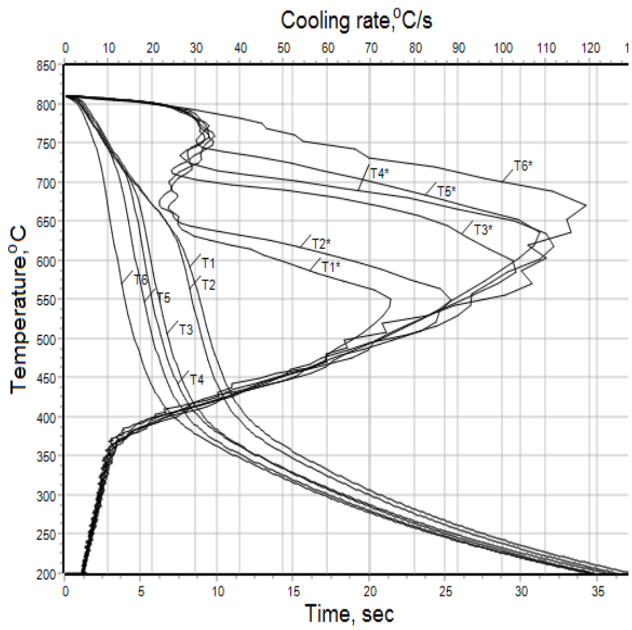
1 Introduction

It is well known that an absence of the film boiling process, especially of the local film boiling process, provides a uniform cooling and decreases part distortion [1, 2, and 3]. According to the conventional approach, researches are trying to decrease duration of the film boiling process by the use of special additives affecting the tension, viscosity, etc. Nobody paid attention to an absolutely different approach based on creating an insulating layer on the surface of quenched steel parts. Such approach was proposed by author [1]. It is an important and qualitatively new because it affects duration of the film boiling process more effectively as compared to existing methods. The aim of the current study is evaluation of the mechanism of the film boiling elimination due to a small addition of the PIB to I-8A, I-12A and I-20A industrial mineral oils using standard probes [4]. Especially important is a knowledge on what kind of the heat transfer mode is observed during quenching in mineral oil I-20 with and without of the additive PIB 2400.

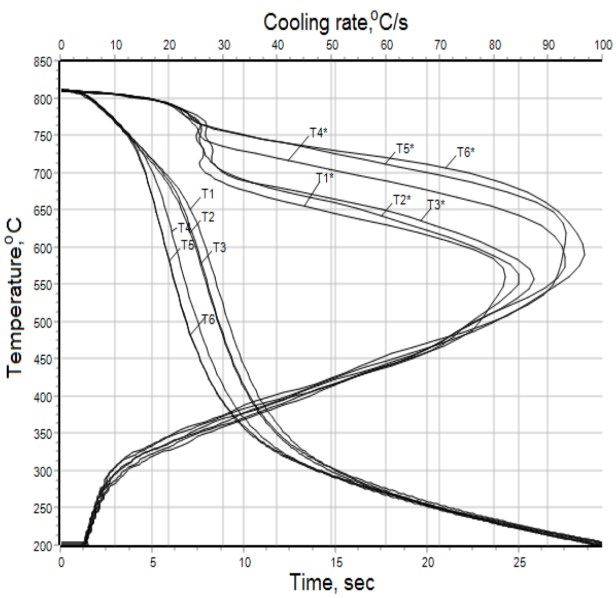
2 Experimental investigations

2.1 Effect of PIB 2400 on film boiling elimination (FBE effect)

Fig. 1 provides cooling curves and cooling rates for solutions of the PIB 2400 in different mineral oils at 50°C. Mineral oil I-20A was investigated at different concentrations (see Fig. 1). Some exact data are provided in Table 1.



a)



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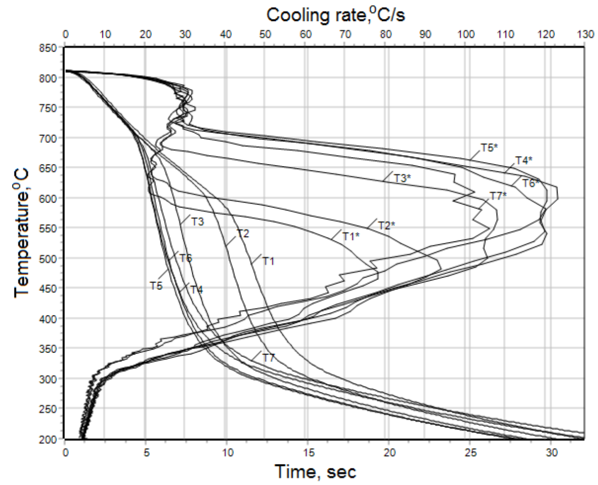

c)

Fig. 1 Cooling curves and cooling rates for solutions of PIB 2400 in different mineral oils at 50°C: a), I-20A oil, concentrations, %wt: 1-0; 2–0.5; 3–1.0; 4-1.5; 5-2.0; 6–3.0; b) , I-12A oil, concentrations, %wt: 1-0; 2–0.5; 3–1.0; 4-1.5; 5-2.0; 6–3.5; c), I =8A, concentrations, %wt: 1-0; 2–0.5; 3 –1.0; 4 –2.0; 5 –3.5; 6 - 10.0; 7–14.0 .

It has been established by experiments that the PIB 2400 can eliminate completely film boiling in mineral oil I-20A, but cannot eliminate completely film boiling in mineral oils I-12A and I-8A. Authors explain such behavior by decreasing critical heat flux densities of I-12A and I-8A oils. It means that a small addition of PIB 2400 to I-20A oil provides the FBE effect with a probability of 100% and for oils I-12A and I- 8A with a probability of 80% - 90%. Authors explain such behavior by decreasing critical heat flux densities of I-12A and I-8A oils. It should be underlined that the film boiling can be eliminated also at a higher concentration of the PIB 680 in I-20A oil (see Fig. 2). The thickness of polymeric layers formed on the surface of steel parts depends on the PIB concentration and can affect part distortion after quenching [5].

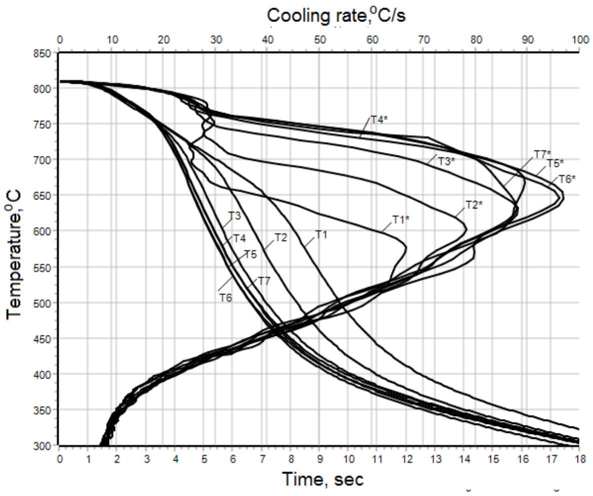

Fig. 2 Cooling curves and cooling rates [4] for PIB 680 s olutions in I-20A oil at 50°C and different concentrations, % wt.: 1-0.0; 2 –3.0; 3–5.0; 4–7.0; 5–10.0; 6-12.5; 7–19.0.

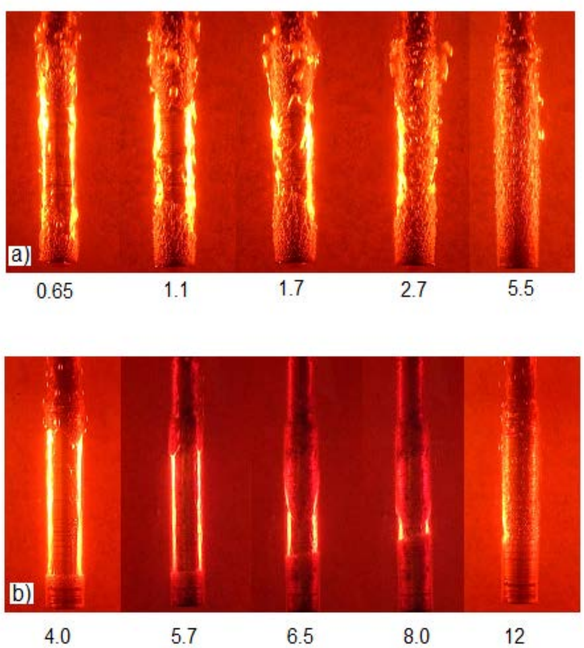

Fig. 3 Film boiling behavior during quenching of standard Inconel 600 pr obe in mineral I-20 oil at 50°C versus time in seconds with PIB additive (a) and without it (b).

As seen from Fig. 3 a), a small amount (approximately 1%) of the PIB 2400 in oil I – 20 decreases significantly duration of the film boiling (see Fig. 3 a). It should be noted that during quenching of the cylindrical probes in mineral oil I-20A with the PIB additive, the first type of the heat transfer mode was clearly observed. The boundaries of the transient nucleate boiling move along the cylindrical probe from both of its ends and its speed is faster when a small amount of the PIB 2400 is present in oil I020A. It can be explained by the creation of the surface polymeric layer which decreases the initial heat flux resulting in the acceleration of the transition to the nucleate boiling process. When there is no P IB 2400 additive in oil, the initial heat flux is higher. This r esults in the d eveloped film boiling process with a smaller heat transfer coefficient that increases the cooling time of the cylindrical probe. F ig. 4 s hows maximal cooling rates V_t^{max} and duration of the film boiling obtained for the PIB 2400 a nd PIB 680 s olutions in oil I- 20A at 50°C.

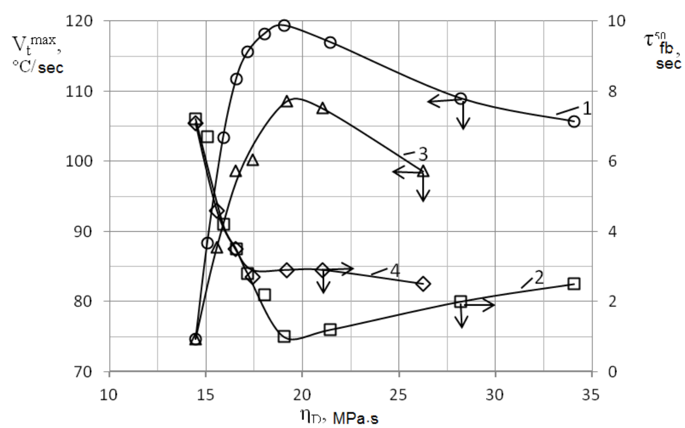

Fig. 4 Maximal cooling rates V_t^{max} (curve 1 and curve 3) and duration of film boiling (curve 2 and curve 4) for PIB 2400 (1, 2) and PIB 680 (3, 4) solutions in oil I-20A at 50°C versus viscosity η_D .

. Since it was impossible to explain decreasing of the film boiling by changing the tension or viscosity of oil (see Table 2), authors came to the conclusion that the PIB surface layer is a main reason. [1-3]. This idea is a good hypothesis for the further investigations of authors using standard and Liscic/Petrofer probes [6]. Such approach is a new direction in the heat treating industry because the elimination of local and full film boiling processes improves the quality of hardened steel parts.

Table 1 Cooling curve and cooling rate data obtained during testing of Inconel 600 probe (10 mm in diameter and 30 mm long) in solutions of oligomer PIB 2400 in oil I-20A at 50°C

Data	Designation	Concentration, % wt.					
		0.0	0.5	1.0	1.5	2.0	3.0
Cooling time from 810°C to 600°C in sec.	τ_{600}	8.1	7.8	5.7	5.3	4.7	3.5
Cooling time from 810°C to 400°C in sec.	τ_{400}	12.0	11.3	9.2	8.8	8.1	7.2
Cooling time from 810°C to 200°C in sec.	τ_{200}	37.3	36.3	34.7	35.7	34.5	34.7
Maximal cooling rate in °C/s	V_t^{max}	74.7	88.4	103.4	111.8	108.8	119.4
Core temperature of probe at maximum cooling rate, °C	$T_3^{Vt\,max}$	551	550	584	617	635	669
Cooling rate in °C/s when core temperature is 300°C	$V_t^{T=300}$	8.6	8.2	8.0	7.7	8.1	8.3

Table 2 Viscosity η_D of oligomeric solutions in mineral oils at 50°C (η_D, MPa·s; Dr=729s^{-1})

PIB 2400

I - 20A	Concentration. C. % wt.										
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	4.5	5.0	7.5	10.0
	14.48	15.08	15.90	16.58	17.17	18.04	19.04	21.45	22.68	28.20	34.07

I- 12A	Concentration. C. % wt.												
	0.0	0.5	1.0	1.5	2.0	3.5	5.0	7.5	9.0	10.0	12.5	14.5	15.0
	9.47	9.84	10.39	10.84	11.21	12.98	15.03	18.52	21.18	23.14	28.61	33.57	35.66

I -8A	Concentration. C. % wt.												
	0.0	0.5	1.0	1.5	2.0	3.5	5.0	10.0	14.0	15.0	16.0	19.0	21.5
	5.10	5.36	5.60	5.92	6.19	7.01	8.06	13.12	18.36	20.13	21.95	28.47	34.79

PIB 1300

I - 20A	Concentration. C. % wt.					
	0.0	3.0	5.0	7.5	10.0	12.5
	14.48	16.94	18.97	21.50	24.64	28.15

PIB 950

I - 20A	Concentration. C. % wt.							
	0.0	3.0	4.3	5.0	7.0	7.5	10.0	16.0
	14.48	16.26	17.26	17.63	19.04	19.54	21.77	28.01

PIB 680

I- 20A	Concentration. C. % wt.						
	0.0	3.0	5.0	7.0	10.0	12.5	19.0
	14.48	15.58	16.53	17.40	19.18	21.04	26.24

Table 3 Cooling curves characteristics for oil I-20A (1), for 7% PIB 950 solution in oil I-20A (2), for 5% PIB 1300 solution in oil I-20A (3), for 3 % PIB 2400 (4), for 10 % PIB 680 solution in oil I-20A at 50^{o}C (5), and solution of 40% I-40A oil in in I-20 oil (6).

Data	Designation	Quenchants					
		1	2	3	4	5	6
Cooling time from 810°C to 600°C, s.	τ_{600}	8.1	3.5	3.7	3.4	5.2	7.6
Cooling time from 810°C to 400°C, s.	τ_{400}	12.0	7.2	7.2	6.8	9.7	13.4
Cooling time from 810°C to 200°C. s.	τ_{200}	37.3	34.7	34.3	33.4	34.7	38.6
Maximum cooling rate. °C/s	V_t^{max}	74.7	119.4	129.8	122.4	96.8	65.8
Temperature at maximum cooling rate. °C	T_3^{Vtmax}	551	669	649	617	650	574
Cooling rate at 300°C, °C/c	$V_t^{T=300}$	8.0	8.3	8.3	7.0	8.5	8.4

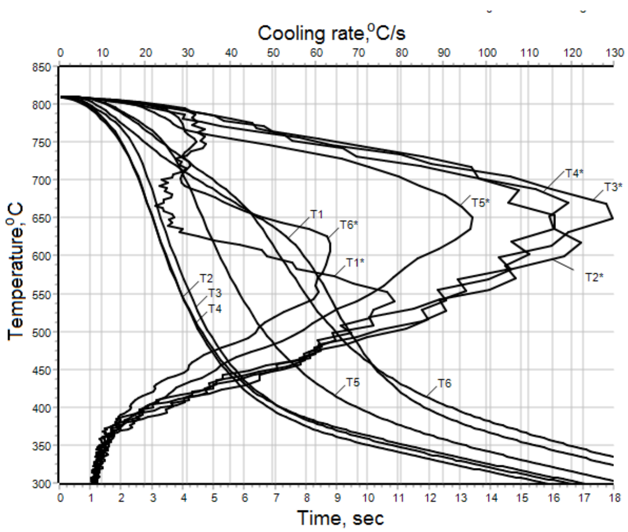

Fig. 5 Cooling curves and cooling rates for different solutions in oil I-20A: for pure oil I-20A (1), for 7% PIB 950 solution in oil I- 20A (2), for 5% PIB 1300 solution in oil I-20A (3), for 3 % PIB 2400 (4), for 10 % PIB 680 solution in oil I-20 A (5), and solution of 40% I-40 A oil in in I-20 A oil (6).

Fig. 5 shows that a concentration of 3% of the PIB 2400 in oil I-20A at 50°C eliminates film boiling completely when quenching the Inconel 600 probe [7].

2.2 Molecular weight of PIB effect on duration of film boiling process

The authors proved an existence of a critical molecular weight of the PIB which provides the FBE effect. There is no the FBE effect at all when the molecular weight of the PIB is less than the critical one (see Fig. 4 and Table 3). An explanation of such behavior of the PIB solutions in oils requires additional investigations. To make a final conclusion on this issue, one should conduct more thorough experiments with different additives and different molecular weights of the PIB.

3 Discussion

As known [8, 9], the following four possible scenarios of the heat transfer on the probe surface were considered:

a. The full film boiling and nucleate boiling are present at the same time on the probe surface. The area of the nucleate boiling moves up a long the probe surface replacing the film boiling.

b. First, the film boiling takes place throughout the entire probe surface area. At a certain point of time, the nucleate boiling process replace instantaneously the film boiling, and then the convection heat transfer replaces nucleate boiling.

c. Some local areas of the probe surface are covered by the vapor blanket, while at the same time, other areas experience nucleate boiling. These local areas do not move.

d. The boiling process takes place on some local areas of the probe surface. The film boiling and nucleate boiling processes appear periodically in these areas, replacing each other.

One more scenario should be added here when any film boiling is absent from the very beginning of the cooling process and only a transient nucleate boiling process and convection take place during quenching.

The approach suggested by the authors has a great practical importance because the elimination of the film and local film boiling results in decreasing of distortion of steel parts after quenching. Especially, this problem is very important for the bearing industry where the elimination of distortion can bring huge benefits. To investigate carefully these processes, it is better to use Liscic/Petrofer probe [6] with three thermocouples instrumented in it. Also, critical heat flux densities and heat transfer coefficients should be carefully investigated to make possible controlling and governing quenching processes. For example , it was shown [5] that complete cooling during batch quenching in polymers of the inverse solubility can lead to big part distortion because dissolving of the polymeric layer resultis in a non – uniform cooling and martensitic transformations. To implement the technology correctly, one should deal with HTCs allowing making a proper interruption of the quench for avoiding excessive distortions. Thus, careful investigation of insulating layers will result in decreasing distortion and will bring great benefits for the industry. Note that polyisobutylene, also known as "PIB" or polyisobutene, $(C_4H_8)_n$, is the homopolymer of isobutylene, or 2-methyl-1-propene, on which butyl rubber is based and is widely available in industry. Moreover, the butyl rubber is produced by polymerization of about 98% of isobutylene with about 2% of isoprene. Structurally, polyisobutylene resembles polypropylene, having two methyl groups substituted on every other carbon atom. Polyisobutylene is a colorless to light yellow viscoelastic material. It is generally odorless and tasteless, though it may exhibit a slight characteristic odor [10]. The molecular weight of PIB 2400 is 2400; PIB 1300 is 1300 and so on. More information on polyisobutilene polymer one can find in literature [11]. The present investigation shows possibilities of use polyisobutelene as an additive to mineral oils to eliminate completely local and full film boiling processes.

4 Conclusions

1. Low addition (3%) of the PIB 2400 into mineral oil I-20A initiates elimination of the film boiling during quenching and the FBE effect with a probability of 100% at certain conditions.

2. During addition of the PIB 2400 into I-8A and I-12A oils decreasing of the film boiling process takes place with a probability of 80% to 90% that can be explained by lower critical heat flux densities.

3. Oligomeric solutions in mineral oils, in contrast to water polymer solutions, do not follow the viscosity criteria.

4. There is a critical molecular weight of the PIB below which the FBE effect doesn't take place.

5. A mechanism of the FBE effect is explained by the formation of the insulating layer on the metallic surface that decreases the initial heat flux density and makes it lesser than the first critical heat flux density [7].

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