



Mechanism of Film Boiling Elimination During Quenching in Mineral Oils Caused by Oligomeric Additives

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Abstract. Previously, it has been shown by authors [1–3] that the addition of a special additives, for example PIB (polyisobutylene oligomer), creates an insulating layer on the surface of steel parts during quenching in mineral oils that eliminates film boiling without affecting physical properties of the oil. Insulating layer decreases initial heat flux density which becomes less than critical one. In current paper, the detailed investigations are provided concerning the mechanism of film boiling elimination or its cardinal decreasing due to presence a small amount of PIB in mineral oil. Experiments were made using Inconel 600 probe (10 mm in diameter and 30 mm long) which was quenched from 810 °C in I-8A, I-12A and I-20A oils. Effect of viscosity and molecular weight of PIB was investigated by authors. By elimination film boiling during quenching, it is possible to govern intensity of cooling and provide uniformity of hardening process. A phenomenon of eliminating film boiling due to presence a small amount of PIB in mineral oil is called EFB effect which has an important practical use.

Keywords: PIB additives · Film boiling elimination · Mechanism Uniformity · EFB effect

1 Introduction

It is well known that absence of film boiling, especially local film boiling, provides uniform cooling and decreases distortion [1–3]. According to existing approach, researches are trying to decrease duration of film boiling process by special additives affecting surface tension, viscosity, etc. Nobody paid attention to absolutely different approach consisting in creating an insulating layer on the surface of quenched steel parts. Such approach was proposed by authors [1] and is revolutionary because it affects duration of film boiling more effectively as compared with existing methods. The aim of current investigation is a study of the mechanism of film boiling elimination

due to small addition of PIB (polyisobutylene oligomer) to I-8A, I-12A and I-20A mineral oils.

2 Experimental Investigations

2.1 Effect of PIB 2400 on Film Boiling Elimination (FBE Effect)

Figure 1 provides cooling curves and cooling rates [4] for solutions of PIB 2400 in different mineral oils at 50 °C. Mineral I-20A oil was investigated at different concentrations: 1–0; 2–0.5; 3–1.0; 4–1.5; 5–2.0; 6–3.0 (see Fig. 1a); mineral oil I-12A at concentrations 1–0; 2–0.5; 3–1.0; 4–1.5; 5–2.0; 6–3.5 (see Fig. 1b) and mineral oil I-8A at concentrations 1–0; 2–0.5; 3–1.0; 4–2.0; 5–3.5; 6–10.0; 7–14.0 (see Fig. 1c). Some exact data are provided in Table 1.

It has been established by experiments that PIB 2400 can eliminate completely film boiling in mineral oil I-20A, however 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 small addition of PIB 2400 to I-20A oil provides FBE effect for 100% and for oils I-20A and I- 8A maximum for 80% – 90%. Authors explain such behavior by decreasing critical heat flux densities of I-12A and I-8A oils. It should be underlined that film boiling can be eliminated also at higher concentration of PIB 680 in I-20A oil (see Fig. 2).

Maximal cooling rates V_t^{\max} and duration of film boiling obtained for PIB 2400 and PIB 680 solutions in oil I 20A at 50 °C are shown in Fig. 3. Since it was impossible to explain decreasing or elimination film boiling during testing of small (10 x 30 mm) Inconel 600 probe in mineral oils by changing tension or viscosity (see Table 2), author came to conclusion that PIB addition creates thin coating on the surface of probe which decreases initial heat flux density and by this way decreases film boiling process or eliminate it completely [1–5]. This idea is a good hypothesis for further investigations of authors.

2.2 Effect of Molecular Weight of PIB on Duration of Film Boiling

It has been established by authors that exists a critical molecular weight of PIB which provides FBE effect. No effect at all when molecular weight of PIB is less than critical one (see Fig. 4 and Table 3).

To make final conclusion on mechanism of elimination film boiling process, one should do more thorough experiments with different additives.

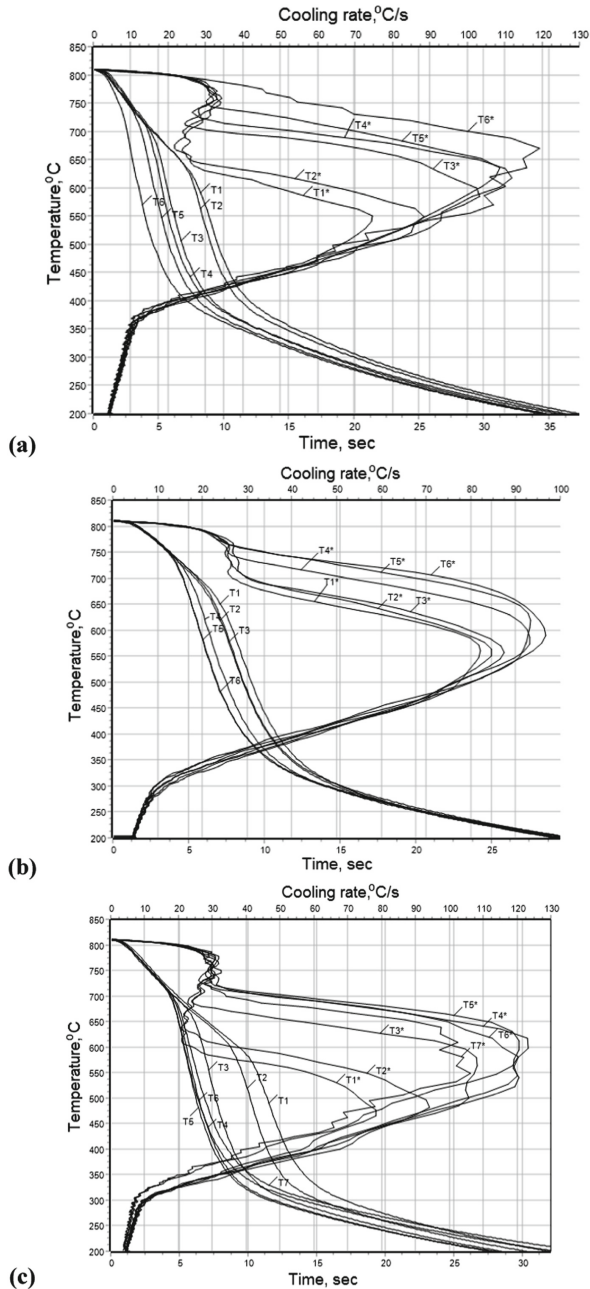


Fig. 1. Cooling curves and cooling rates for solutions of PIB 2400 in different mineral oils at 50 °C: (a), I-20A oil, concentrations 1-0; 2-0.5; 3-1.0; 4-1.5; 5-2.0; 6-3.0; (b), I-12A oil, concentrations 1-0; 2-0.5; 3-1.0; 4-1.5; 5-2.0; 6-3.5; (c), I = 8A, concentrations %wt 1-0; 2-0.5; 3-1.0; 4-2.0;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

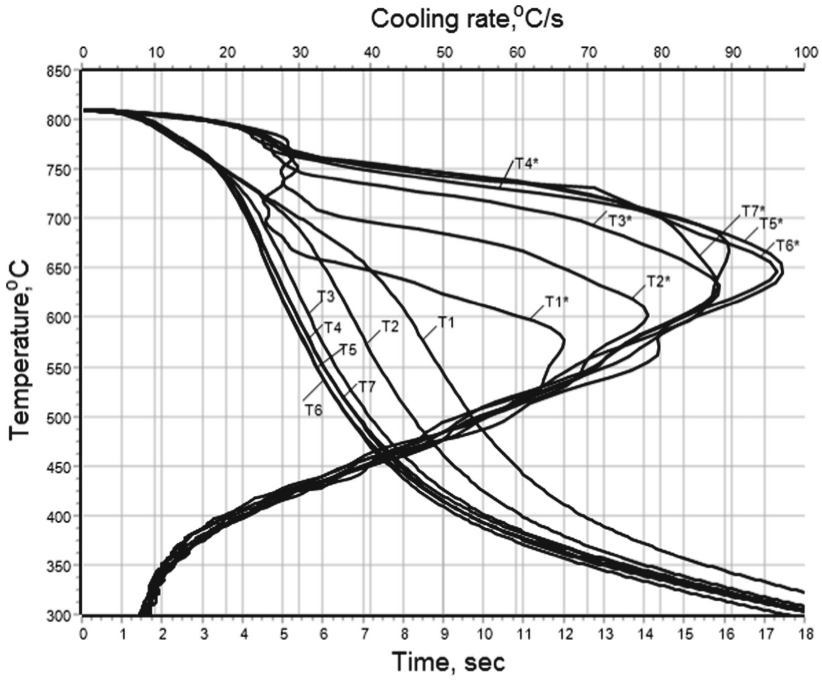


Fig. 2. Cooling curves and cooling rates for PIB 680 solutions in I-20 Oil at 50 °C and different concentrations, % wt.: 1-0.0; 2-3.0; 3-5.0; 4-7.0; 5-10.0; 6-12.5; 7-19.0.

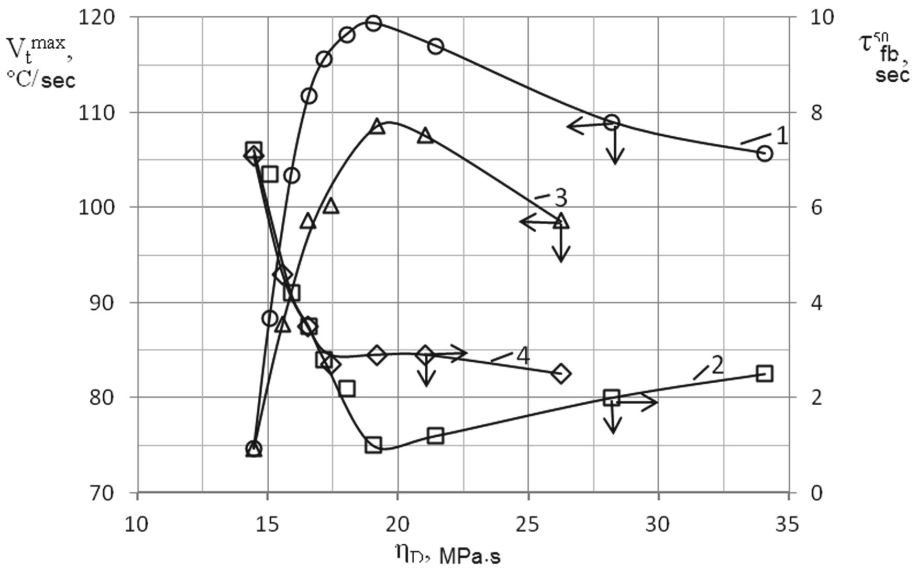


Fig. 3. Maximal cooling rates V_t^{max} (curve 1 and curve 3) and duration of film boiling (curve 2 and curve 4) for PIB 2400 (1, 2) and PIB 680 (3, 4) solutions in oil I-20A at 50 °C versus viscosity η_D .

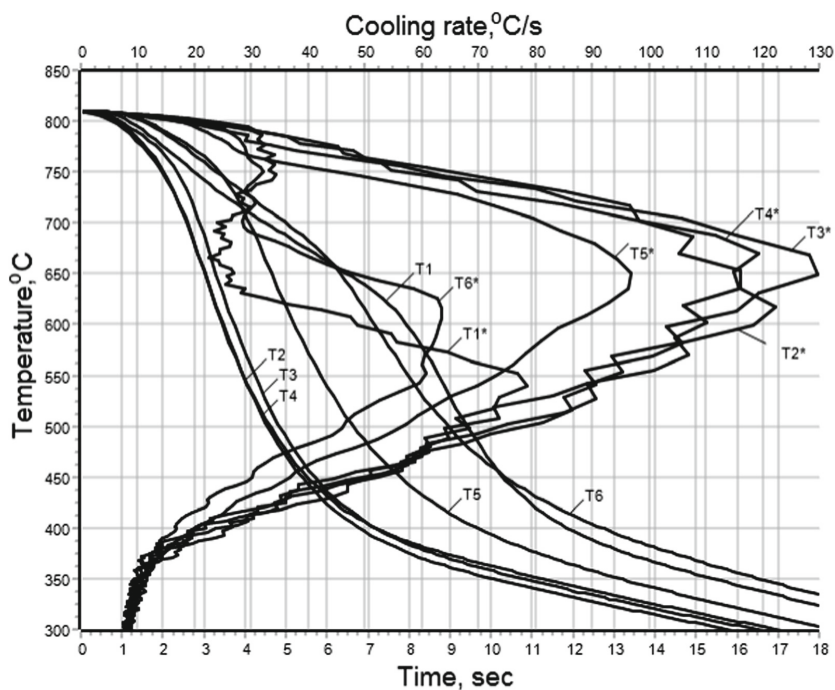


Fig. 4. Cooling curves and cooling rates for different solutions in oil I-20A: for oil I-20A (1), for 7% PIB 950 solution in oil I-20 (2), for 5% PIB 1300 solution in oil I-20 (3), for 3% PIB 2400 (4), for 10% PIB 680 solution in oil I-20 (5), and solution of 40% I-40 oil in I-20 oil (6).

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, % vt.					
			0.0	0.5	1.0	1.5	2.0	3.0
1	Cooling time from 810 °C to 600 °C in sec.	τ_{600}	8.1	7.8	5.7	5.3	4.7	3.5
2	Cooling time from 810 °C to 400 °C in sec.	τ_{400}	12.0	11.3	9.2	8.8	8.1	7.2
3	Cooling time from 810 °C to 200 °C in sec.	τ_{200}	37.3	36.3	34.7	35.7	34.5	34.7
4	Maximal cooling rate in °C/s	V_t^{\max}	74.7	88.4	103.4	111.8	108.8	119.4
5	Core temperature of probe at maximum cooling rate, °C	$T_3^{V_t \max}$	551	550	584	617	635	669
6	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; $Dr = 729 \text{ s}^{-1}$)

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-20 (2), for 5% PIB 1300 solution in oil I-20 (3), for 3% PIB 2400 (4), for 10% PIB 680 solution in oil I-20 at 50 °C (5), and solution of 40% I-40 oil in in I-20 oil in (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	$T_3^{Vt\max}$	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

3 Discussion

The approach of authors has a great practical importance because elimination of film and local film boiling results in decreasing distortion of steel parts after quenching. Especially, this problem is very important for bearing industry where elimination distortion can bring the 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 inverse solubility can lead to big distortion because dissolving of polymeric layer resulting in non – uniform cooling and martensitic transformations. To run technology correctly, one should deal with HTC's allowing make proper interruption to avoid big distortions. Thus, careful investigation of insulating layers will result in decreasing distortion and bring great benefits for industry.

4 Conclusions

1. Low addition (3%) of PIB 2400 into mineral oil I-20A eliminates completely film boiling during quenching which is called FBE effect.
2. Addition of PIB 2400 into I-8A and I-12A oils decreases film boiling process for 80% and 90% accordingly that is explained by lower critical heat flux densities of I-8A and I-12A oils.
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 PIB below of which FBE effect doesn't take place.
5. Mechanism and FBE effect is explained by formation an insulating layer on the metallic surface. It decreases initial heat flux density and makes it lesser than the first critical heat flux density [7].
6. The FBE effect opens the great opportunity to optimize investigations on designing and content of the new oil quenchants for heat treatment of metals.

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