CONTRIBUTION TO THE ADVANCED ANALYSIS AND PREVENTION OF THE MECHANISMS OF NATURAL FIRE INDUCED STRUCTURAL COLLAPSE IN HIGH-RISE BUILDINGS

APORTACIÓN AL ANÁLISIS AVANZADO Y PREVENCIÓN DE LOS MECANISMOS DE COLAPSO ESTRUCTURAL DE EDIFICIOS DE GRAN ALTURA ANTE UNA SOLICITACIÓN DE INCENDIO REAL

Doctoral Thesis presented by / *Tesis Doctoral presentada por*
Angel Guerrero Castells *Ingeniero Industrial con Suficiencia Investigadora*
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Thesis Directors / *Directores de la Tesis:*
Dr Frederic Marimon Carvajal from the / *de la Universidad Politécnica de Cataluña*
Dr Francesco Pesavento from the / *de la Università degli Studi di Padova*

PROGRAMA DE DOCTORADO DE ANÁLISIS ESTRUCTURAL
Departamento de Resistencia de Materiales y Estructuras en la Ingeniería
Escuela Técnica Superior de Ingenieros Industriales de Barcelona

Appendix 4A

Appendix 4A.1 SPALLING INDEX EVOLUTION FOR EACH COMBINATION

As it has been explained on previous paragraphs, to predict both the time and position of concrete rupture a spalling index developed by [A.1] and called 'intuitive' or I_{s4} has been selected, being its capabilities analysed in this paragraph.

The selected spalling index [A.1] is obtained choosing the following factors favouring thermal spalling: high local values of gas overpressure, p^g- p_{atm}, and mechanical damage parameter, d, high values of averaged transversal traction stresses, $\overline{\sigma}_{th}$, and constrained elastic energy $\overline{U}$ .The considered factors impeding thermal spalling are high average values of traction strength, $\overline{f}_t$, and specific fracture energy, $\overline{G}f$, for the material layer between a current position and the heated surface. Additionally, to obtain a non-dimensional quantity, [A.1] introduced a reference pressure (assume as equal to atmospheric pressure, p_{atm}) and a characteristic element dimension L (e.g. thickness for a wall, radius for a cylindrical specimen). Finally, internal geometrical parameters involved are unknown and are jointly described by a scaling factor, C_s, which is a non-dimensional parameter. Therefore, the fourth spalling index selected herein, I_{s4}, is given by the following relation:

$$I_{s4} = \frac{\overline{\sigma}_{th} \cdot \overline{U} \cdot d}{\overline{f}_t \cdot \overline{G}_f} \cdot \frac{p^g - p_{atm}}{p_{atm}} \cdot L \cdot C_s \qquad (4A.1)$$

Herein,

- The values of $\overline{\sigma}_{th}$, d, $\overline{U}$, p^g and the temperatures at each position are obtained from Hitecosp software [A.2] and then averaged for the material layer between a current position and the heated surface.
- The values of the specific fracture energy are obtained from experimental tests [A.3].
- The value of $\overline{f}_t$ is obtained from the material tensile strength equation for the temperature at each temperature and then averaged as described.

The results obtained applying in this equation the values obtained from the analysed case, for each of the ninety one combinations, are shown on figures 4A-1 to 4A-91.

For a better understanding, one must remember the type of notation used to describe each of these ninety one combinations:

TH**K***RH**PAR*C**, where,

TH** indicates the value of the thickness of the model (in cm) used in the computation,

K*** indicates the value of the intrinsic permeability (in m^2),

RH** indicates the value of the initial saturation degree (in %),

PAR* indicates the parametric heating curve taken into account in the computation,

C** indicates the material considered in the computation.

Thus, for example, TH12K018RH50PAR1C60 stands for a case characterised by a *thickness*=12 cm, k=10^{-18} m^2, S_{init}*=50%, Parametric curve*=ISO Curve (Par1) and C60 material.

The following figures are in the same order as the combination numbering to easy their use (a collection table is included in next page to remind the whole set of combinations):

		PC1 (RH) [%]			PC2 (K) [m^2]			PC3 (TH) [cm]			PC4 (Heating curve)			PC5 (Mat)	
#	**Combination**	**40**	**50**	**60**	**10^{-19}**	**10^{-18}**	**10^{-17}**	**12**	**24**	**50**	**PAR1**	**PAR2**	**PAR3**	**C60**	**C90**
1	TH12K017RH40PAR1C60	X					X	X			X			X	
2	TH12K018RH40PAR1C60	X				X		X			X			X	
3	TH12K019RH40PAR1C60	X			X			X			X			X	
4	TH12K017RH50PAR1C60		X				X	X			X			X	
5	TH12K018RH50PAR1C60		X			X		X			X			X	
6	TH12K019RH50PAR1C60		X		X			X			X			X	
7	TH12K017RH60PAR1C60			X			X	X			X			X	
8	TH12K018RH60PAR1C60			X		X		X			X			X	
9	TH12K019RH60PAR1C60			X	X			X			X			X	
10	TH12K017RH40PAR2C60	X					X	X				X		X	
11	TH12K018RH40PAR2C60	X				X		X				X		X	
12	TH12K019RH40PAR2C60	X			X			X				X		X	
13	TH12K017RH50PAR2C60		X				X	X				X		X	
14	TH12K018RH50PAR2C60		X			X		X				X		X	
15	TH12K019RH50PAR2C60		X		X			X				X		X	
16	TH12K017RH60PAR2C60			X			X	X				X		X	
17	TH12K018RH60PAR2C60			X		X		X				X		X	
18	TH12K019RH60PAR2C60			X	X			X				X		X	
19	TH24K017RH40PAR1C60	X					X		X		X			X	
20	TH24K018RH40PAR1C60	X				X			X		X			X	
21	TH24K019RH40PAR1C60	X			X				X		X			X	
22	TH24K017RH50PAR1C60		X				X		X		X			X	
23	TH24K018RH50PAR1C60		X			X			X		X			X	
24	TH24K019RH50PAR1C60		X		X				X		X			X	
25	TH24K017RH60PAR1C60			X			X		X		X			X	
26	TH24K018RH60PAR1C60			X		X			X		X			X	
27	TH24K019RH60PAR1C60			X	X				X		X			X	
28	TH24K017RH40PAR2C60	X					X		X			X		X	
29	TH24K018RH40PAR2C60	X				X			X			X		X	
30	TH24K019RH40PAR2C60	X			X				X			X		X	
31	TH24K017RH50PAR2C60		X				X		X			X		X	
32	TH24K018RH50PAR2C60		X			X			X			X		X	
33	TH24K019RH50PAR2C60		X		X				X			X		X	
34	TH24K017RH60PAR2C60			X			X		X			X		X	
35	TH24K018RH60PAR2C60			X		X			X			X		X	
36	TH24K019RH60PAR2C60			X	X				X			X		X	
37	TH12K017RH40PAR1C90	X					X	X			X				X
38	TH12K018RH40PAR1C90	X				X		X			X				X
39	TH12K019RH40PAR1C90	X			X			X			X				X
40	TH12K017RH50PAR1C90		X				X	X			X				X
41	TH12K018RH50PAR1C90		X			X		X			X				X
42	TH12K019RH50PAR1C90		X		X			X			X				X
43	TH12K017RH60PAR1C90			X			X	X			X				X
44	TH12K018RH60PAR1C90			X		X		X			X				X
45	TH12K019RH60PAR1C90			X	X			X			X				X
46	TH12K017RH40PAR2C90	X					X	X				X			X
47	TH12K018RH40PAR2C90	X				X		X				X			X
48	TH12K019RH40PAR2C90	X			X			X				X			X

Table 4A-1. *Set of combinations analysed for the development of the Spalling Nomograms*

	(continued)	PC1 (RH) [%]			PC2 (K) [m²]			PC3 (TH) [cm]			PC4 (Heating curve)			PC5 (Mat)	
#	**Combination**	**40**	**50**	**60**	**10^{-19}**	**10^{-18}**	**10^{-17}**	**12**	**24**	**50**	**PAR1**	**PAR2**	**PAR3**	**C60**	**C90**
49	TH12K017RH50PAR2C90		X				X	X				X			X
50	TH12K018RH50PAR2C90		X			X		X				X			X
51	TH12K019RH50PAR2C90		X		X			X				X			X
52	TH12K017RH60PAR2C90			X			X	X				X			X
53	TH12K018RH60PAR2C90			X		X		X				X			X
54	TH12K019RH60PAR2C90			X	X			X				X			X
55	TH24K017RH40PAR1C90	X					X		X		X				X
56	TH24K018RH40PAR1C90	X				X			X		X				X
57	TH24K019RH40PAR1C90	X			X				X		X				X
58	TH24K017RH50PAR1C90		X				X		X		X				X
59	TH24K018RH50PAR1C90		X			X			X		X				X
60	TH24K019RH50PAR1C90		X		X				X		X				X
61	TH24K017RH60PAR1C90			X			X		X		X				X
62	TH24K018RH60PAR1C90			X		X			X		X				X
63	TH24K019RH60PAR1C90			X	X				X		X				X
64	TH24K017RH40PAR2C90	X					X		X			X			X
65	TH24K018RH40PAR2C90	X				X			X			X			X
66	TH24K019RH40PAR2C90	X			X				X			X			X
67	TH24K017RH50PAR2C90		X				X		X			X			X
68	TH24K018RH50PAR2C90		X			X			X			X			X
69	TH24K019RH50PAR2C90		X		X				X			X			X
70	TH24K017RH60PAR2C90			X			X		X			X			X
71	TH24K018RH60PAR2C90			X		X			X			X			X
72	TH24K019RH60PAR2C90			X	X				X			X			X
73	TH50K018RH50PAR1C60		X			X				X	X			X	
74	TH12K017RH40PAR3C60	X					X	X					X	X	
75	TH12K018RH40PAR3C60	X				X		X					X	X	
76	TH12K019RH40PAR3C60	X			X			X					X	X	
77	TH12K017RH50PAR3C60		X				X	X					X	X	
78	TH12K018RH50PAR3C60		X			X		X					X	X	
79	TH12K019RH50PAR3C60		X		X			X					X	X	
80	TH12K017RH60PAR3C60			X			X	X					X	X	
81	TH12K018RH60PAR3C60			X		X		X					X	X	
82	TH12K019RH60PAR3C60			X	X			X					X	X	
83	TH12K017RH40PAR3C90	X					X	X					X		X
84	TH12K018RH40PAR3C90	X				X		X					X		X
85	TH12K019RH40PAR3C90	X			X			X					X		X
86	TH12K017RH50PAR3C90		X				X	X					X		X
87	TH12K018RH50PAR3C90		X			X		X					X		X
88	TH12K019RH50PAR3C90		X		X			X					X		X
89	TH12K017RH60PAR3C90			X			X	X					X		X
90	TH12K018RH60PAR3C90			X		X		X					X		X
91	TH12K019RH60PAR3C90			X	X			X					X		X

Table 4A-1. *Set of combinations analysed for the development of the Spalling Nomograms (continued)*

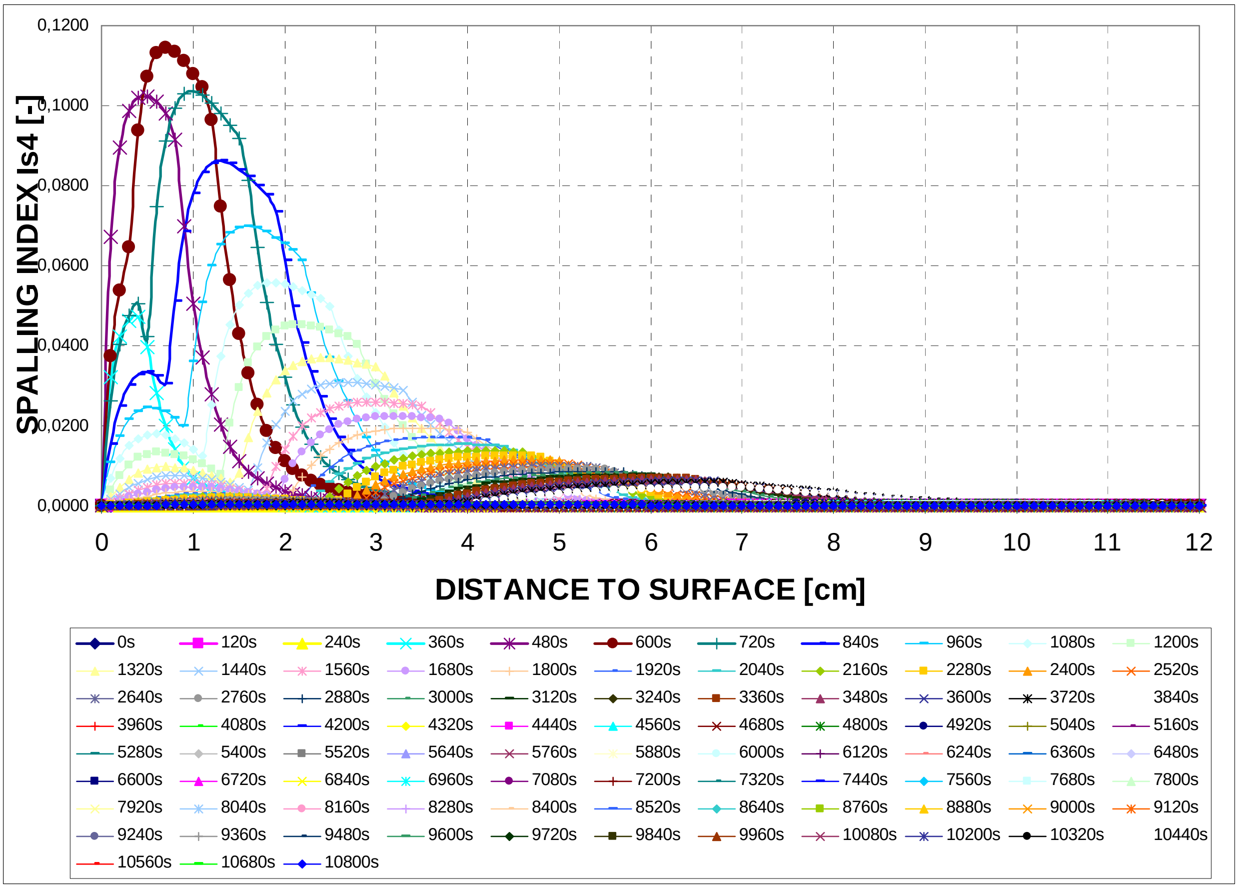

Figure 4A-1. *Spalling Index IS4 evolution for combination 1-TH12K017RH40PAR1C60*

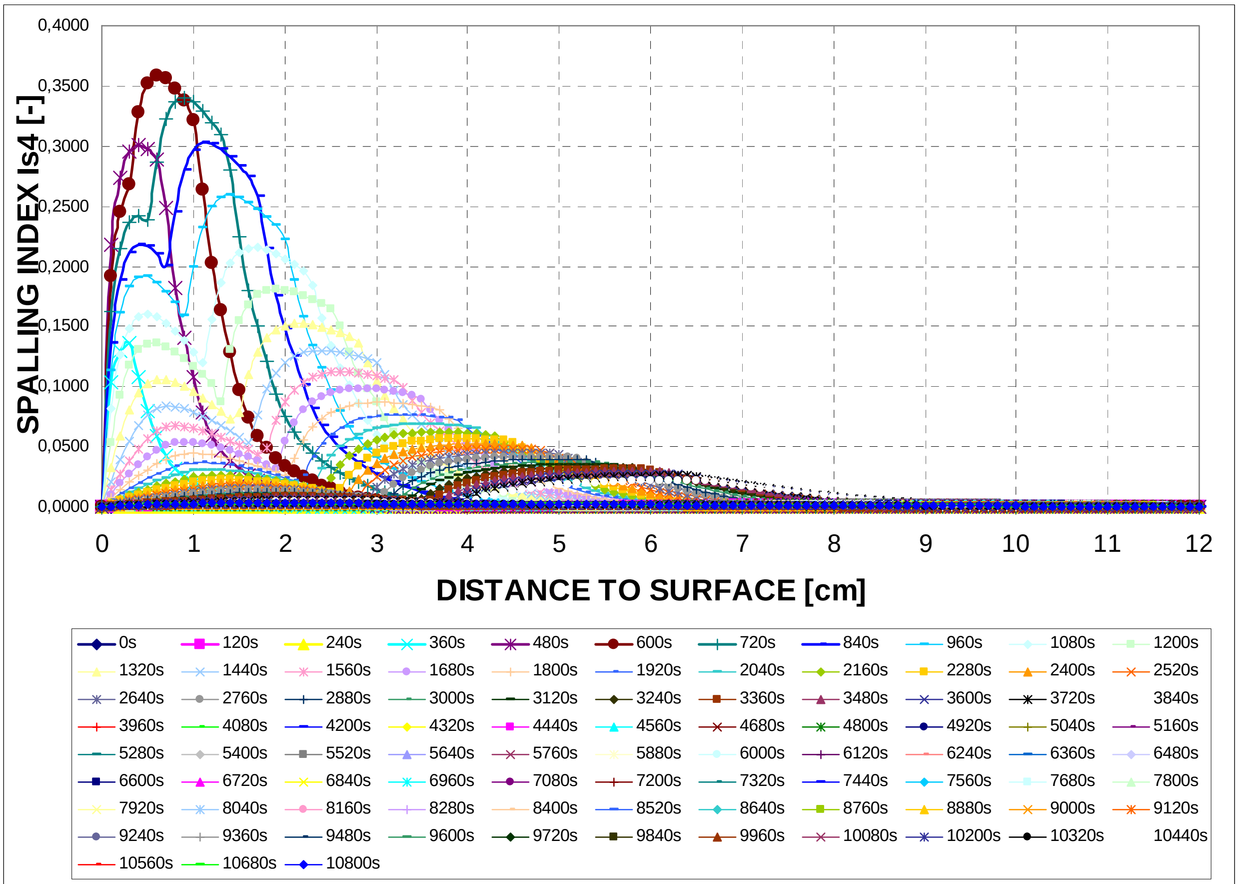

Figure 4A-2. *Spalling Index IS4 evolution for combination 2-TH12K018RH40PAR1C60*

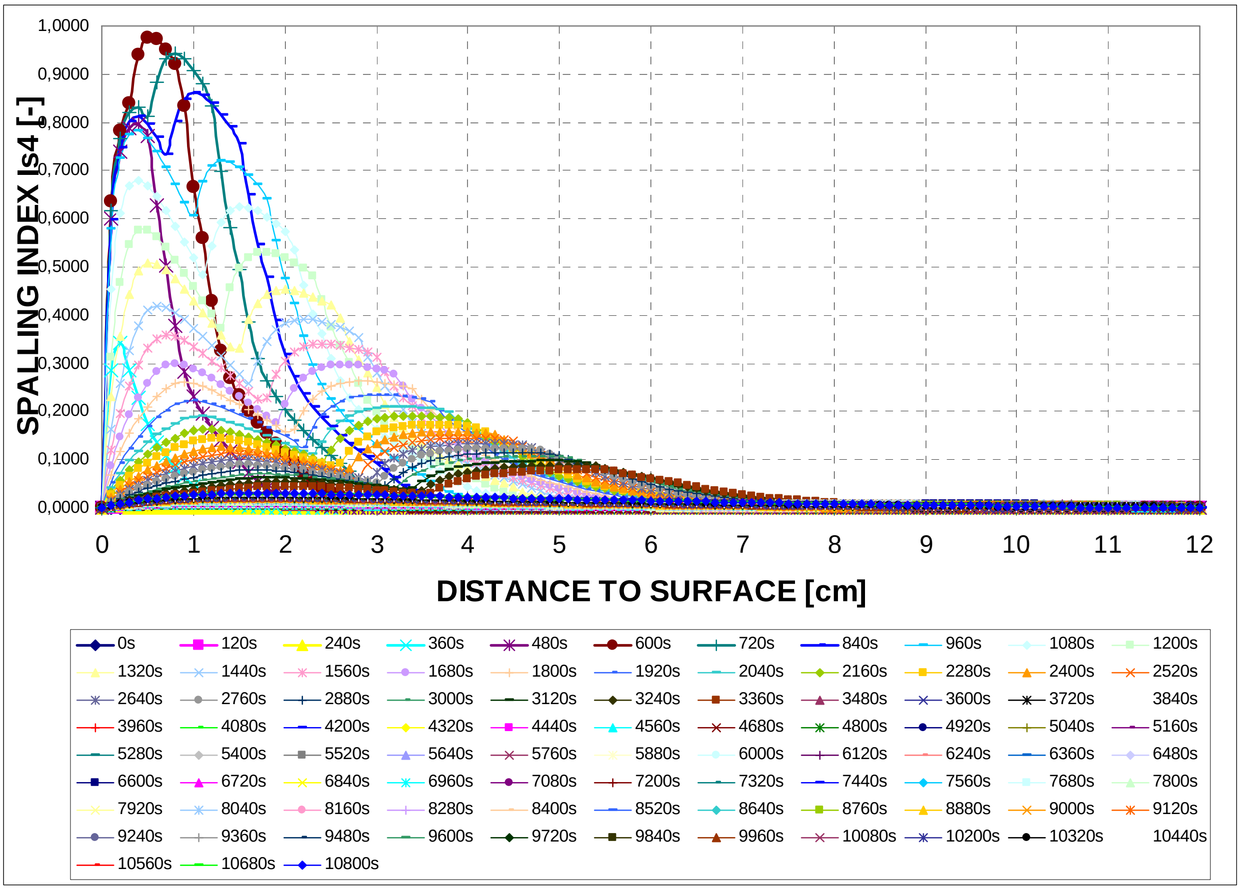

Figure 4A-3. *Spalling Index IS4 evolution for combination 3-TH12K019RH40PAR1C60*

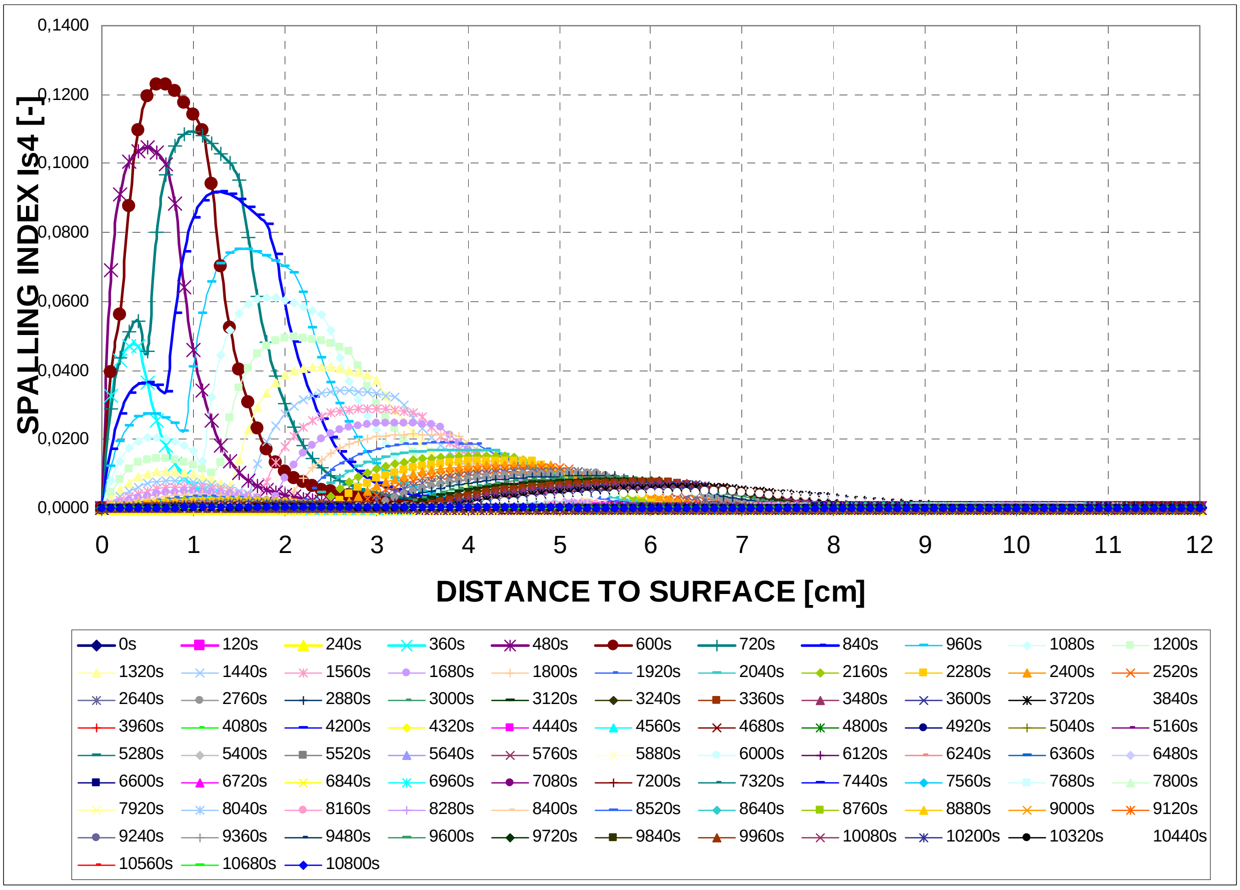

Figure 4A-4. *Spalling Index IS4 evolution for combination 4-TH12K017RH50PAR1C60*

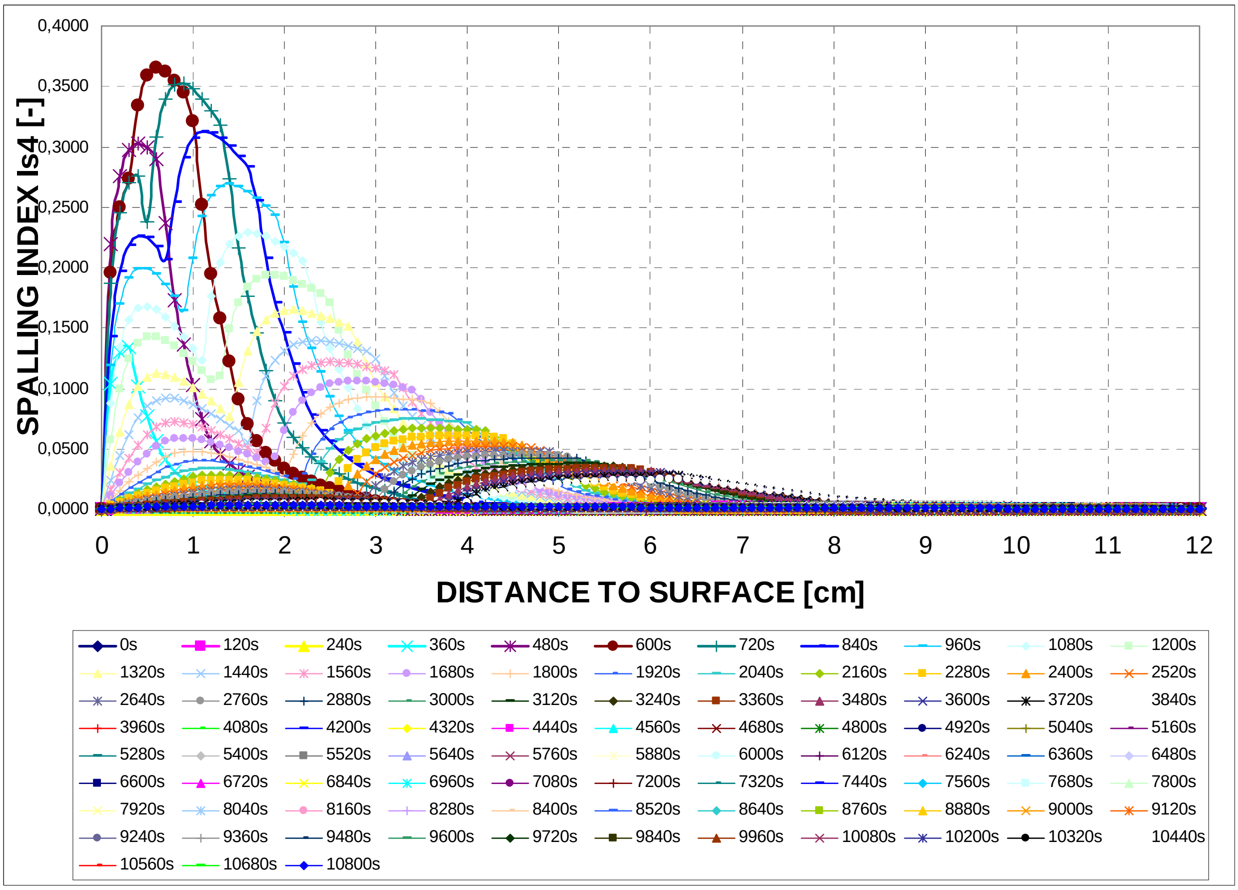

Figure 4A-5. *Spalling Index IS4 evolution for combination 5-TH12K018RH50PAR1C60*

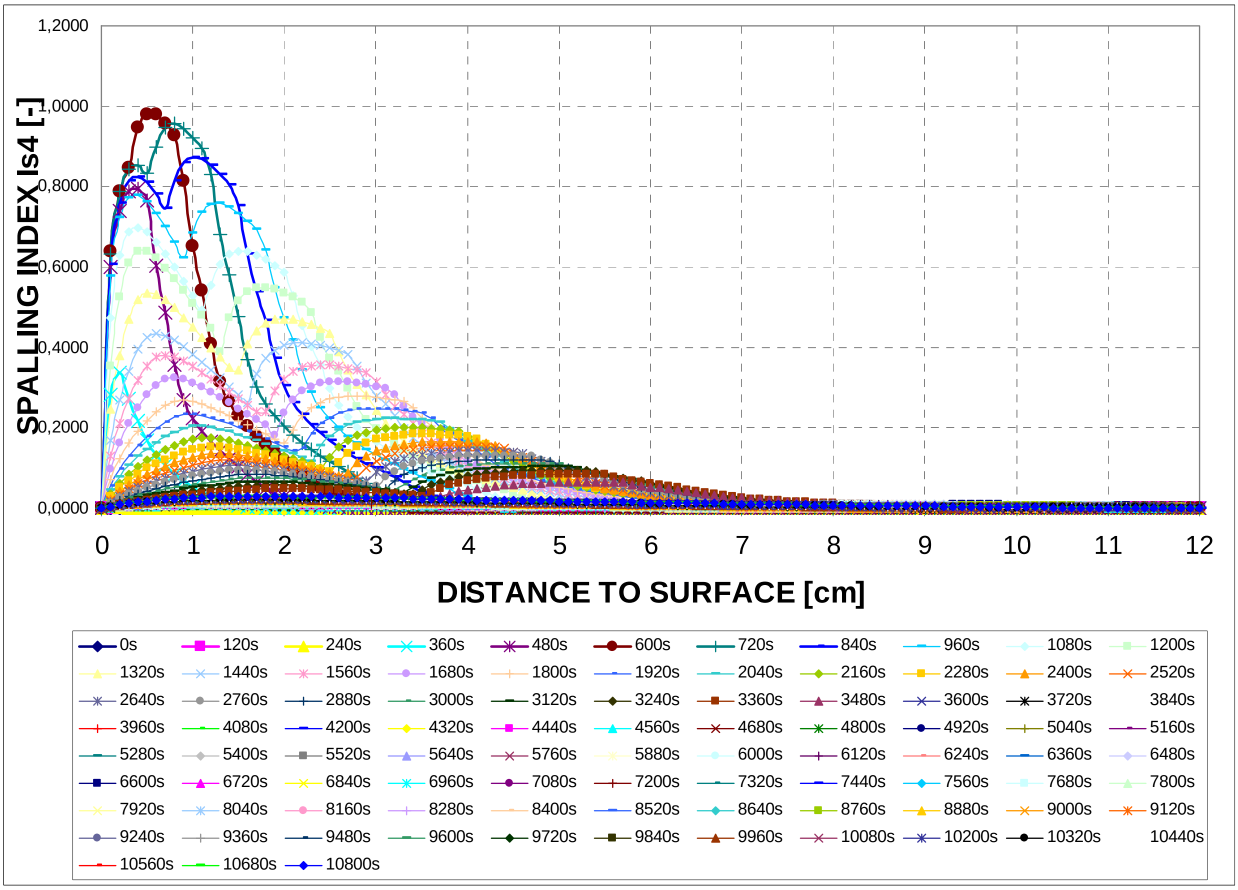

Figure 4A-6. *Spalling Index IS4 evolution for combination 6-TH12K019RH50PAR1C60*

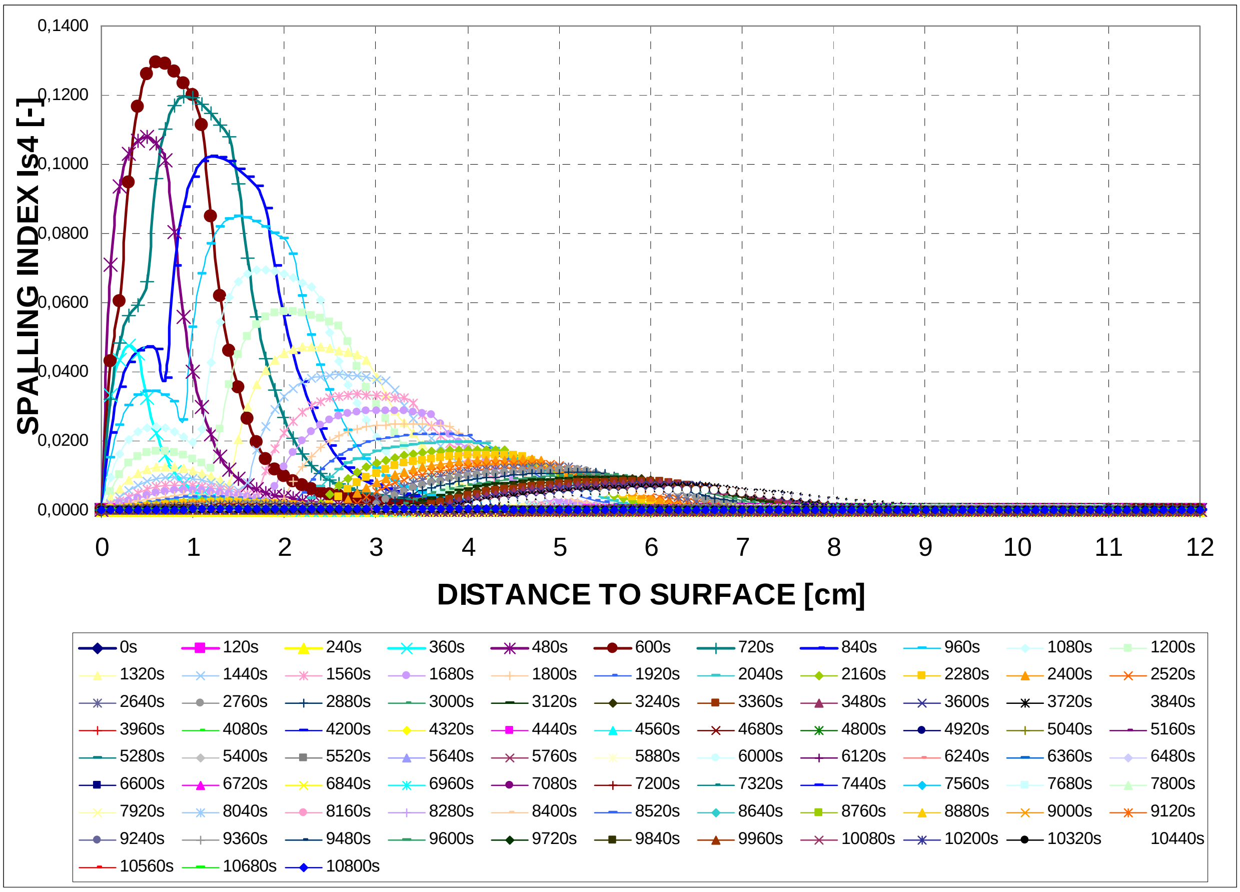

***Figure 4A-7.** Spalling Index IS4 evolution for combination 7-TH12K017RH60PAR1C60*

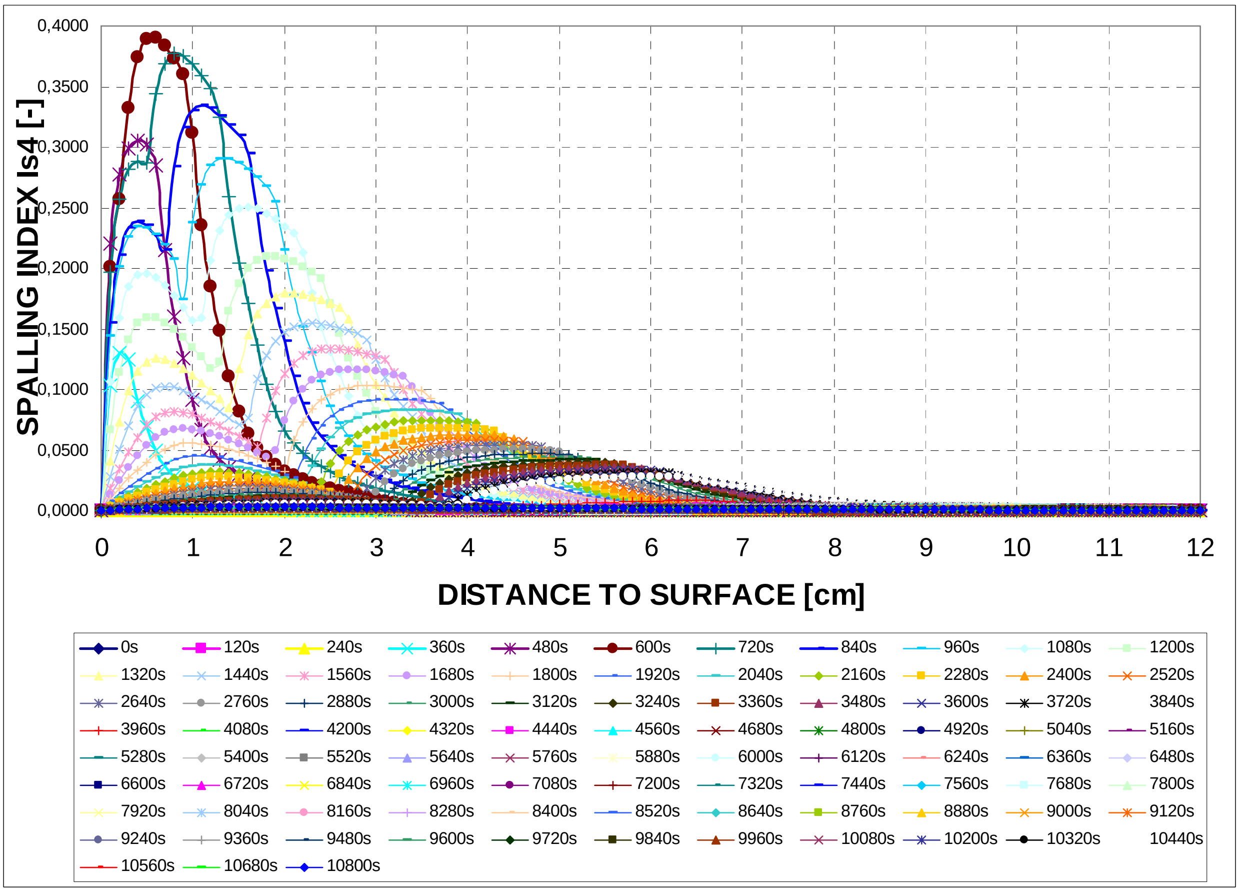

***Figure 4A-8.** Spalling Index IS4 evolution for combination 8-TH12K018RH60PAR1C60*

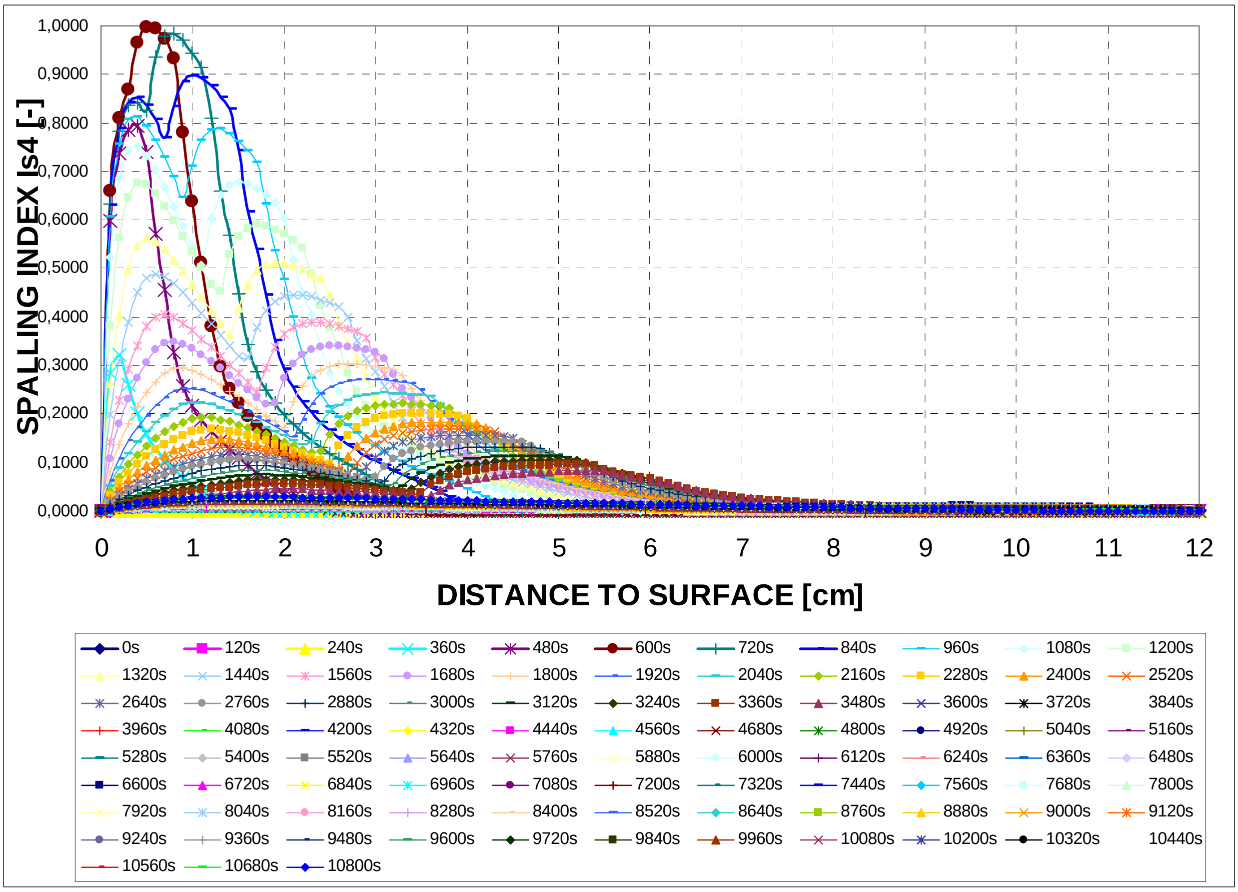

Figure 4A-9. *Spalling Index IS4 evolution for combination 9-TH12K019RH60PAR1C60*

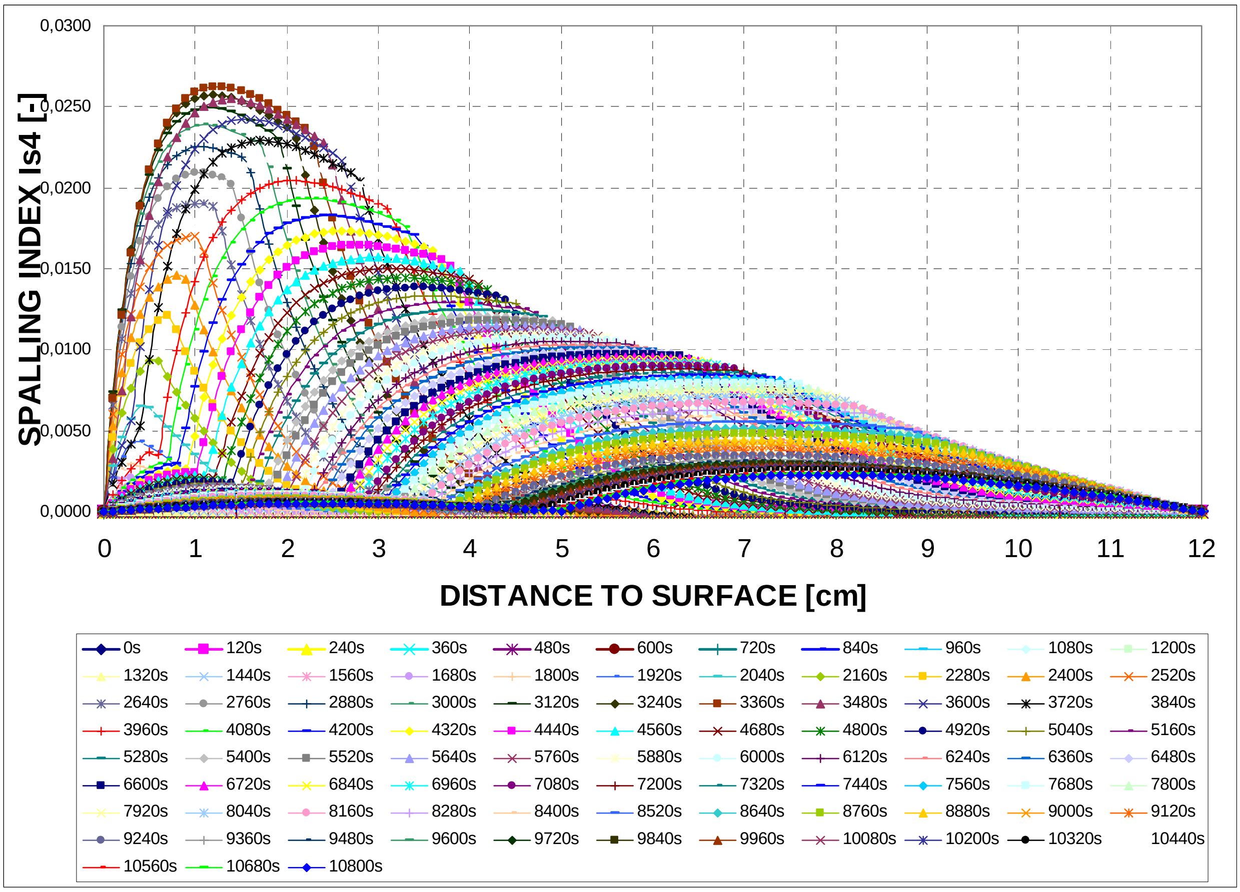

Figure 4A-10. *Spalling Index IS4 evolution for combination 10-TH12K017RH40PAR2C60*

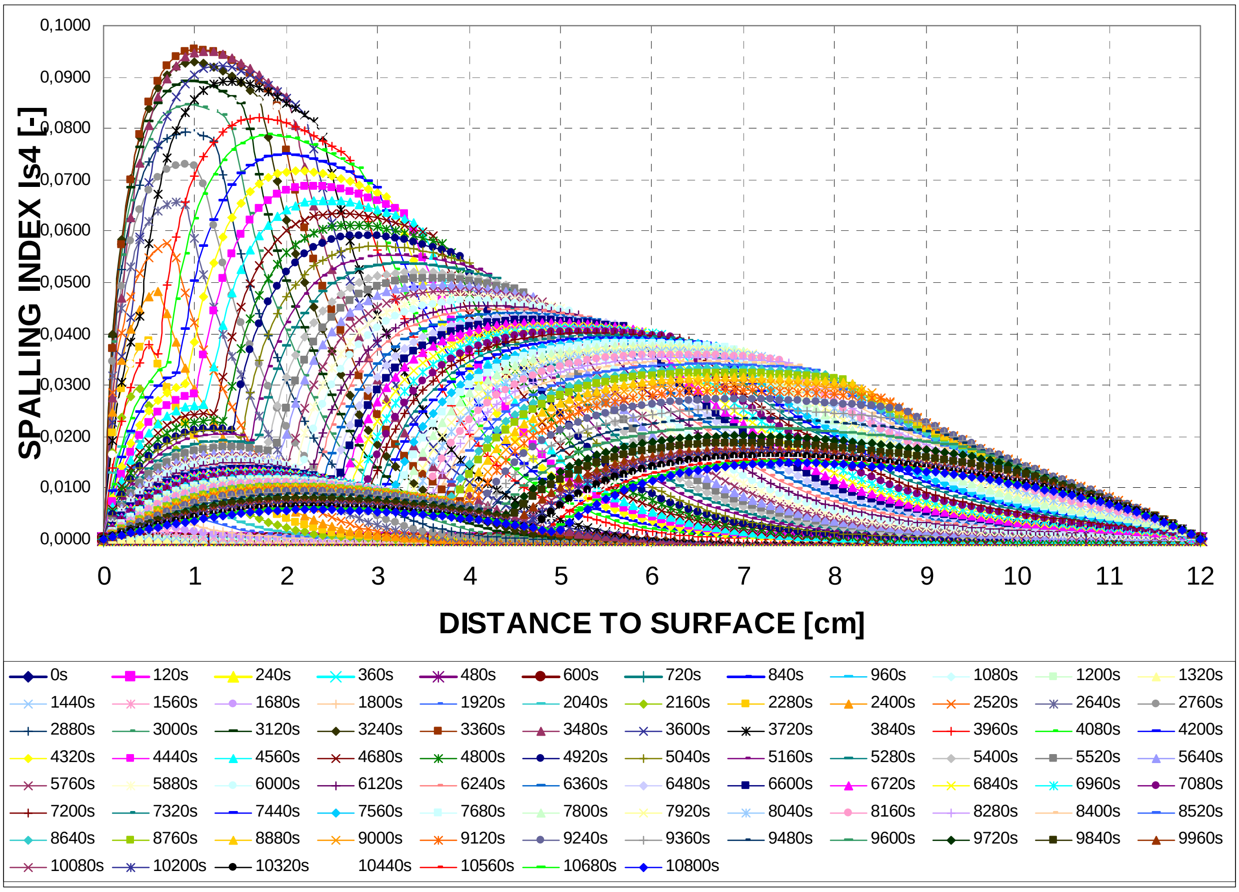

Figure 4A-11. *Spalling Index IS4 evolution for combination 11-TH12K018RH40PAR2C60*

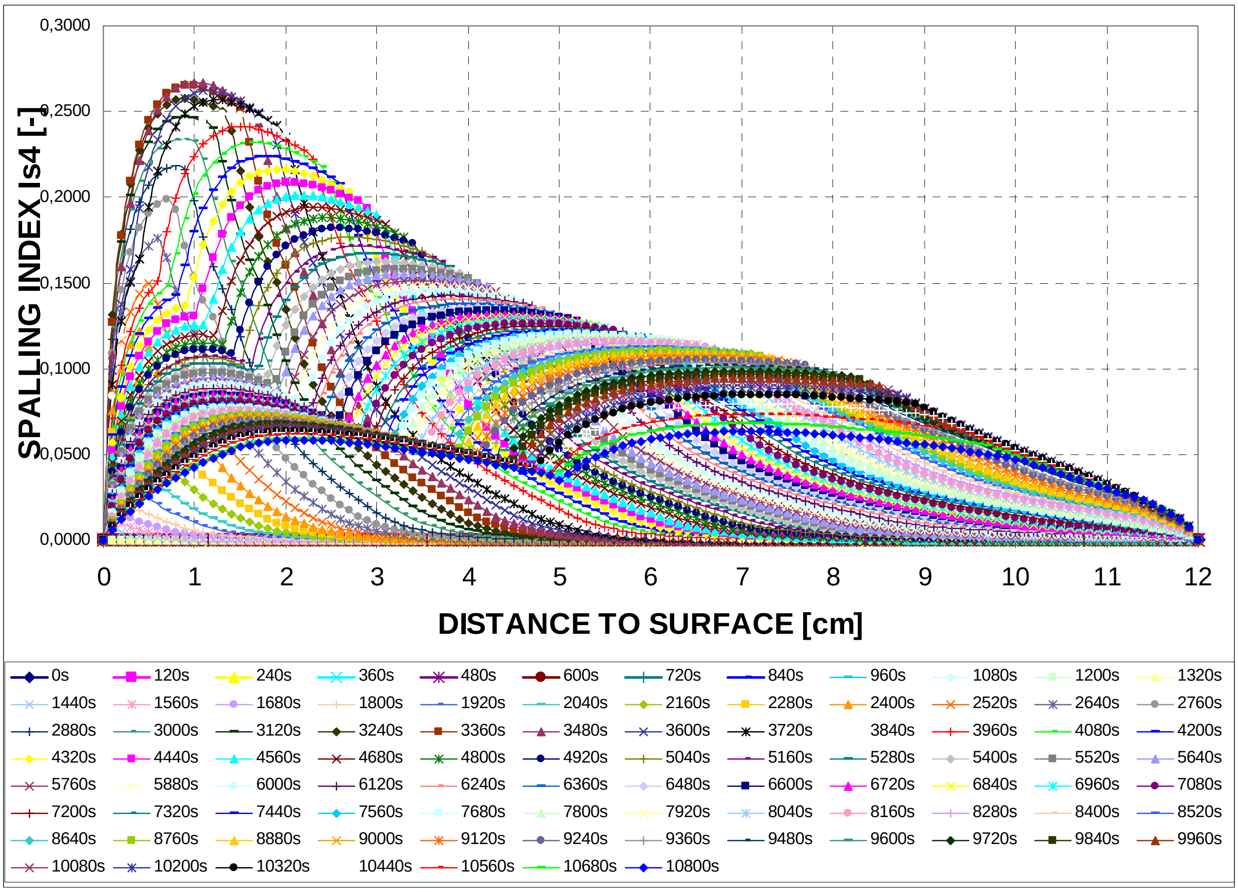

Figure 4A-12. *Spalling Index IS4 evolution for combination 12-TH12K019RH40PAR2C60*

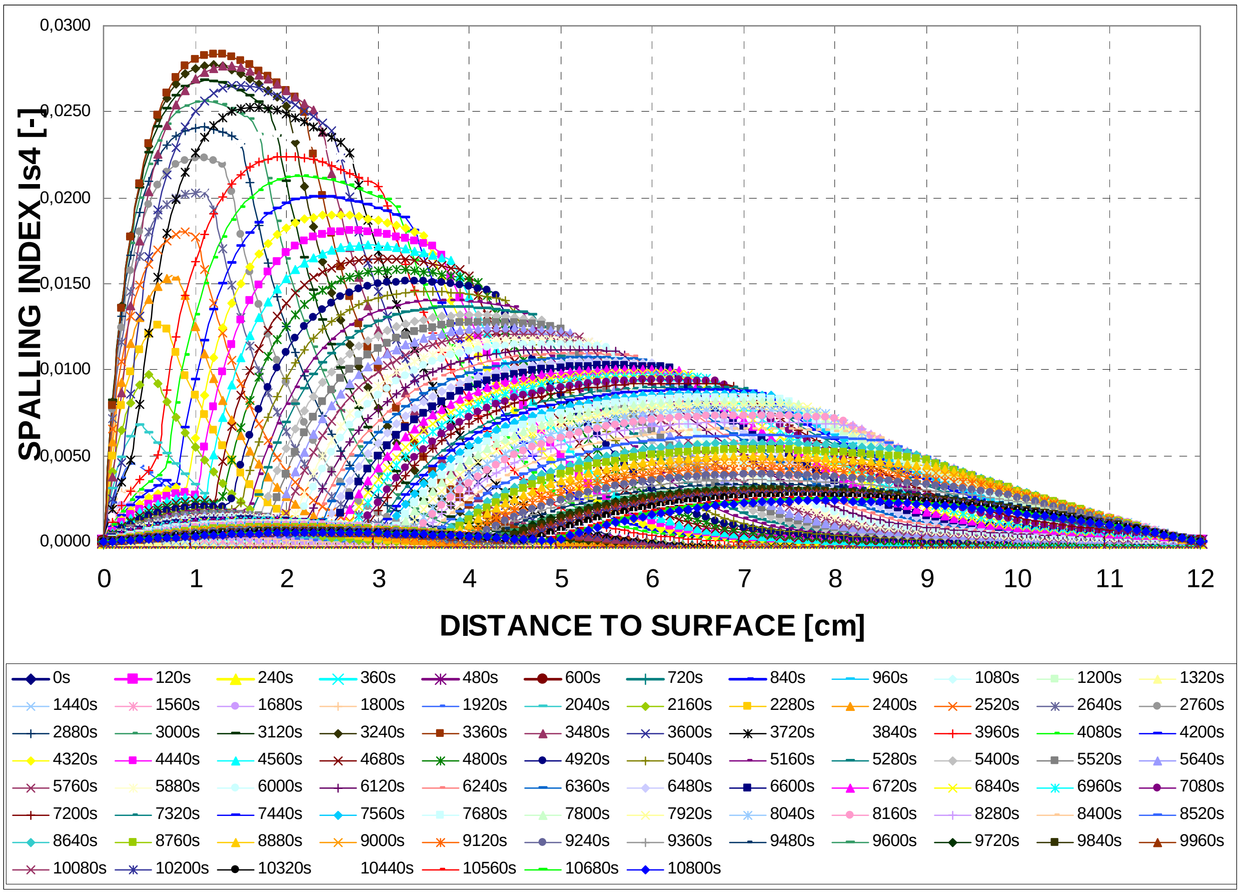

Figure 4A-13. *Spalling Index IS4 evolution for combination 13-TH12K017RH50PAR2C60*

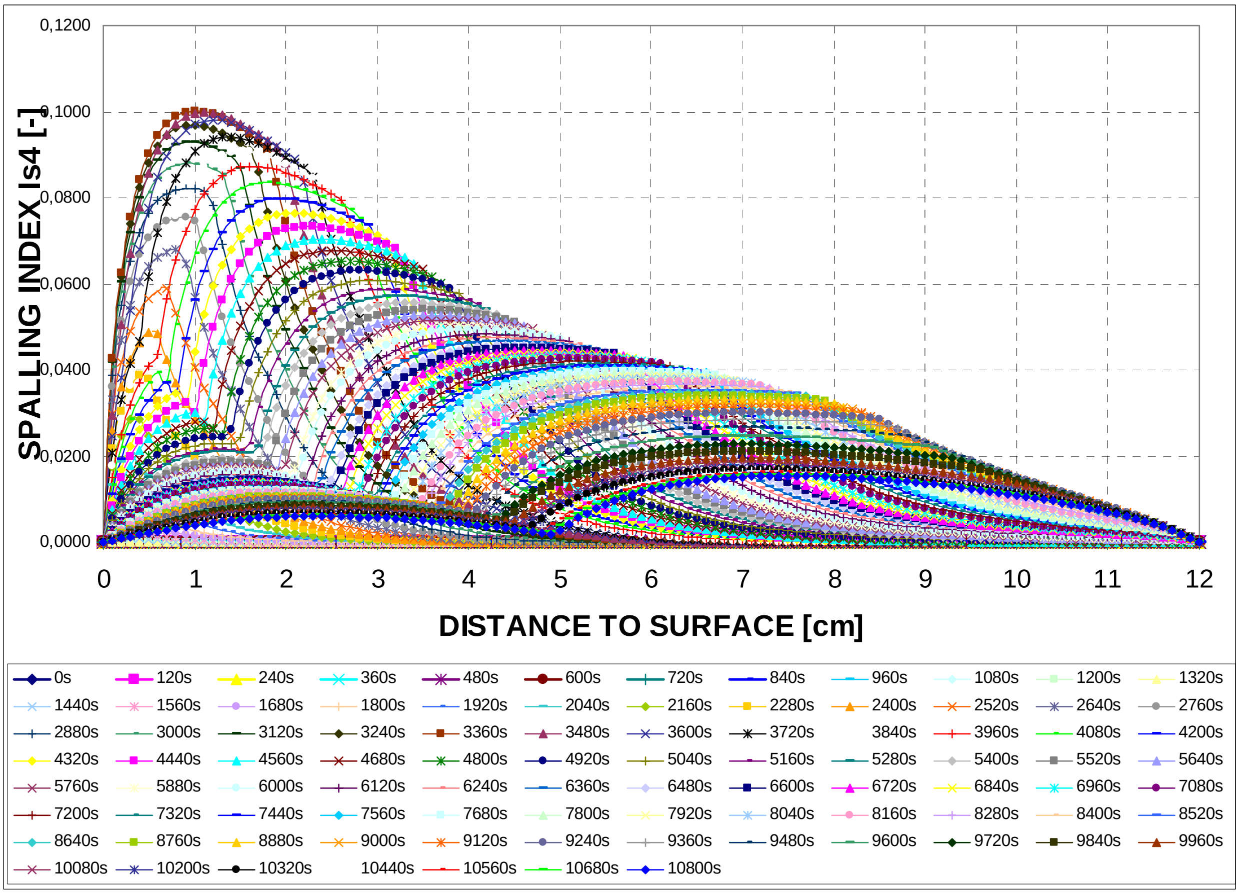

Figure 4A-14. *Spalling Index IS4 evolution for combination 14-TH12K018RH50PAR2C60*

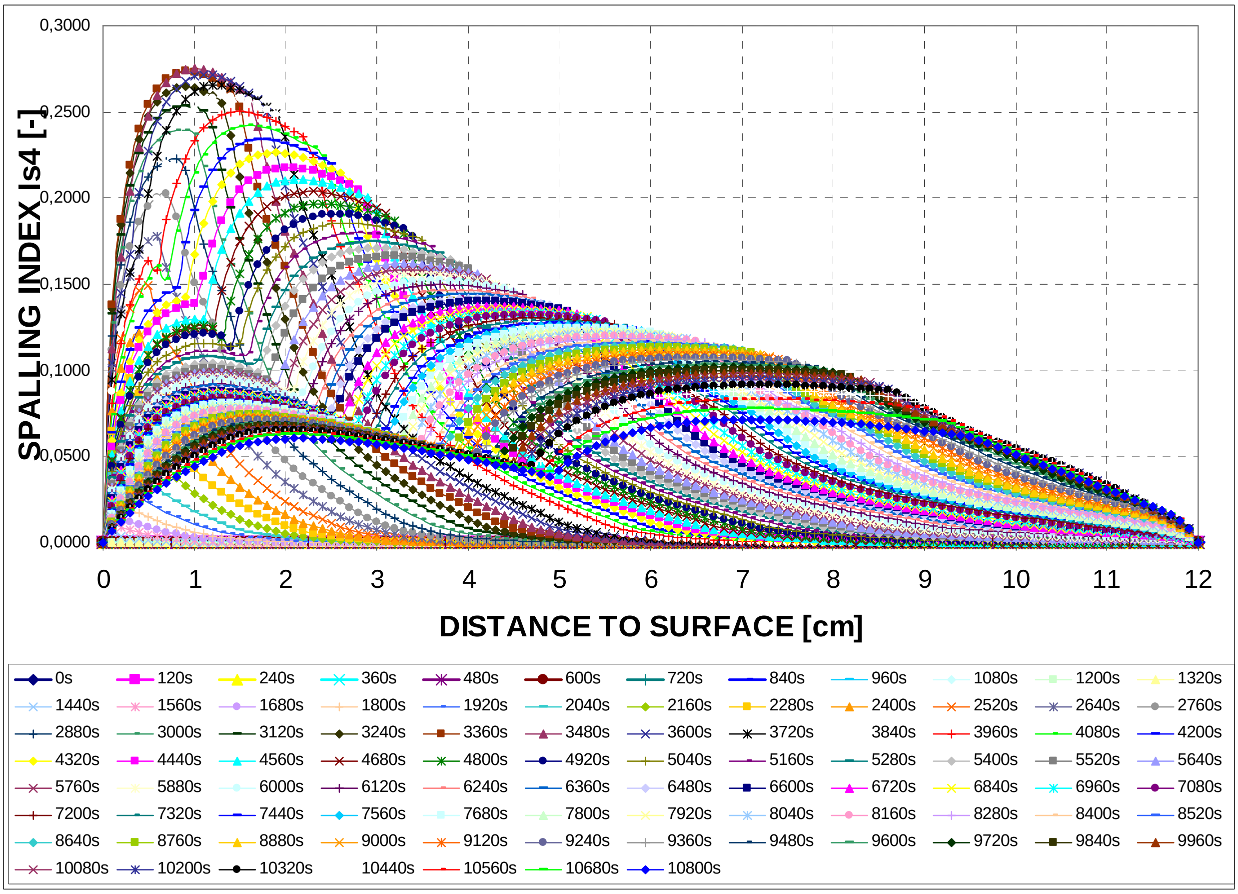

Figure 4A-15. *Spalling Index IS4 evolution for combination 15-TH12K019RH50PAR2C60*

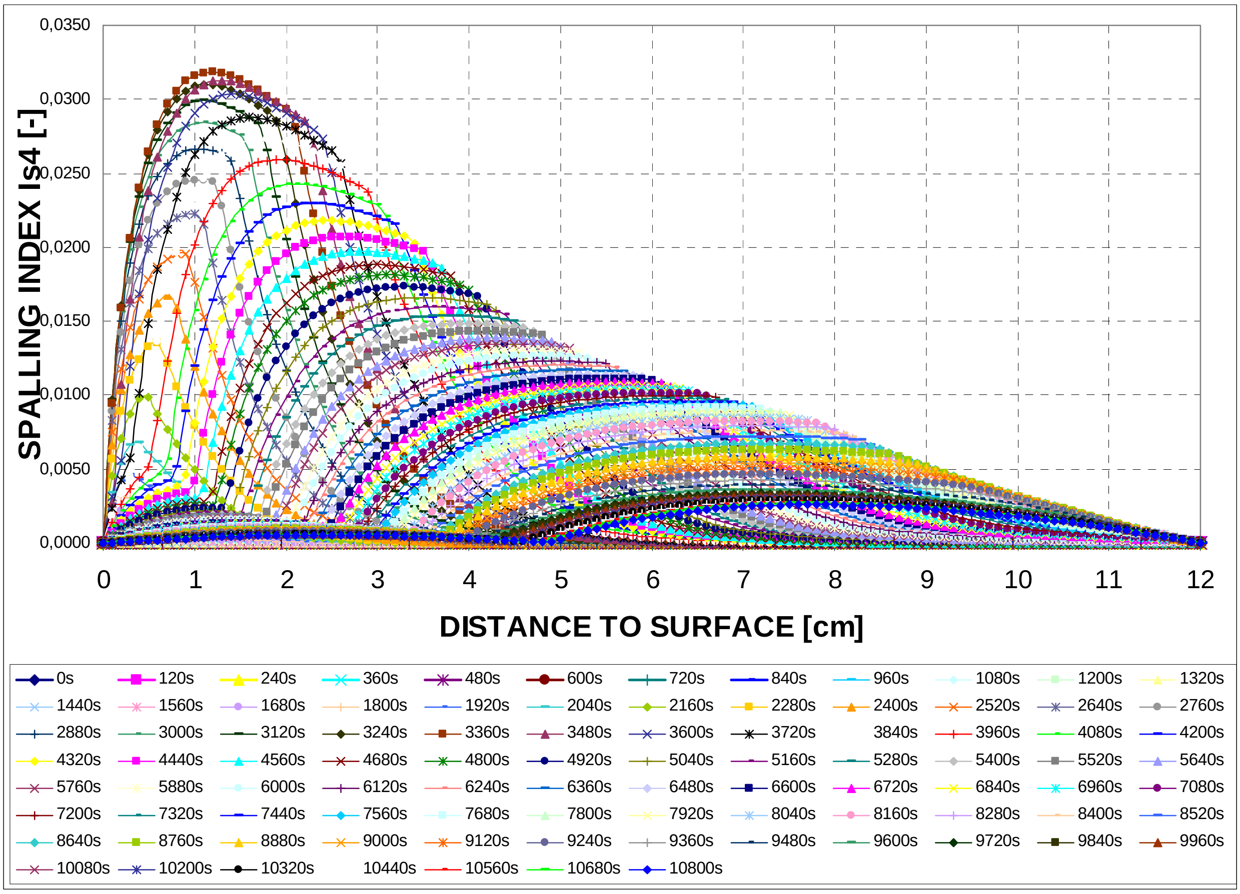

Figure 4A-16. *Spalling Index IS4 evolution for combination 16-TH12K017RH60PAR2C60*

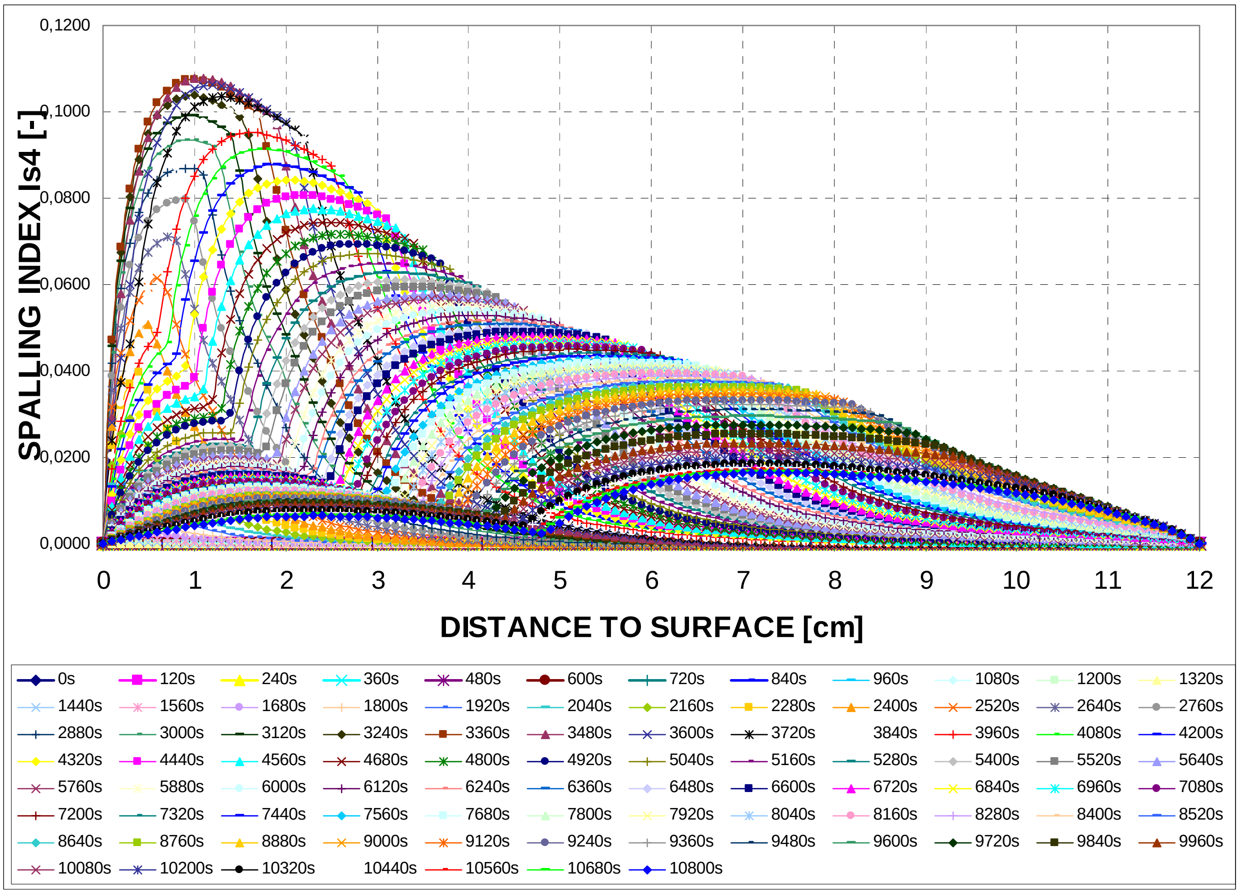

Figure 4A-17. *Spalling Index IS4 evolution for combination 17-TH12K018RH60PAR2C60*

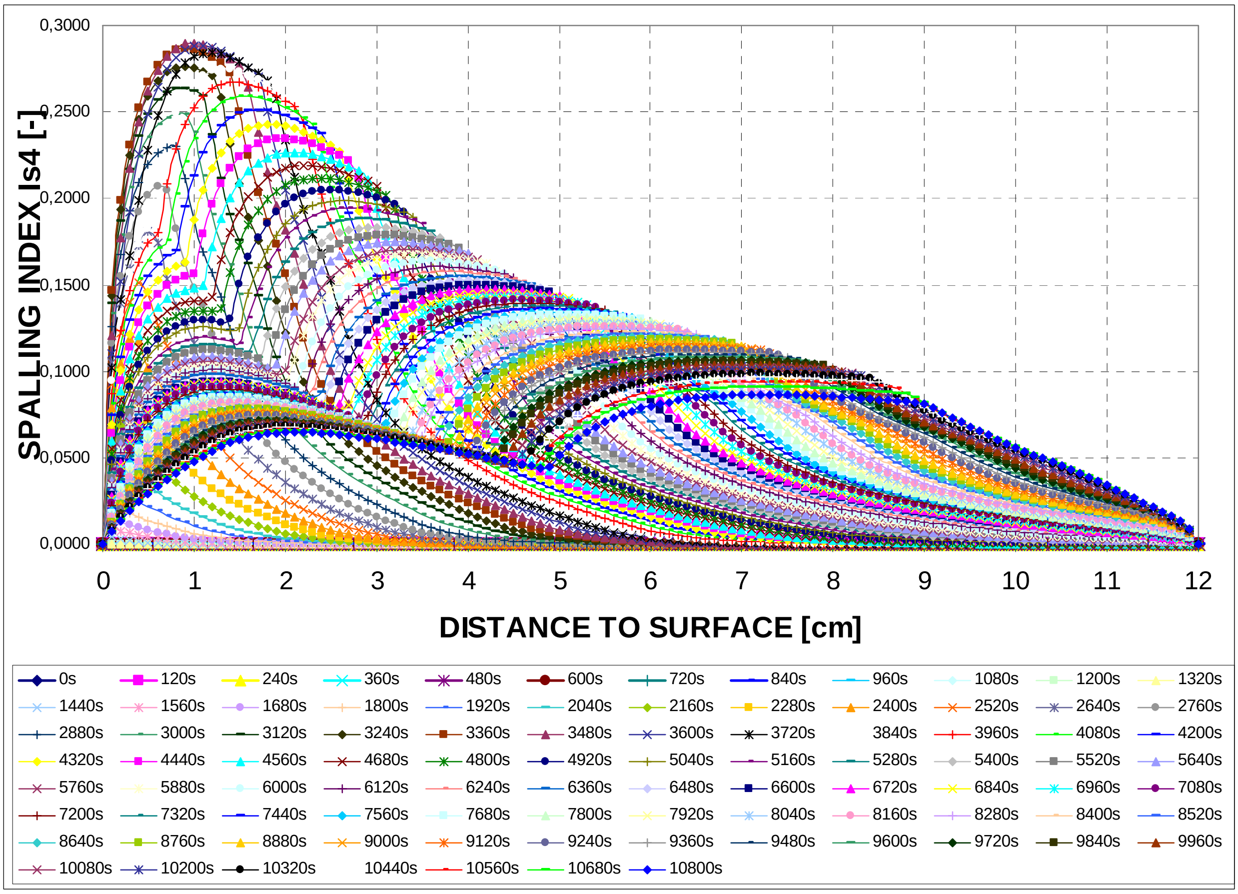

Figure 4A-18. *Spalling Index IS4 evolution for combination 18-TH12K019RH60PAR2C60*

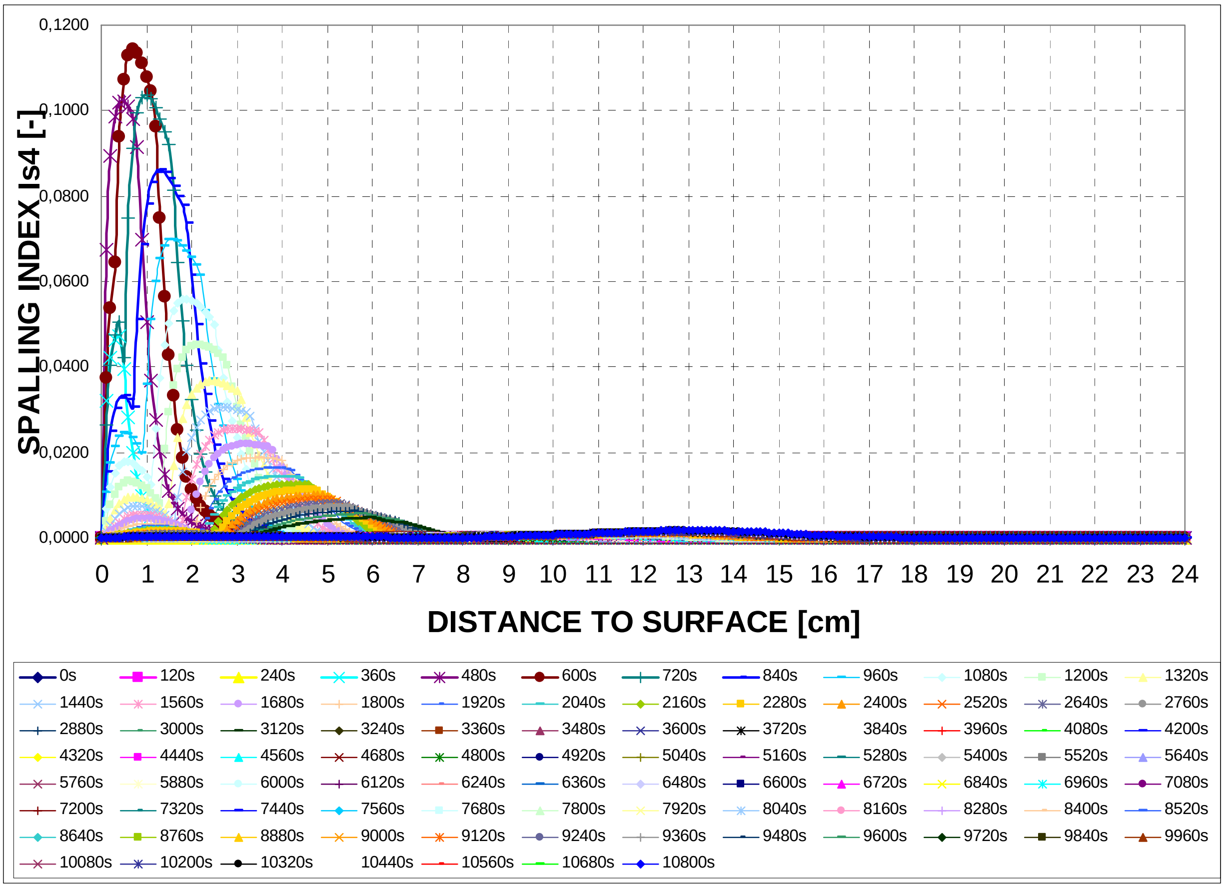

Figure 4A-19. *Spalling Index IS4 evolution for combination 19-TH24K017RH40PAR1C60*

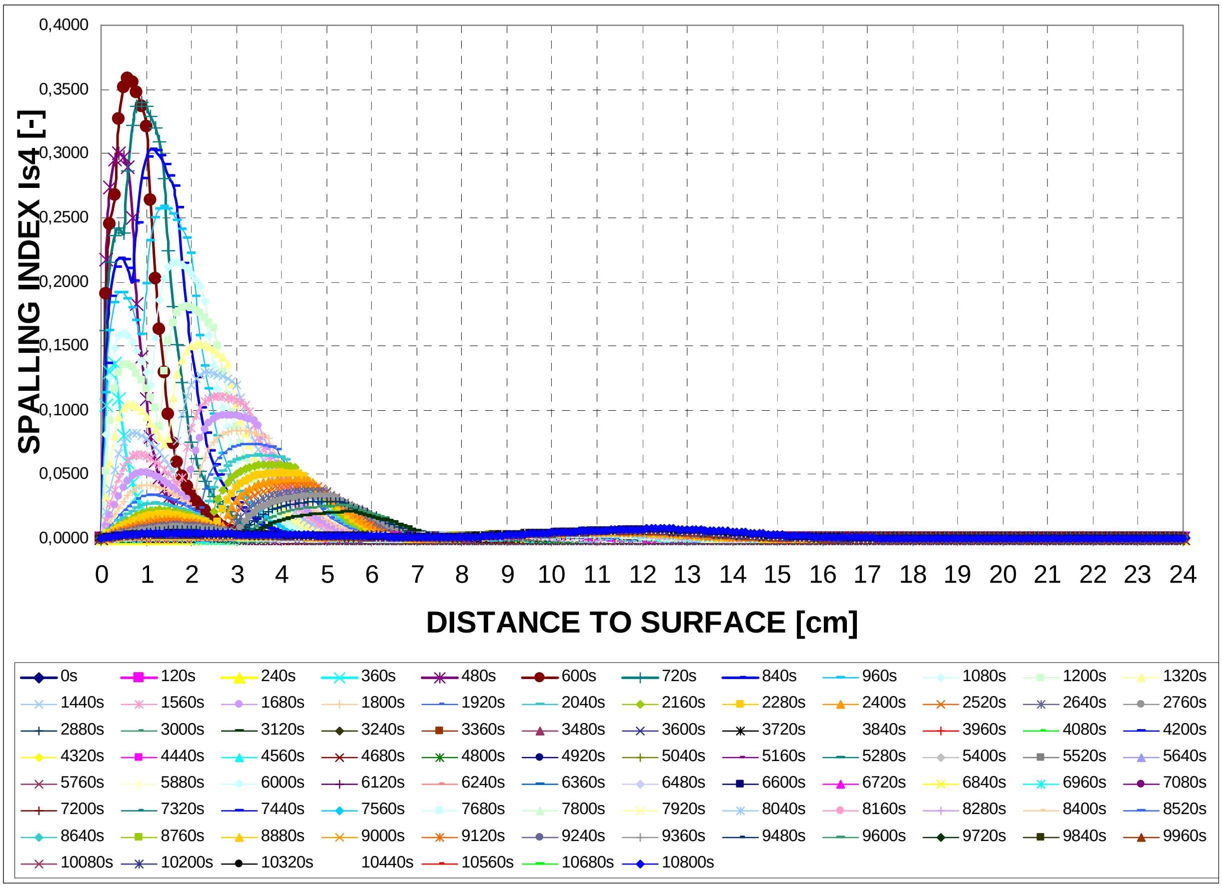

Figure 4A-20. *Spalling Index IS4 evolution for combination 20-TH24K018RH40PAR1C60*

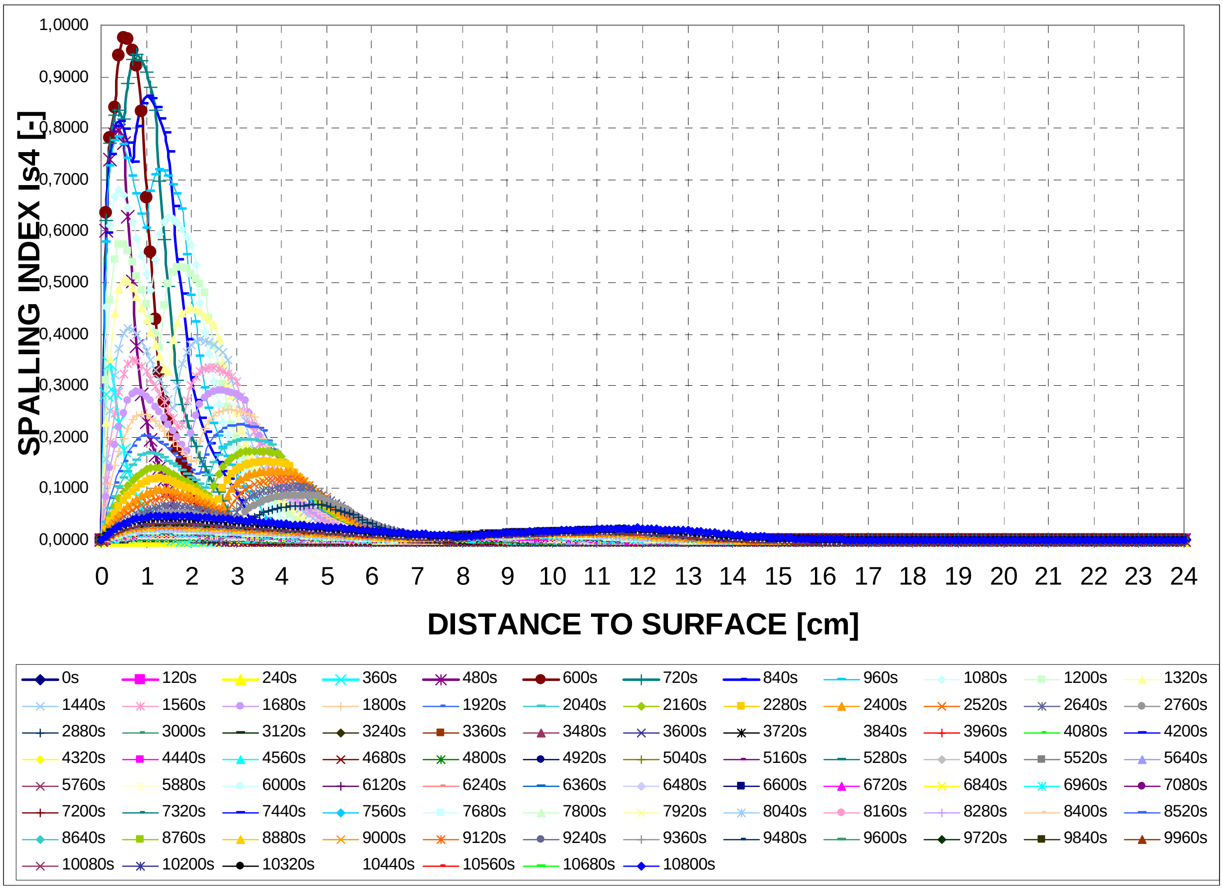

Figure 4A-21. *Spalling Index IS4 evolution for combination 21-TH24K019RH40PAR1C60*

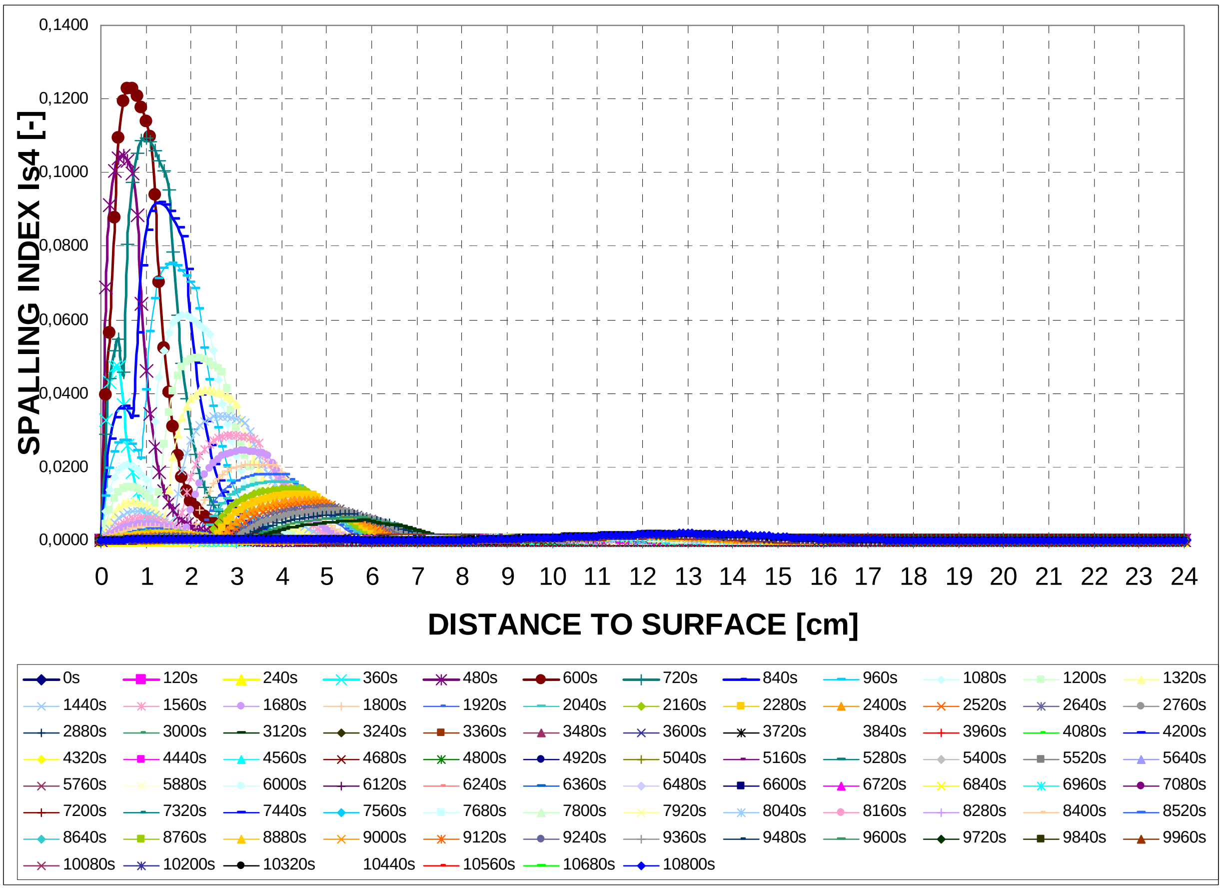

Figure 4A-22. *Spalling Index IS4 evolution for combination 22-TH24K017RH50PAR1C60*

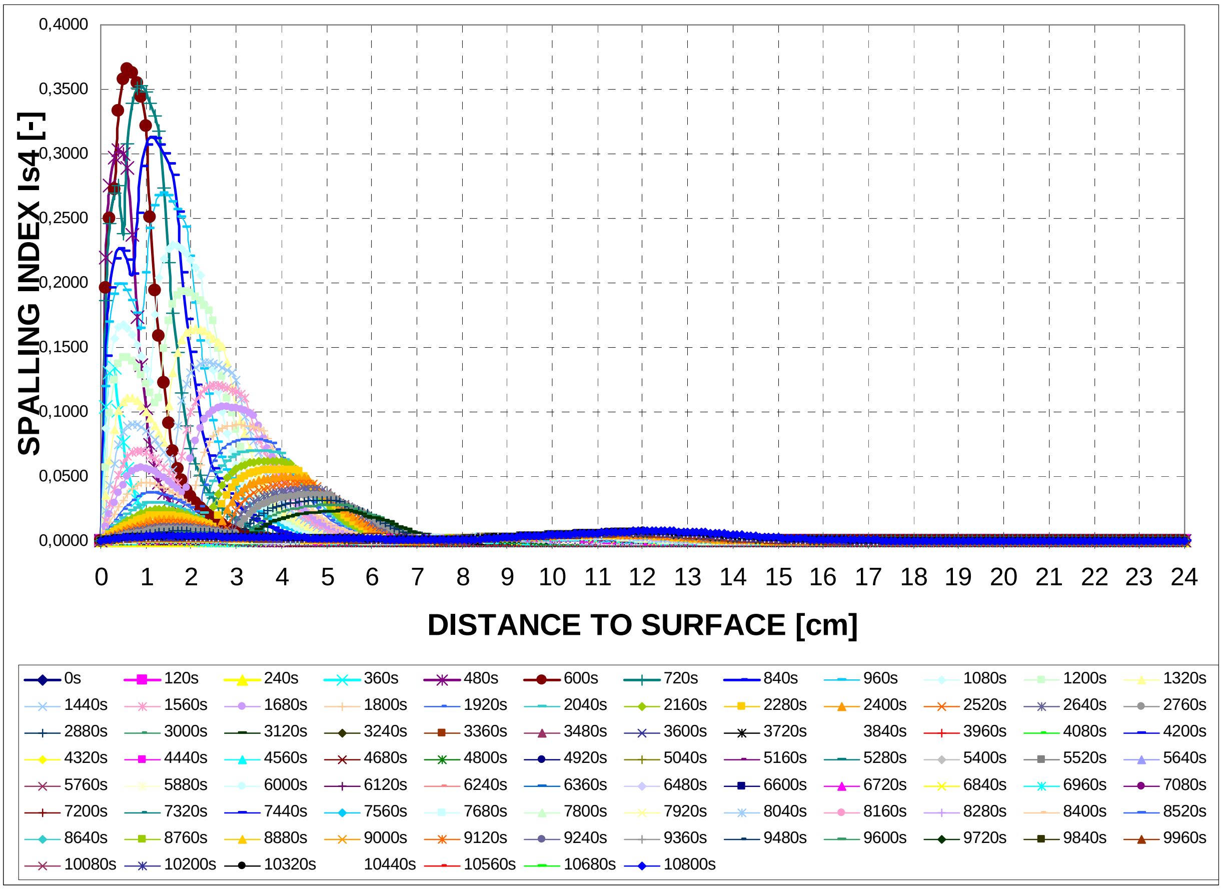

Figure 4A-23. *Spalling Index IS4 evolution for combination 23-TH24K018RH50PAR1C60*

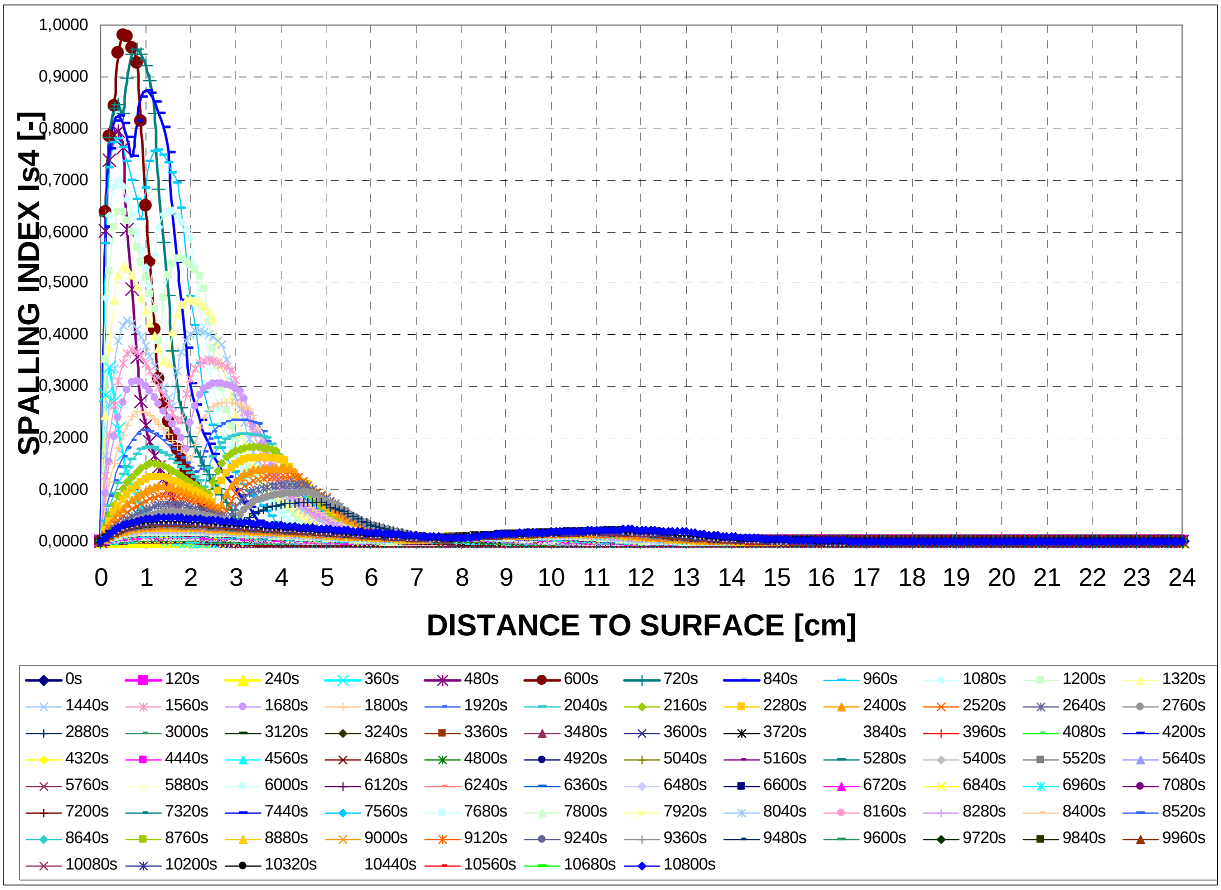

Figure 4A-24. *Spalling Index IS4 evolution for combination 24-TH24K019RH50PAR1C60*

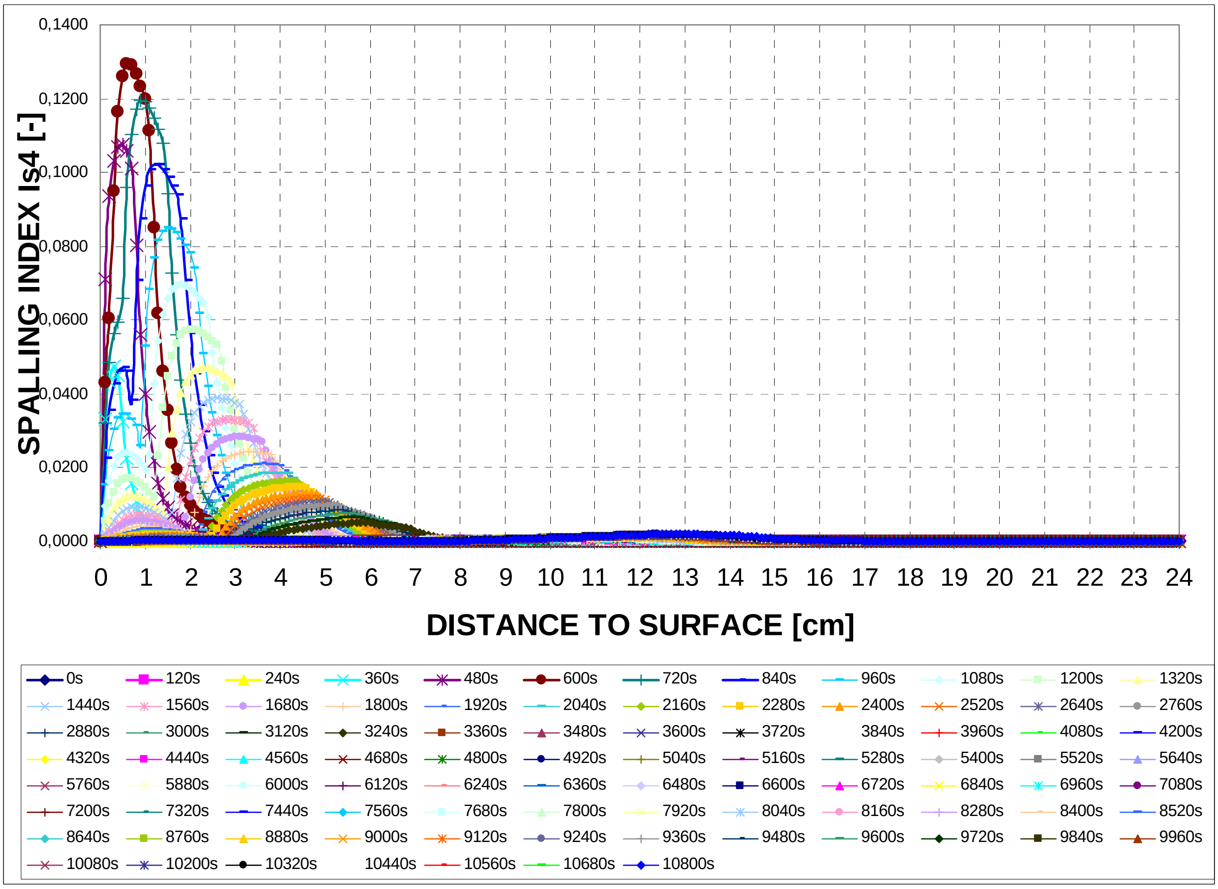

Figure 4A-25. *Spalling Index IS4 evolution for combination 25-TH24K017RH60PAR1C60*

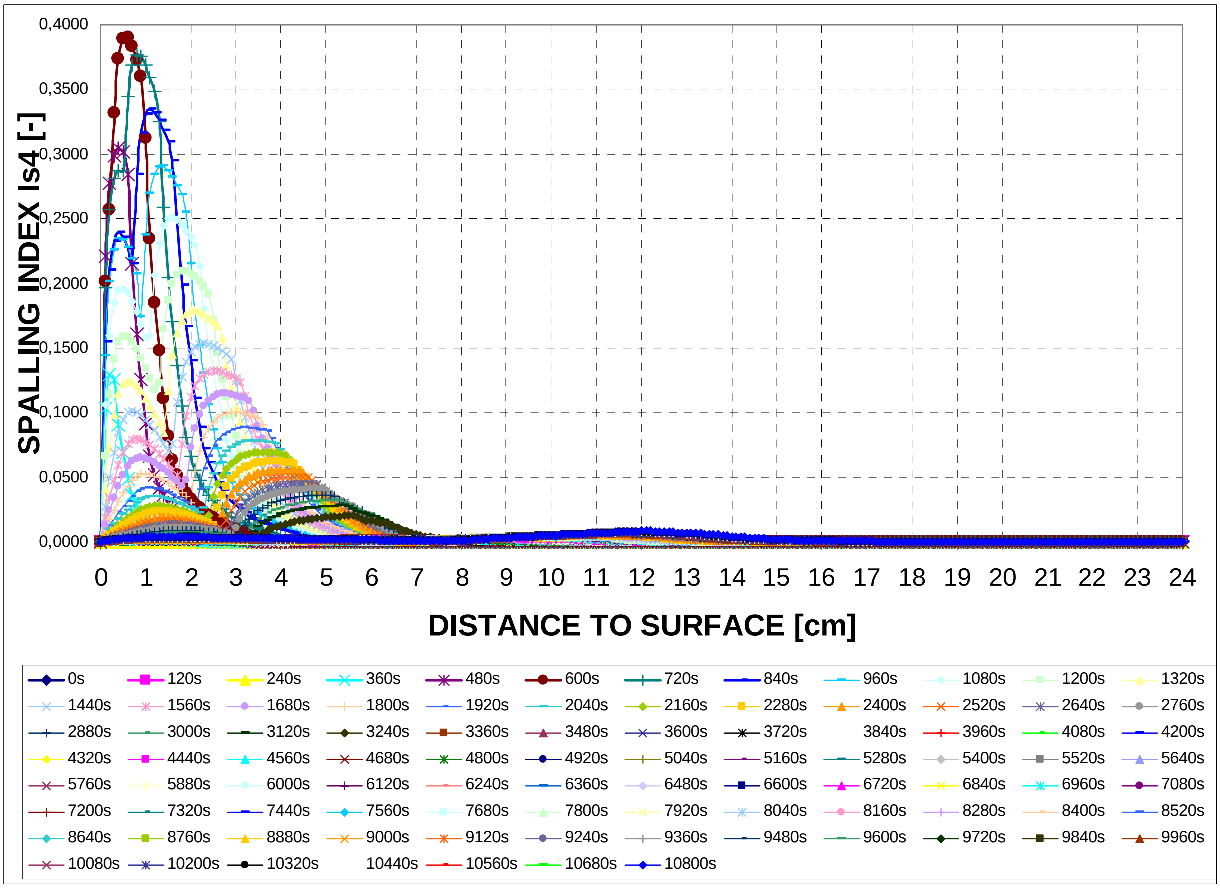

Figure 4A-26. *Spalling Index IS4 evolution for combination 26-TH24K018RH60PAR1C60*

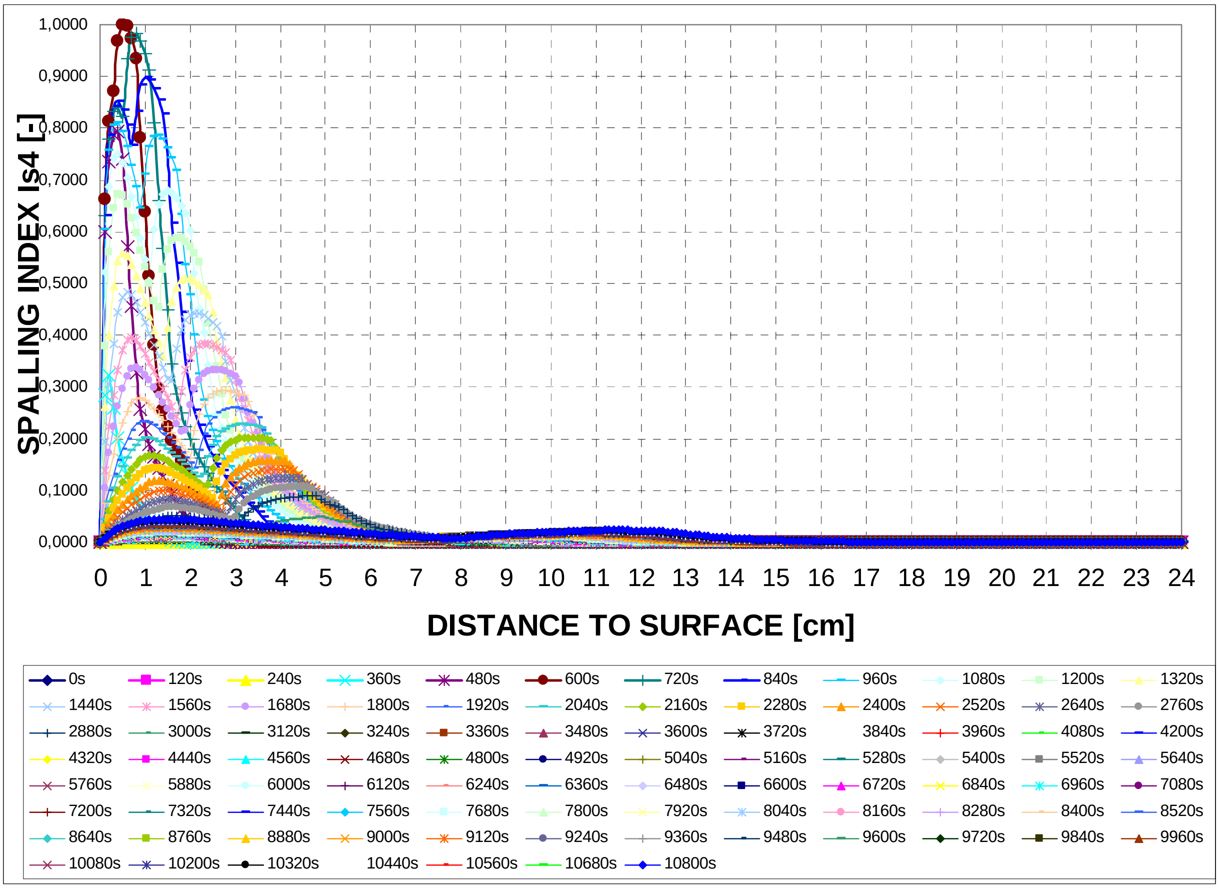

Figure 4A-27. *Spalling Index IS4 evolution for combination 27-TH24K019RH60PAR1C60*

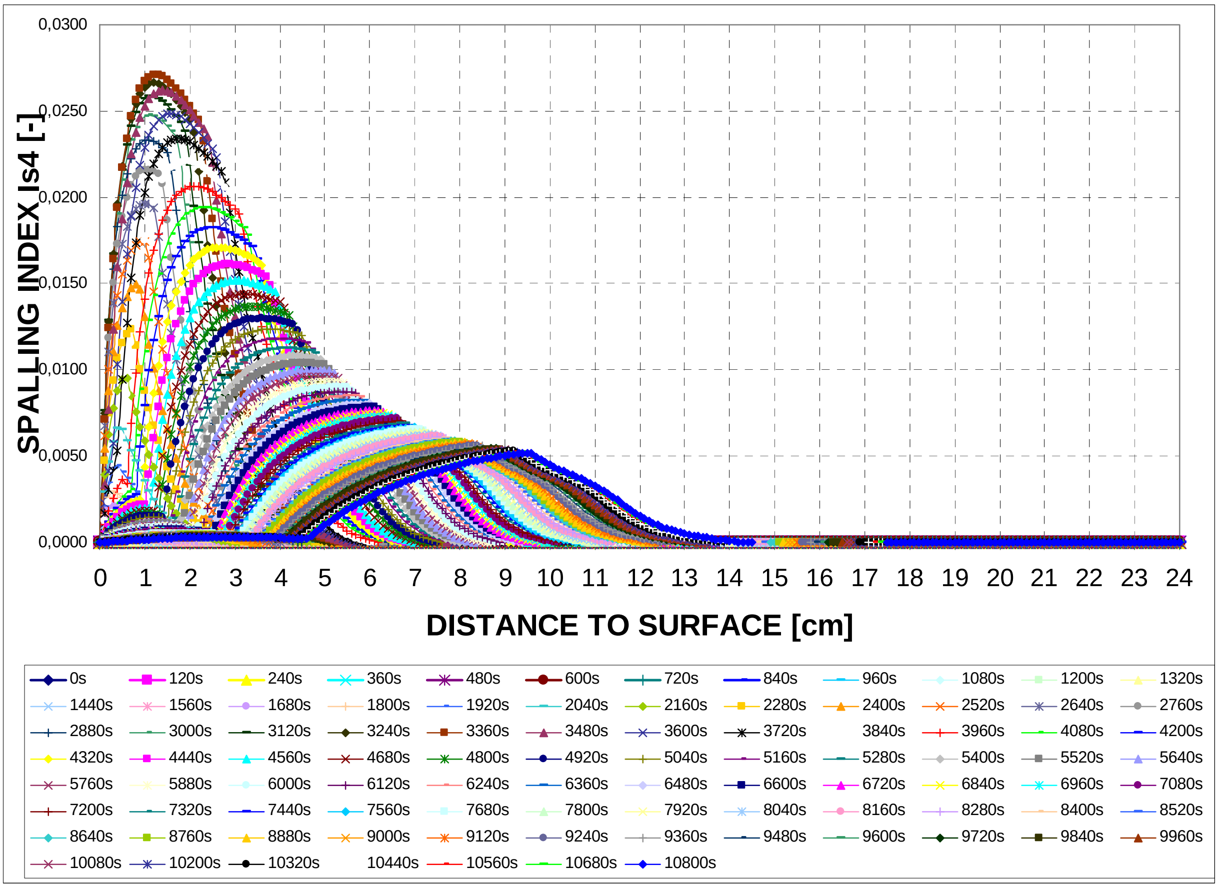

Figure 4A-28. *Spalling Index IS4 evolution for combination 28-TH24K017RH40PAR2C60*

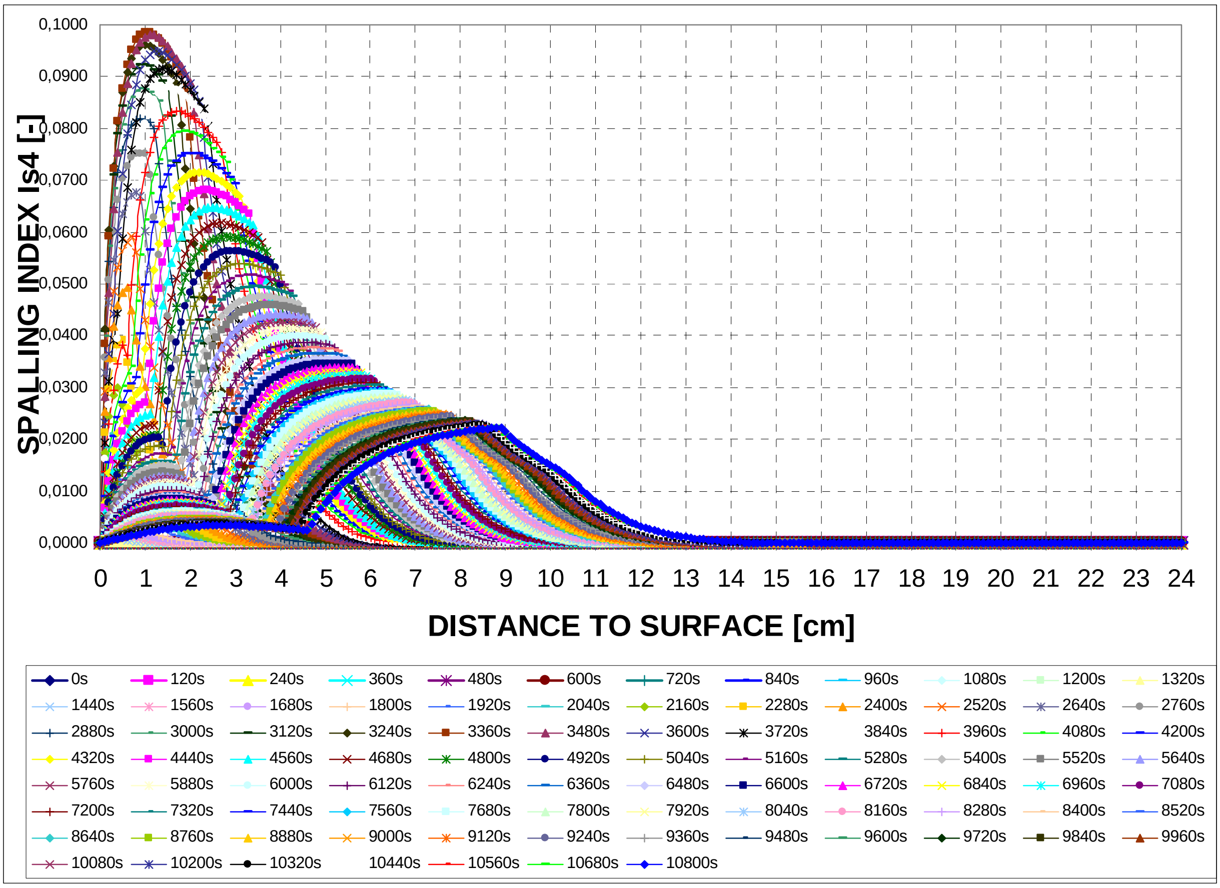

Figure 4A-29. *Spalling Index IS4 evolution for combination 29-TH24K018RH40PAR2C60*

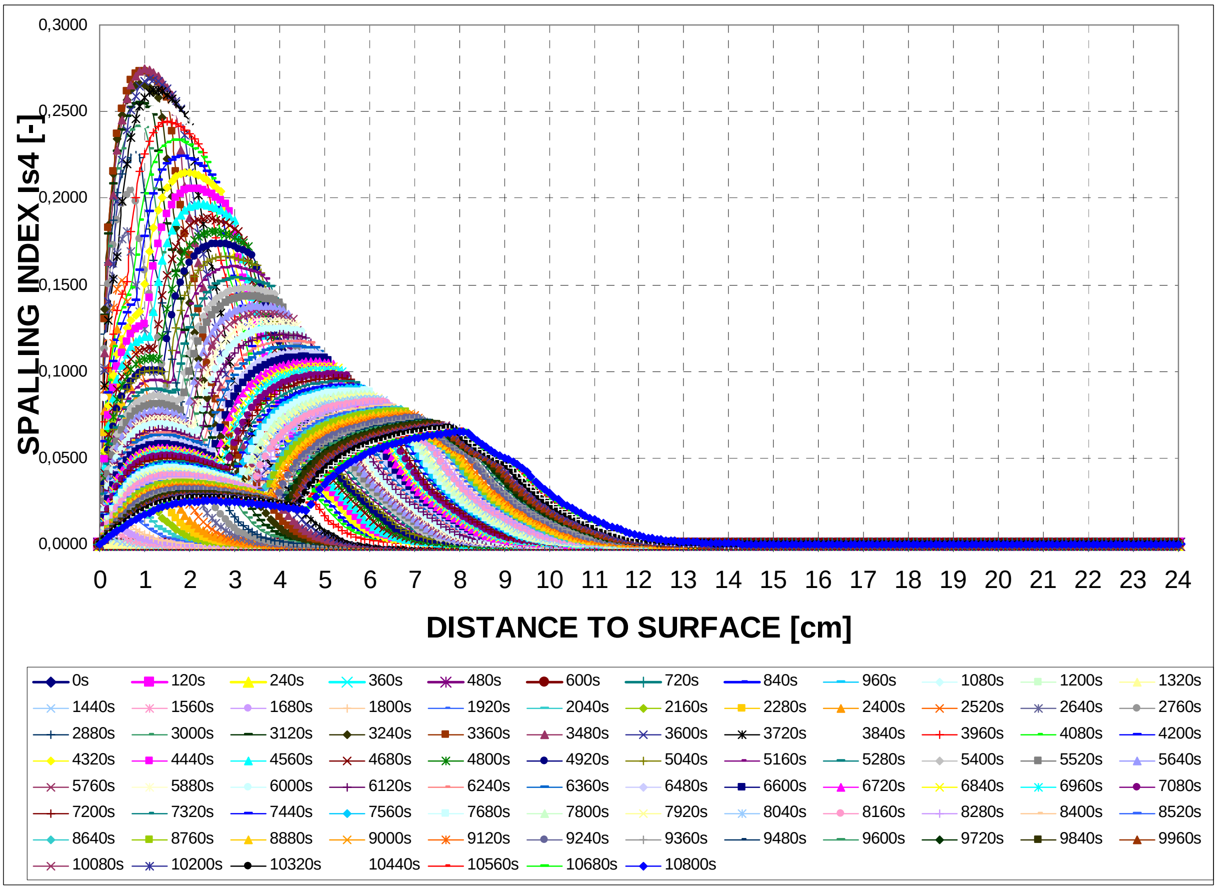

Figure 4A-30. *Spalling Index IS4 evolution for combination 30-TH24K019RH40PAR2C60*

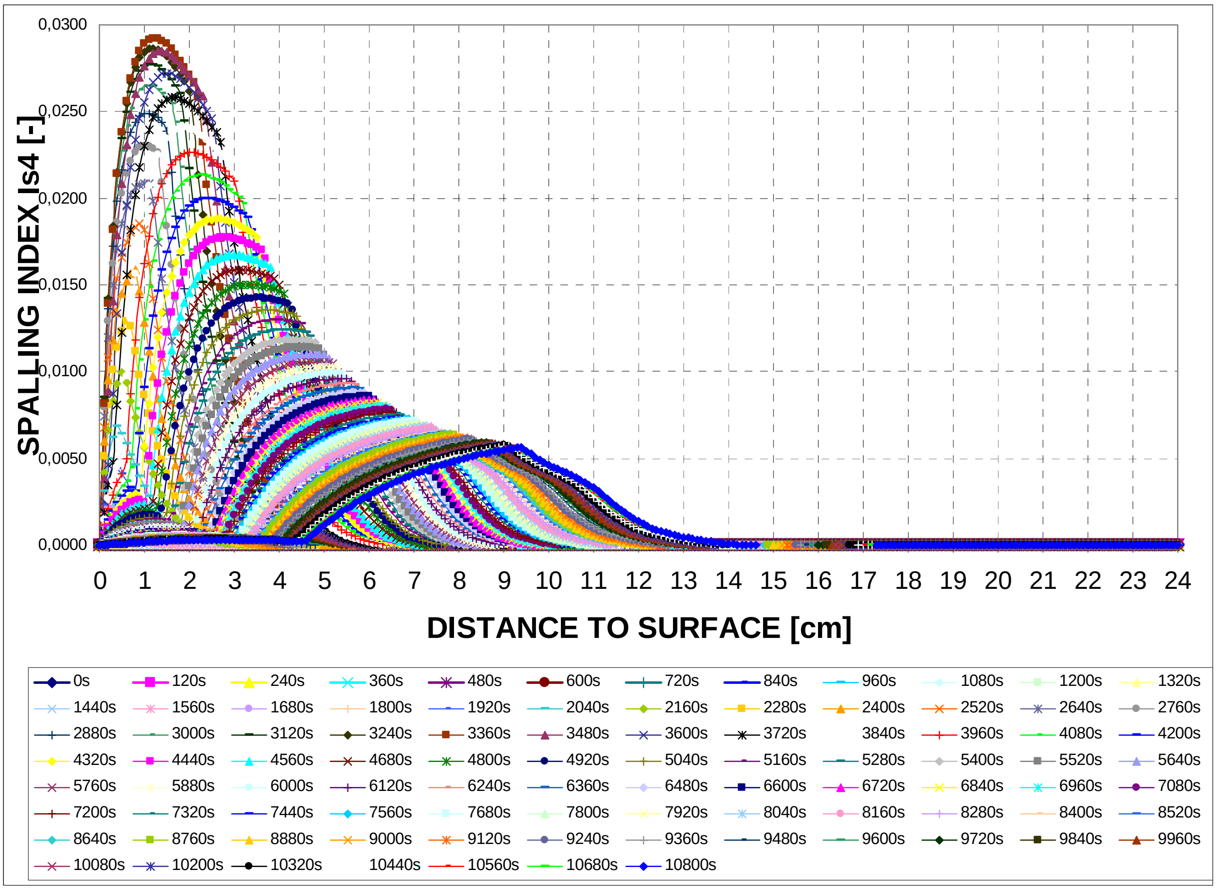

Figure 4A-31. *Spalling Index IS4 evolution for combination 31-TH24K017RH50PAR2C60*

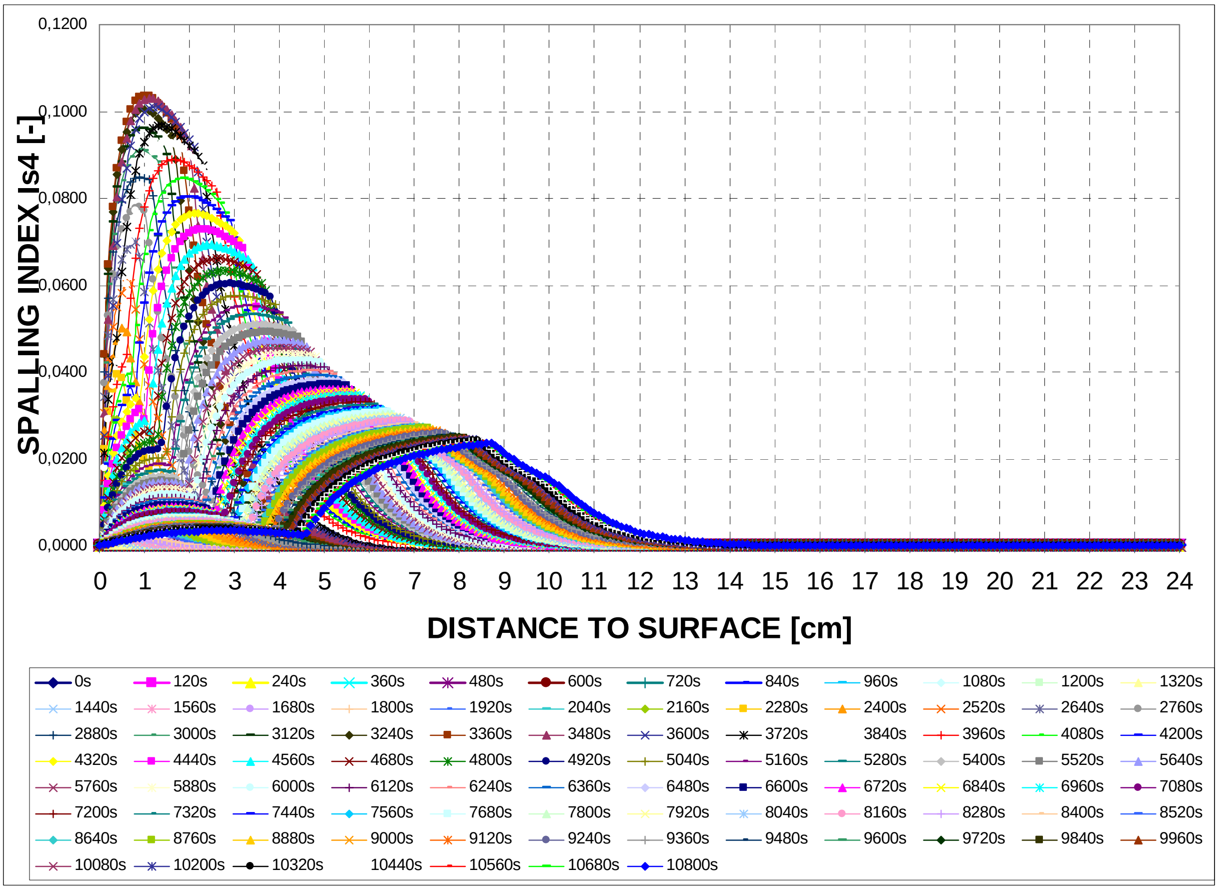

Figure 4A-32. *Spalling Index IS4 evolution for combination 32-TH24K018RH50PAR2C60*

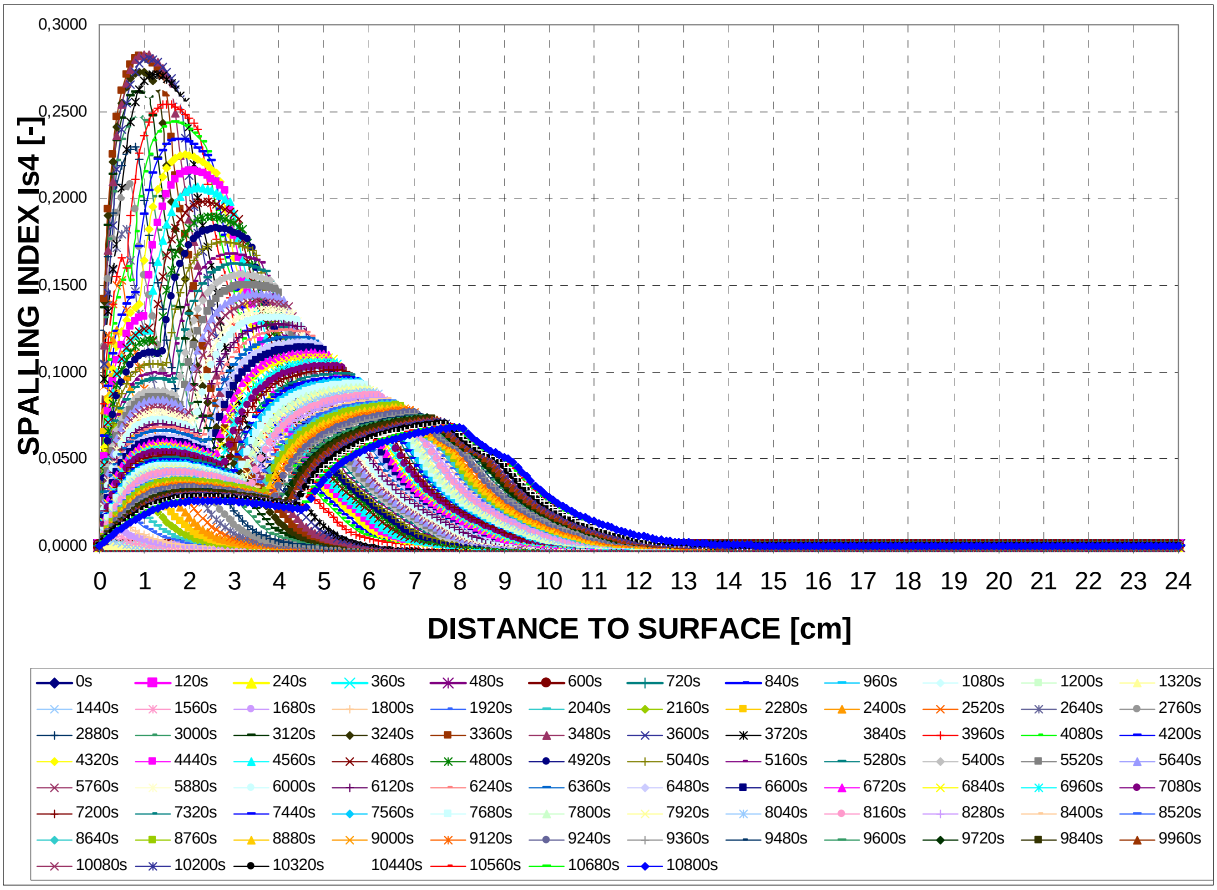

Figure 4A-33. *Spalling Index IS4 evolution for combination 33-TH24K019RH50PAR2C60*

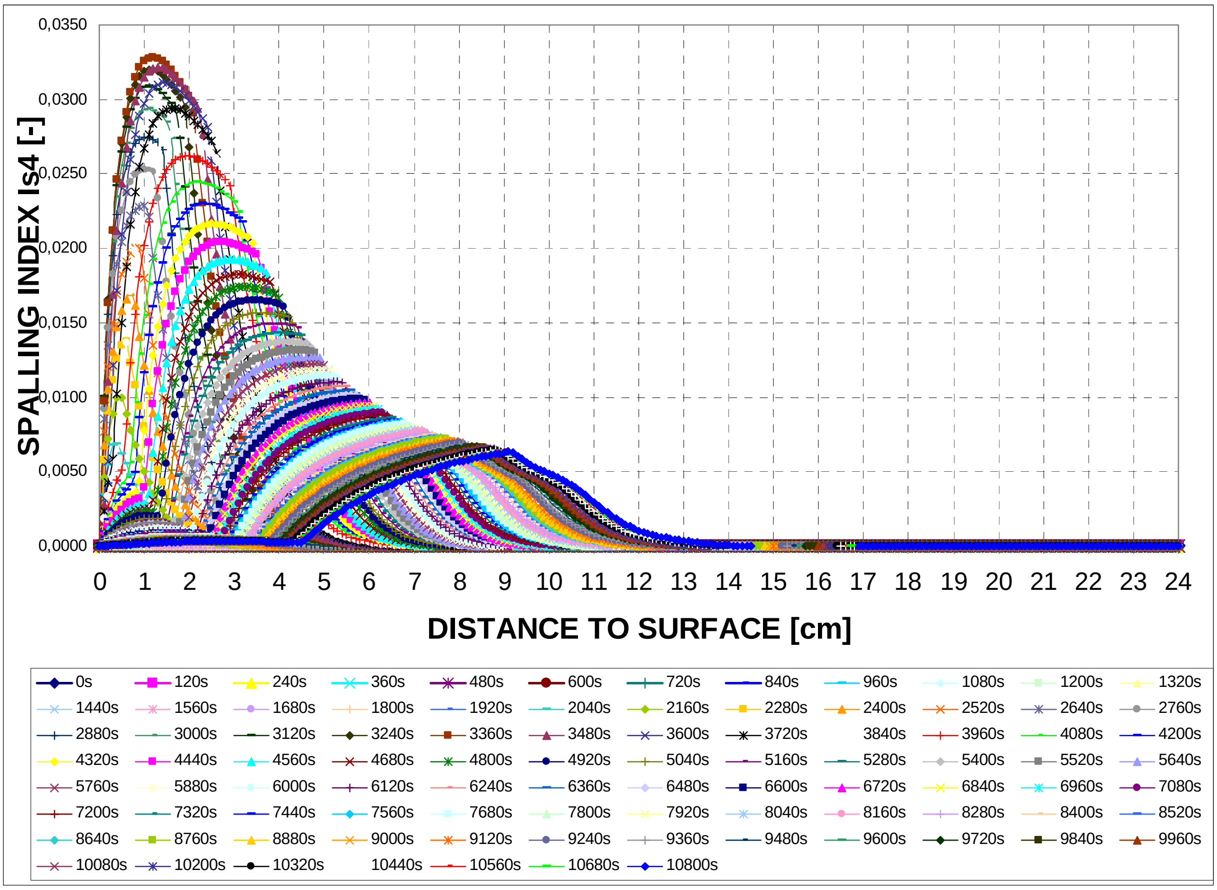

Figure 4A-34. *Spalling Index IS4 evolution for combination 34-TH24K017RH60PAR2C60*

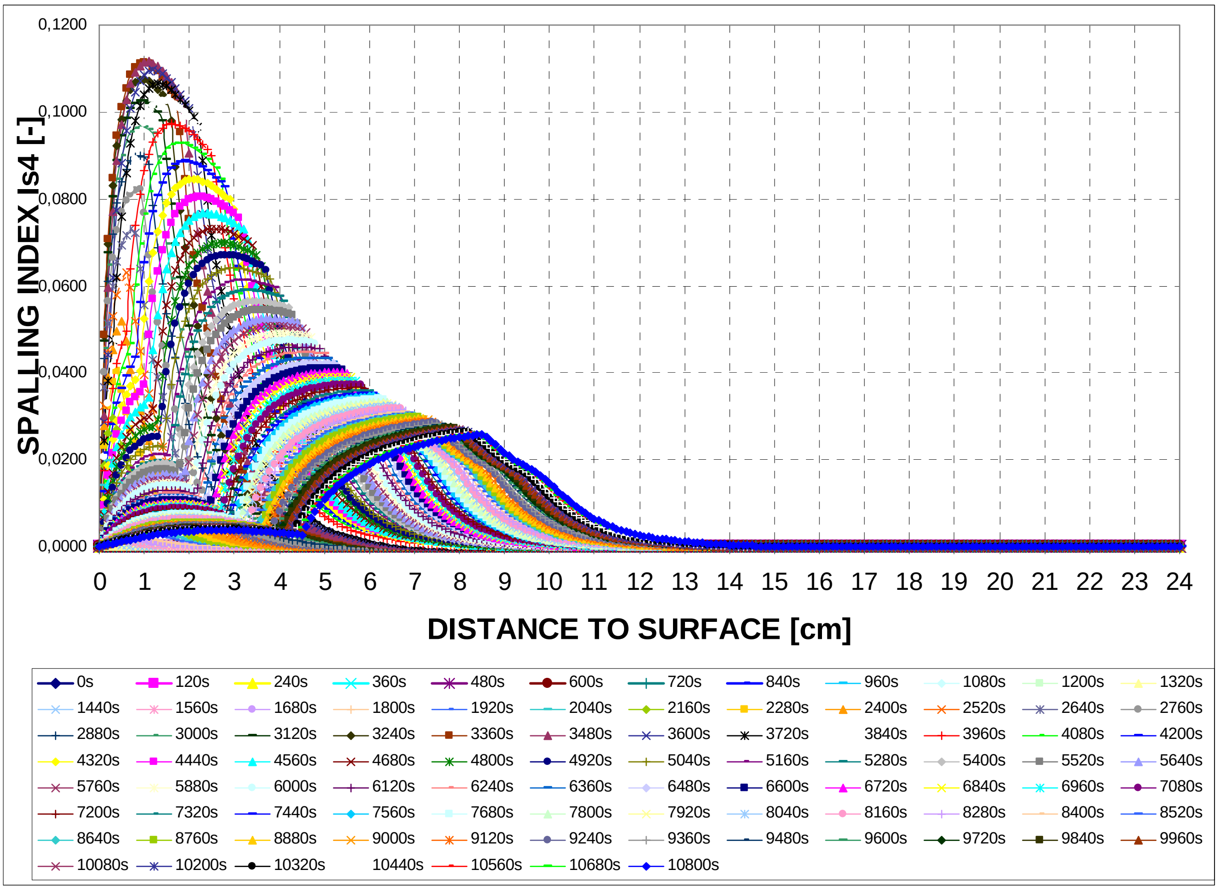

Figure 4A-35. *Spalling Index IS4 evolution for combination 35-TH24K018RH60PAR2C60*

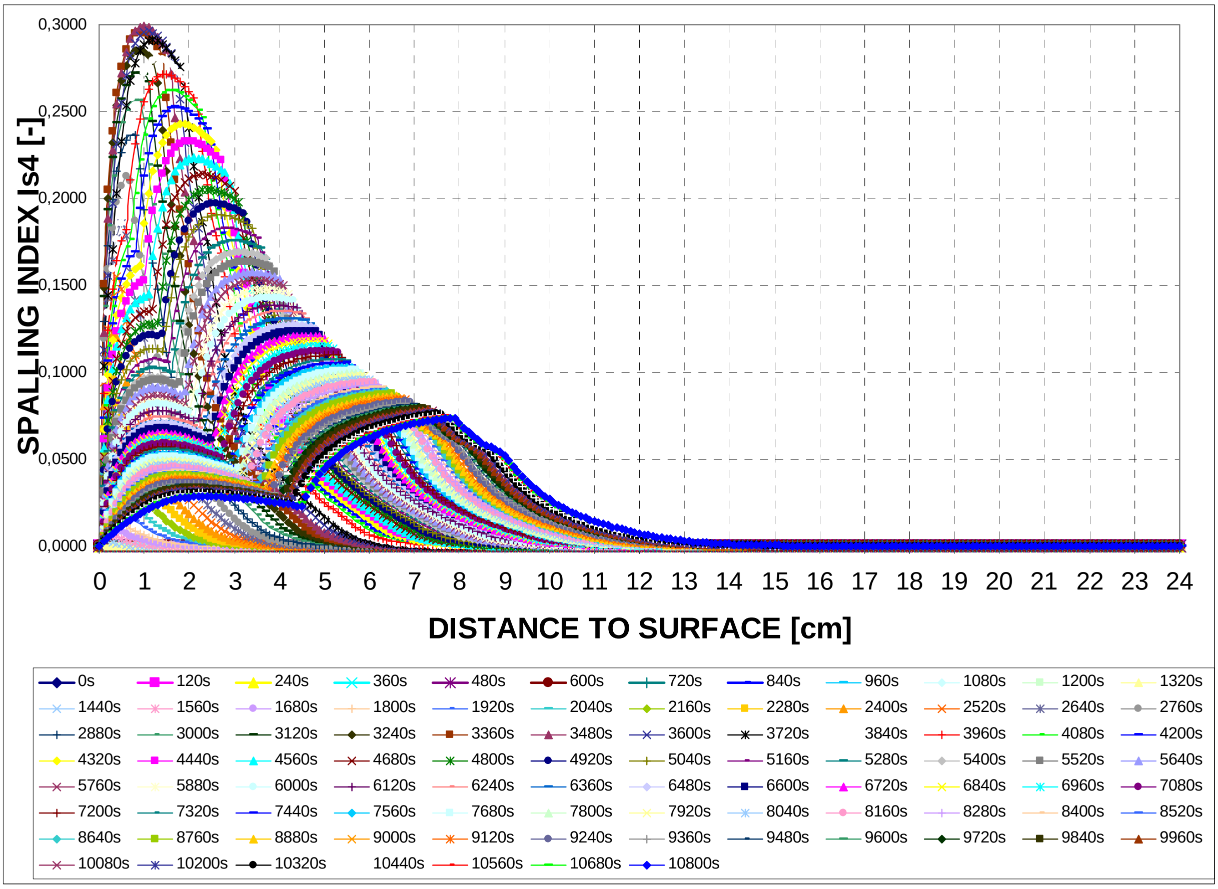

Figure 4A-36. *Spalling Index IS4 evolution for combination 36-TH24K019RH60PAR2C60*

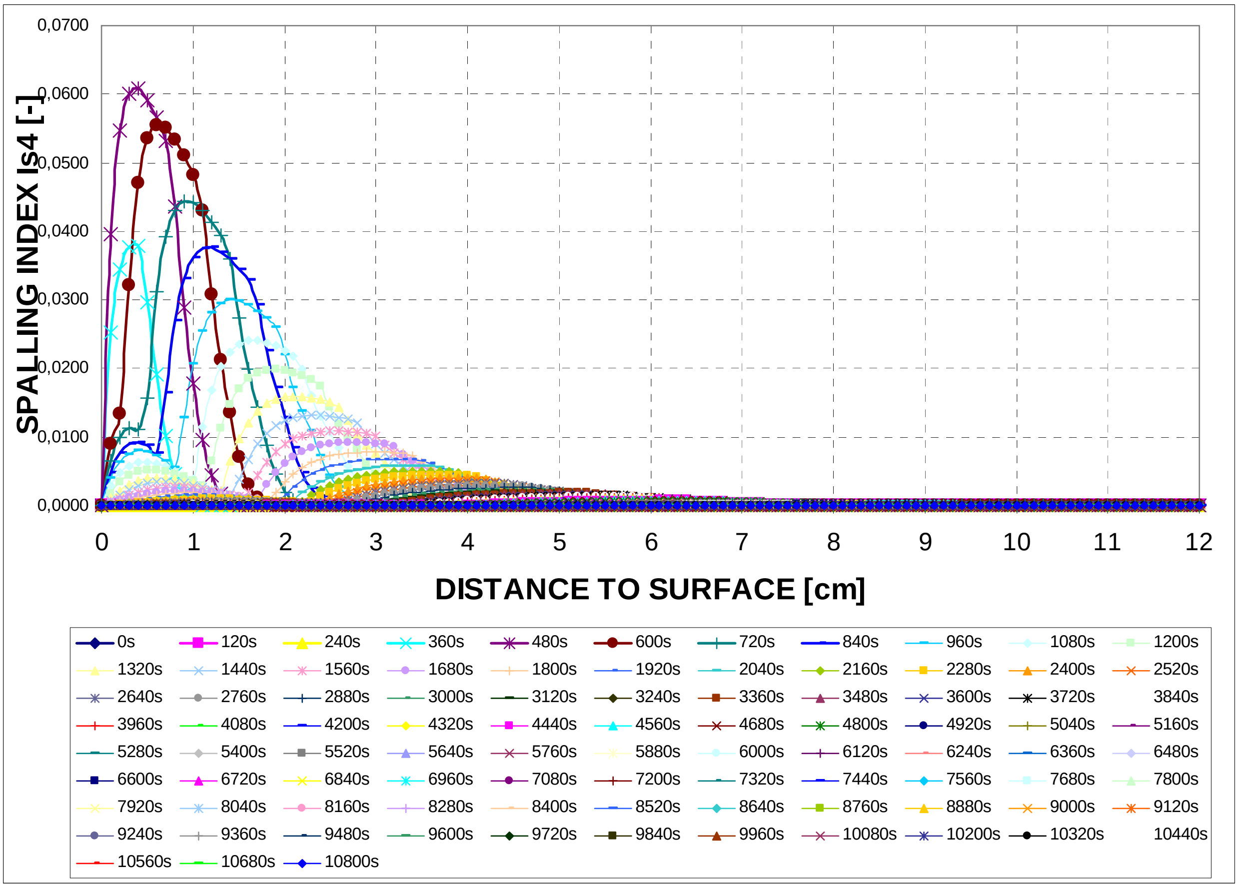

Figure 4A-37. *Spalling Index IS4 evolution for combination 37-TH12K017RH40PAR1C90*

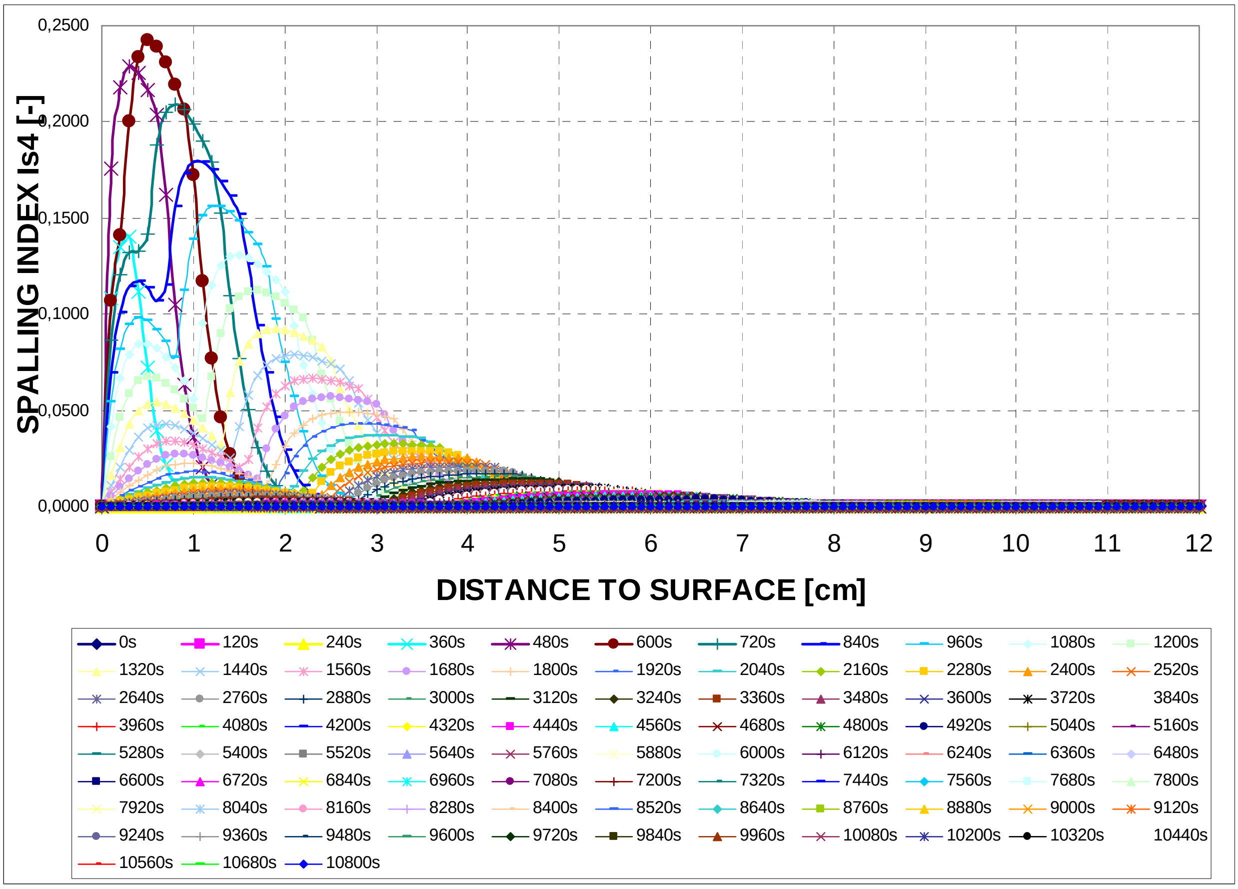

Figure 4A-38. *Spalling Index IS4 evolution for combination 38-TH12K018RH40PAR1C90*

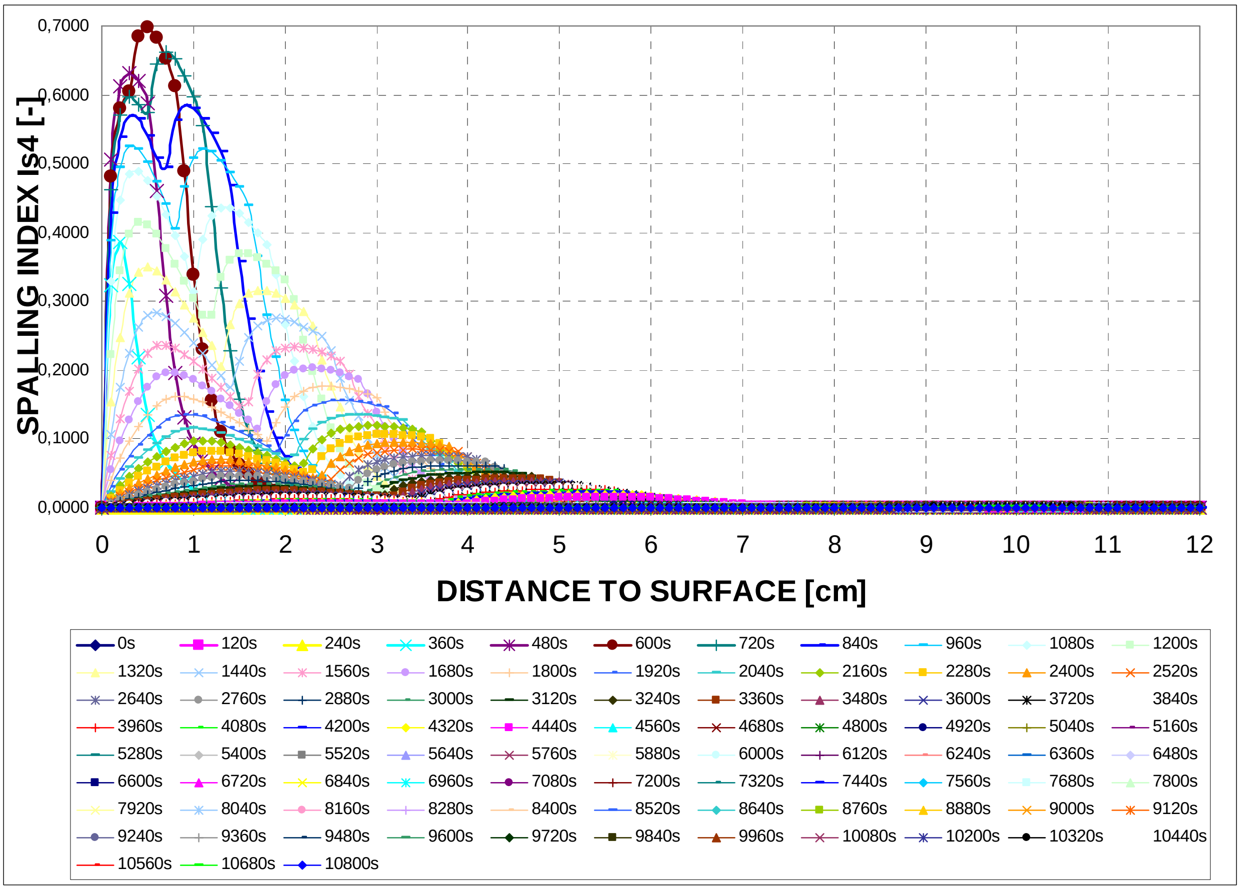

Figure 4A-39. *Spalling Index IS4 evolution for combination 39-TH12K019RH40PAR1C90*

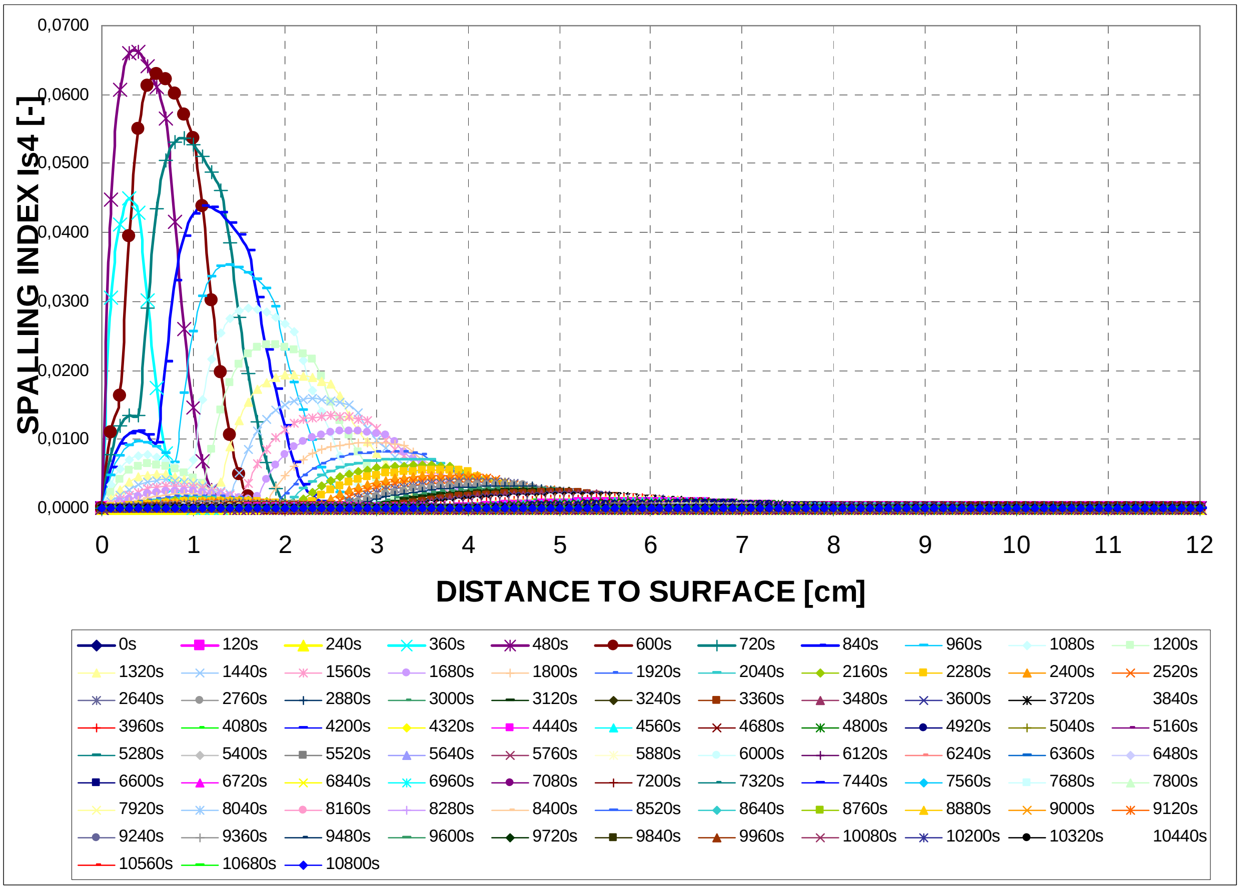

Figure 4A-40. *Spalling Index IS4 evolution for combination 40-TH12K017RH50PAR1C90*

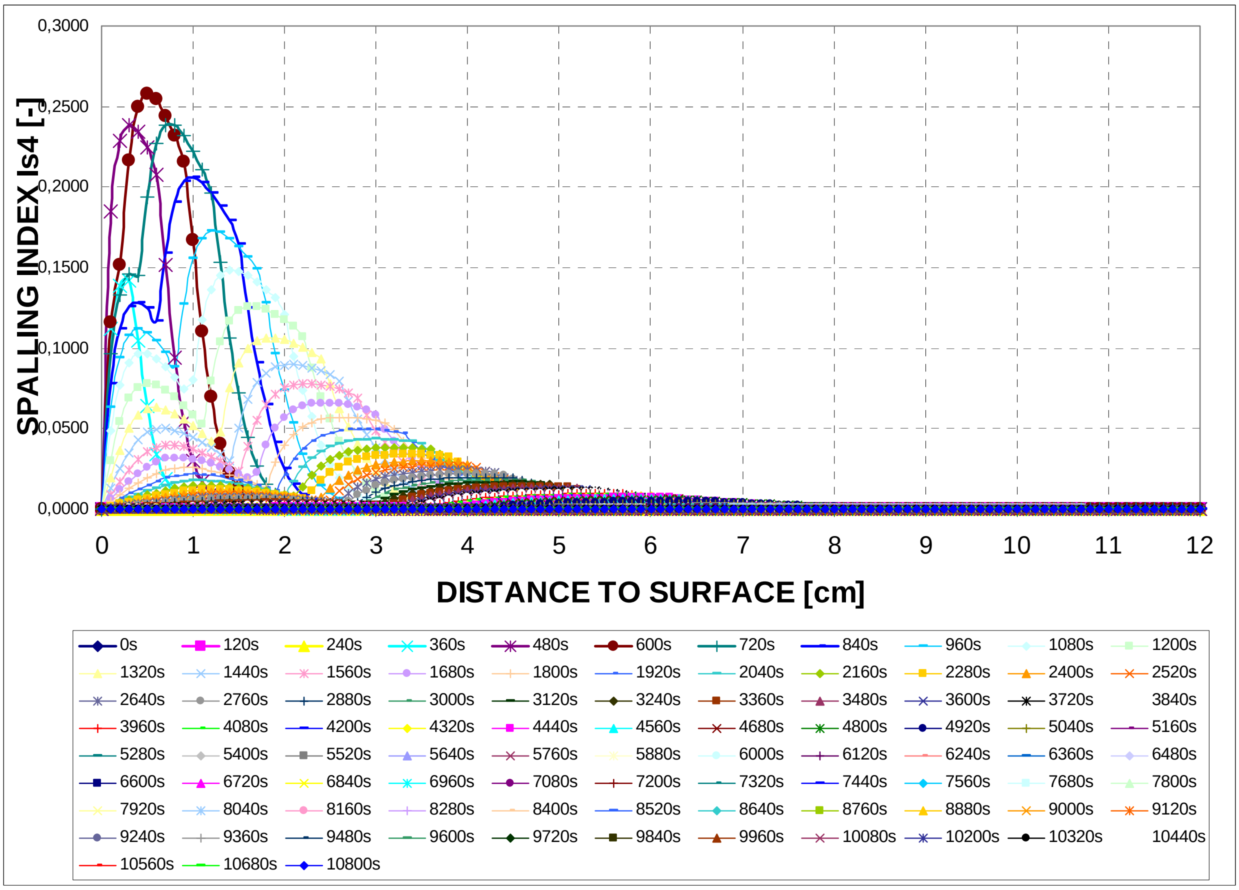

Figure 4A-41. *Spalling Index IS4 evolution for combination 41-TH12K018RH50PAR1C90*

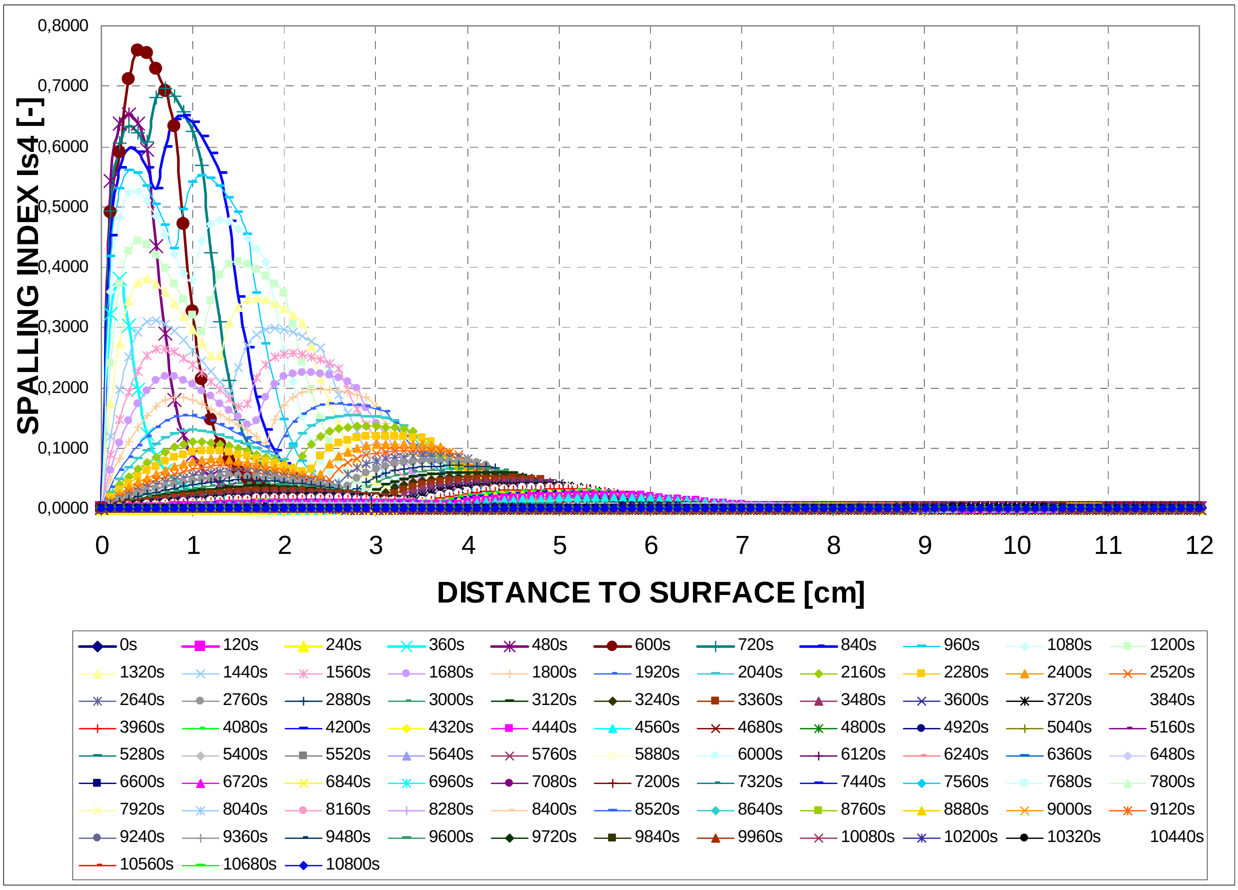

Figure 4A-42. *Spalling Index IS4 evolution for combination 42-TH12K019RH50PAR1C90*

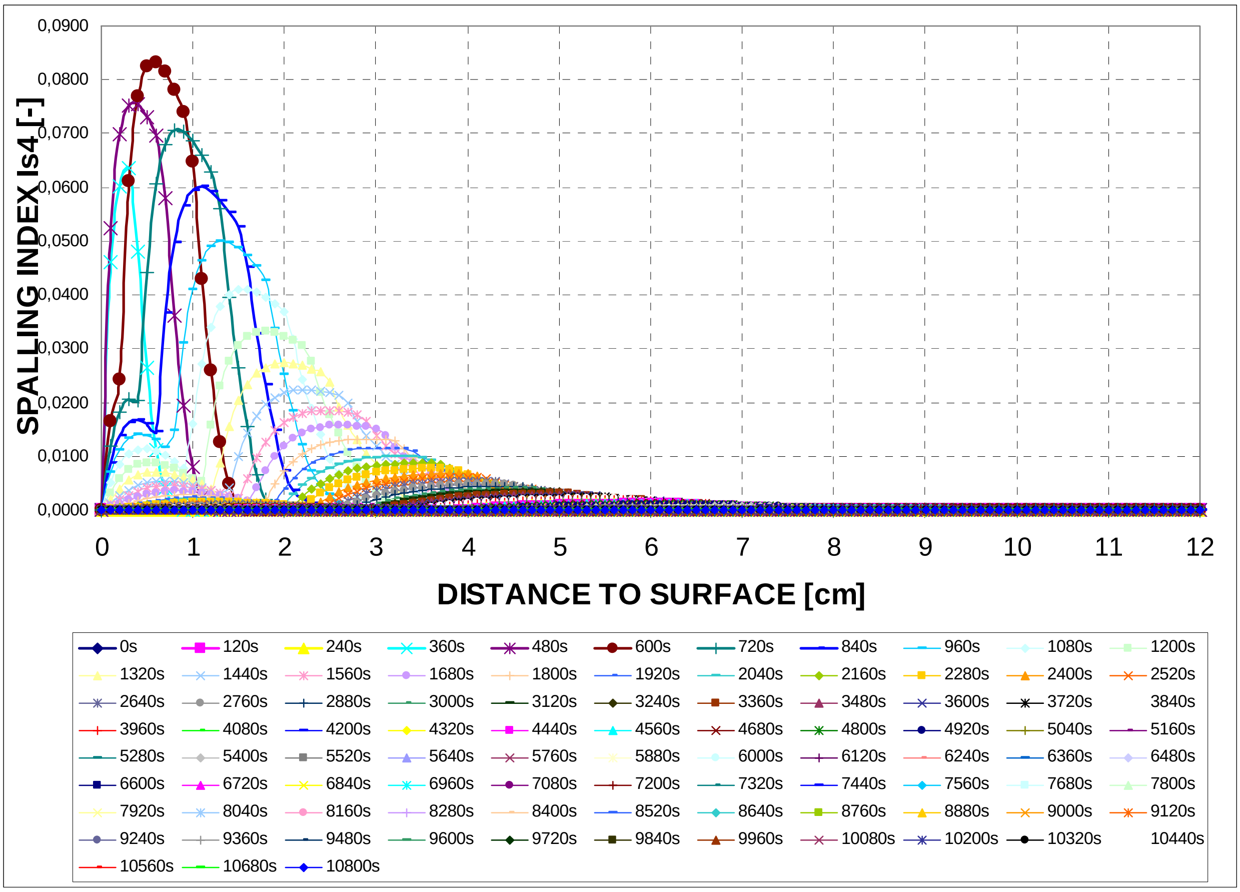

Figure 4A-43. *Spalling Index IS4 evolution for combination 43-TH12K017RH60PAR1C90*

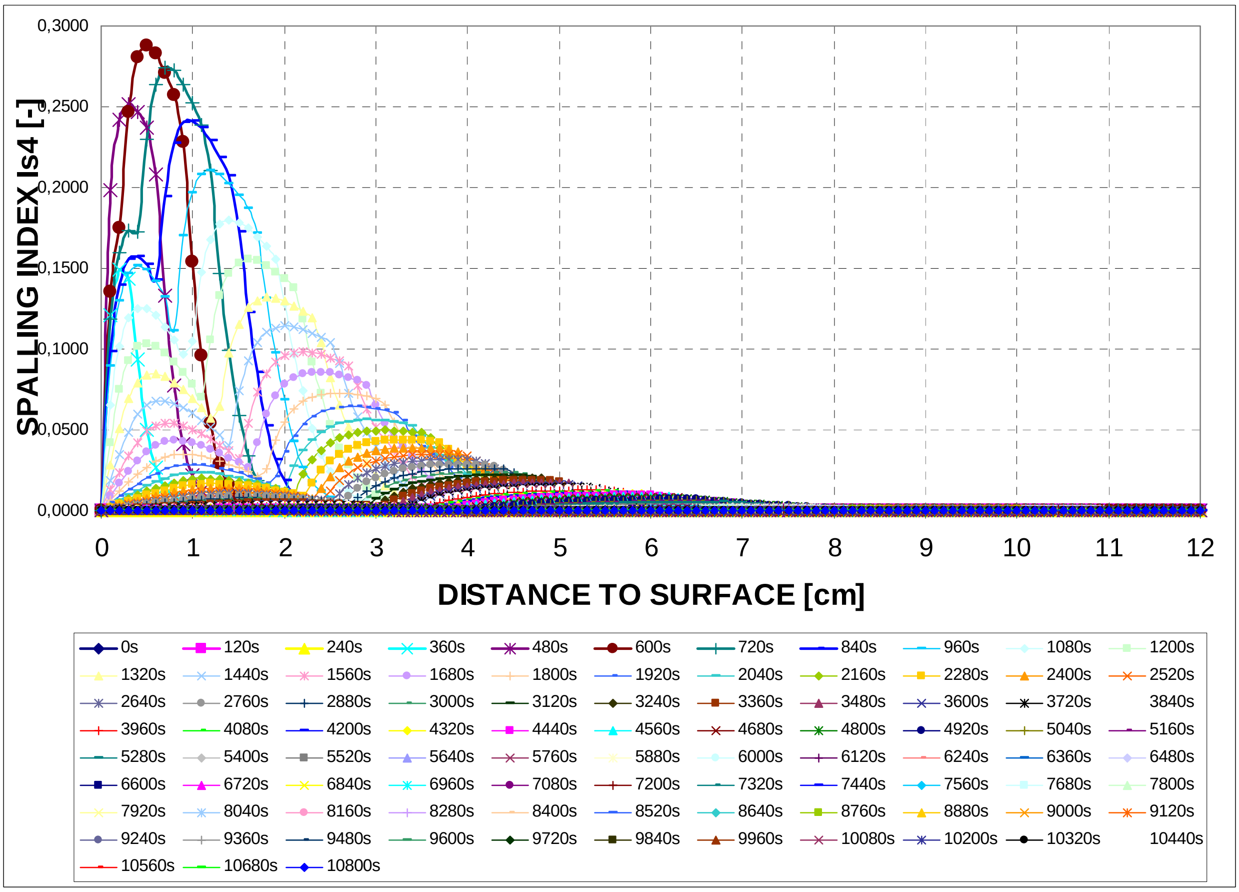

Figure 4A-44. *Spalling Index IS4 evolution for combination 44-TH12K018RH60PAR1C90*

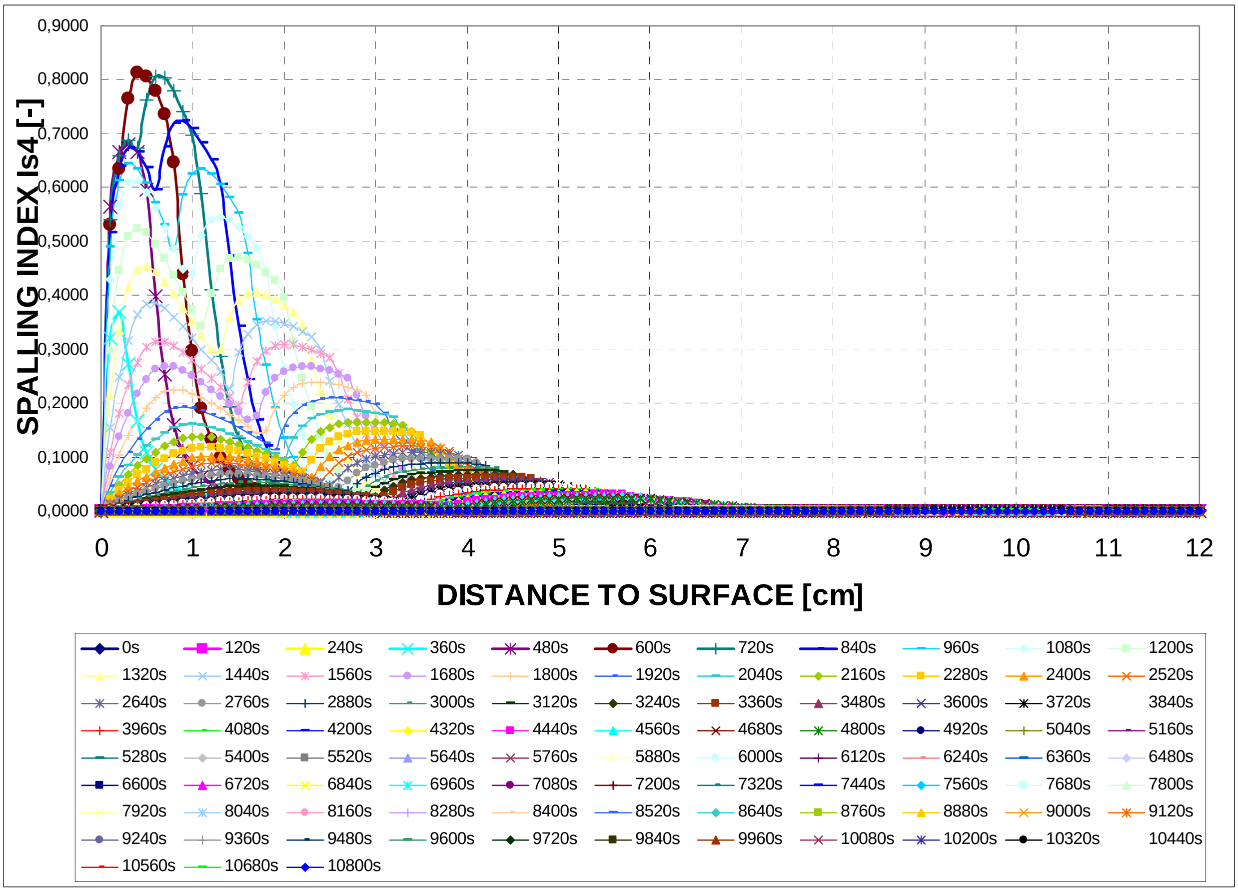

Figure 4A-45. *Spalling Index IS4 evolution for combination 45-TH12K019RH60PAR1C90*

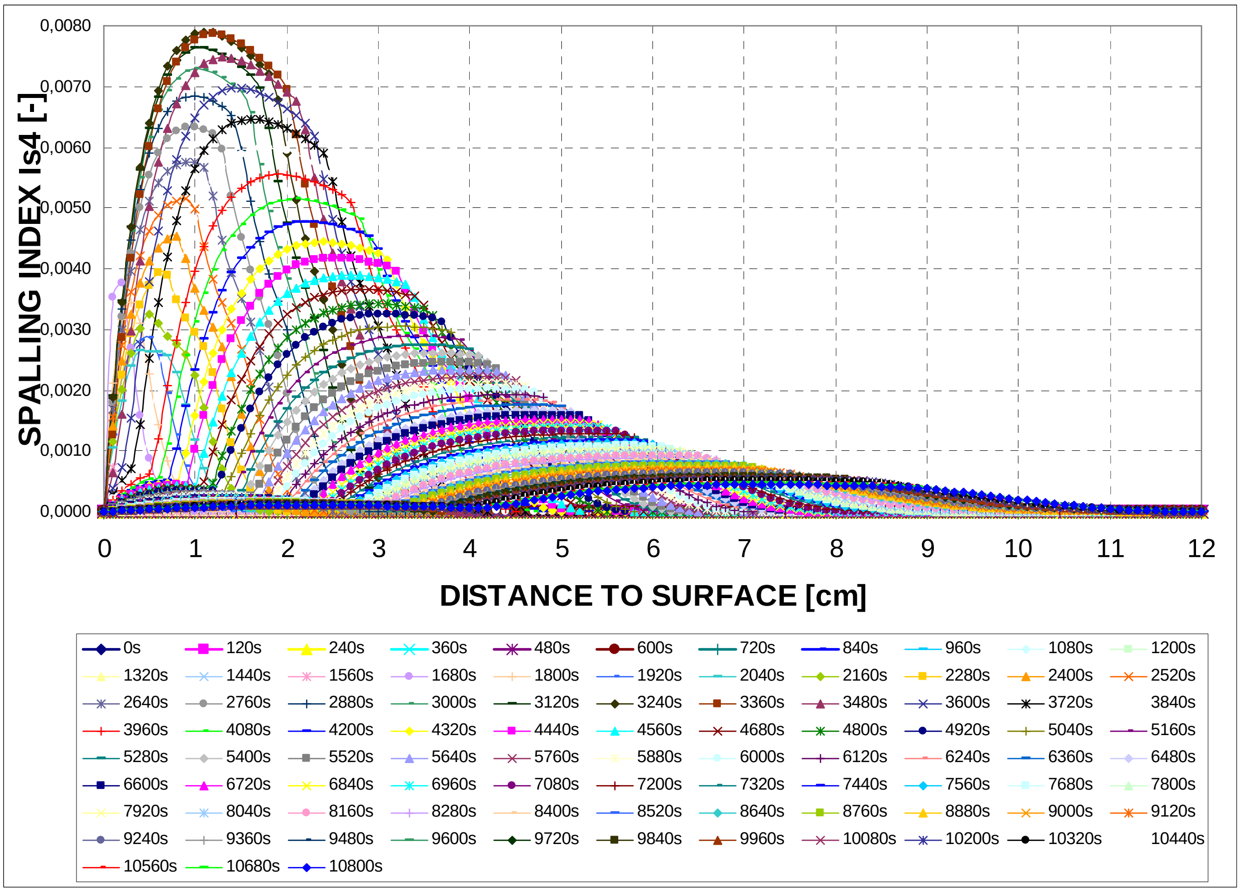

Figure 4A-46. *Spalling Index IS4 evolution for combination 46-TH12K017RH40PAR2C90*

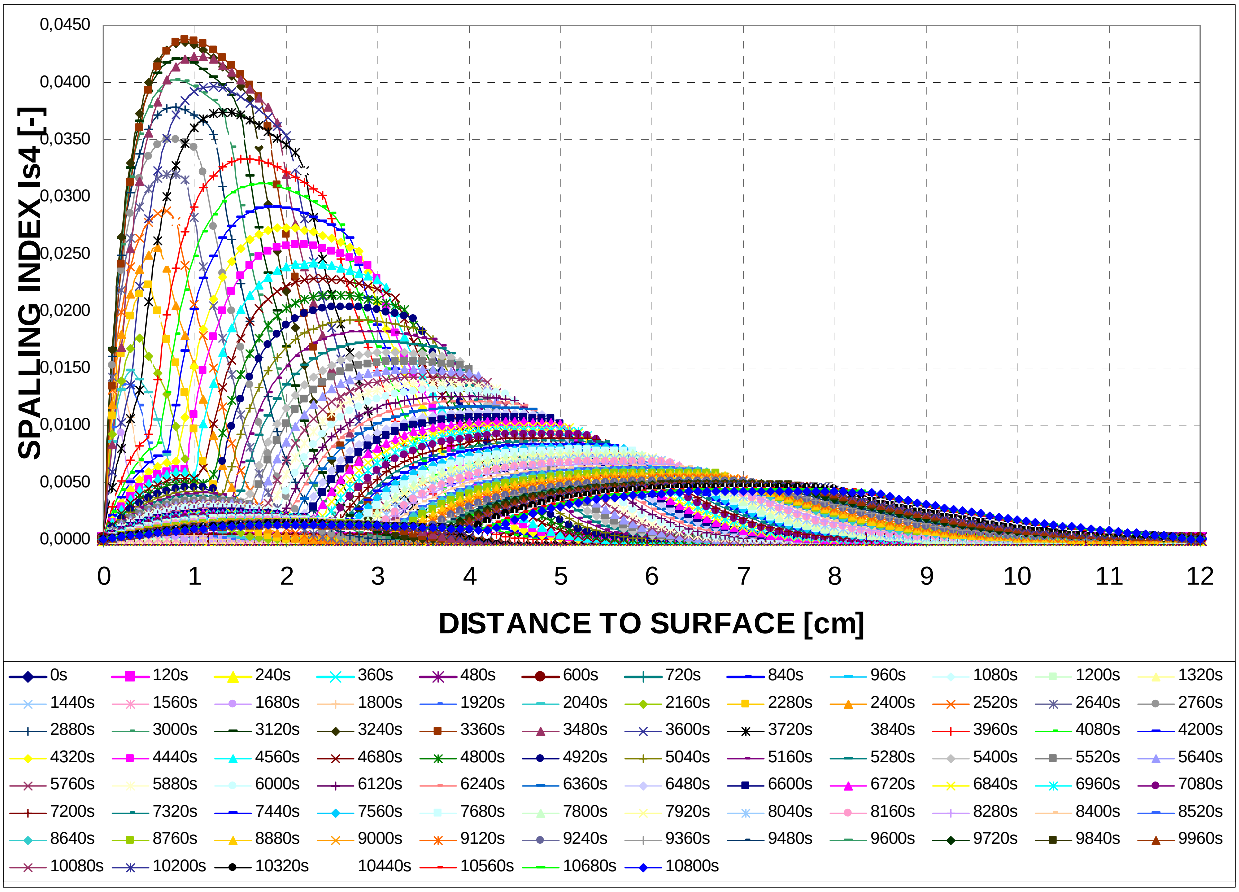

Figure 4A-47. *Spalling Index IS4 evolution for combination 47-TH12K018RH40PAR2C90*

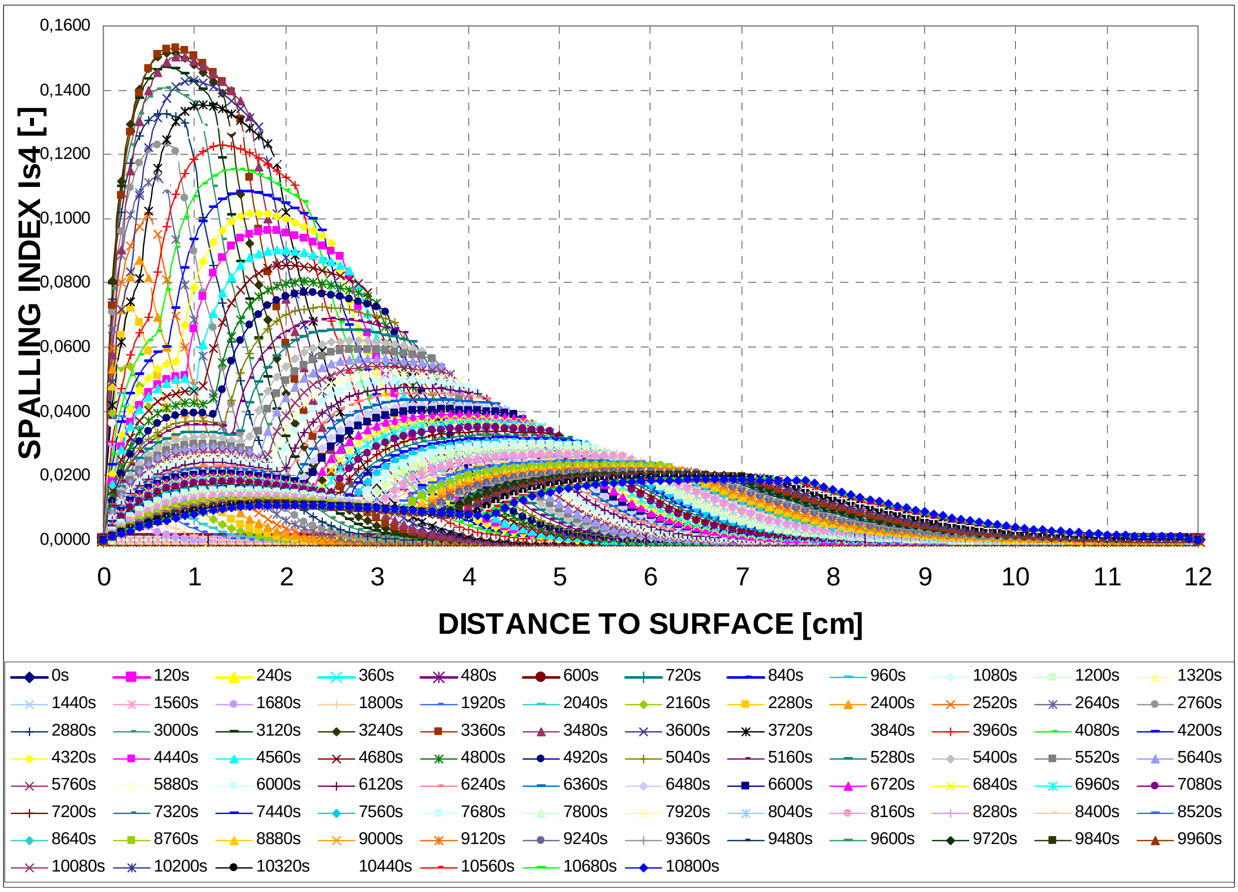

Figure 4A-48. *Spalling Index IS4 evolution for combination 48-TH12K019RH40PAR2C90*

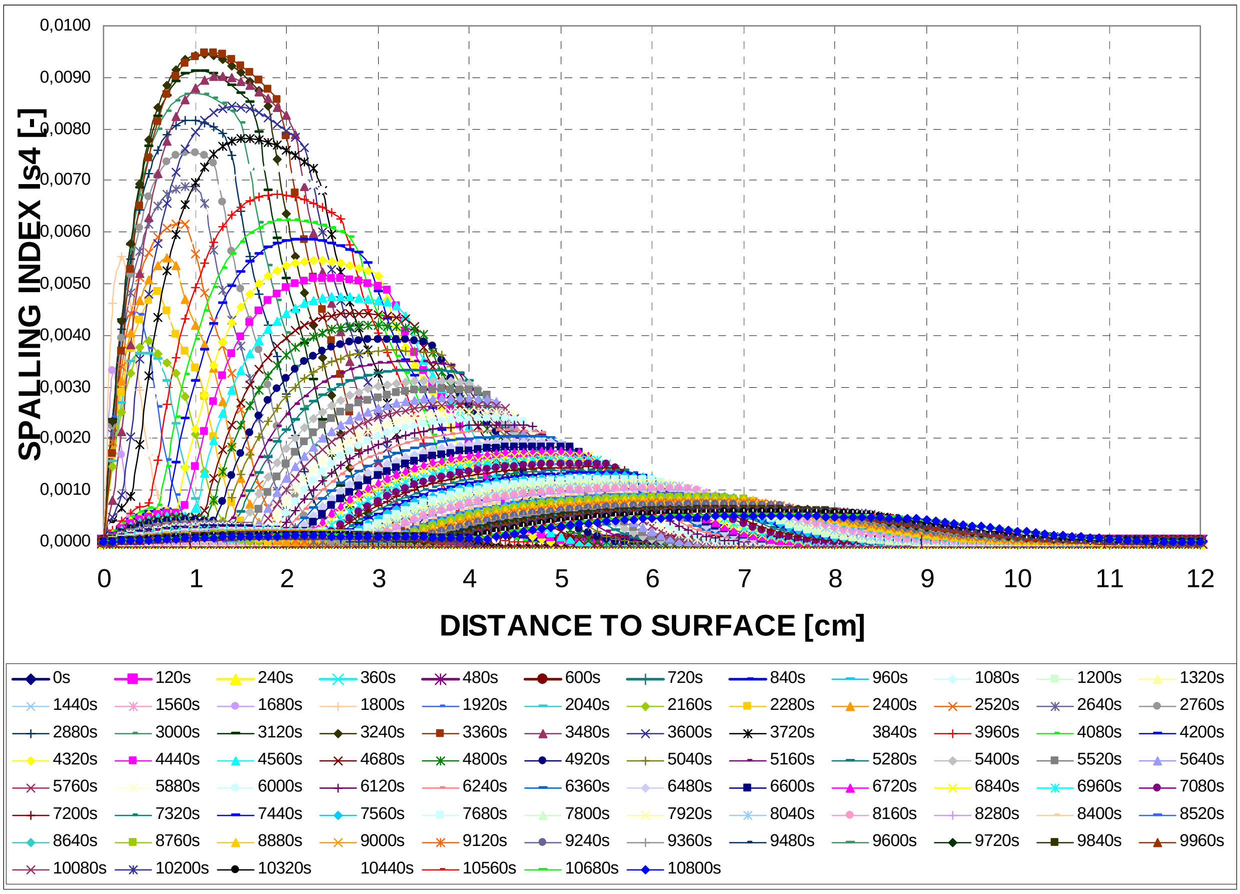

Figure 4A-49. *Spalling Index IS4 evolution for combination 49-TH12K017RH50PAR2C90*

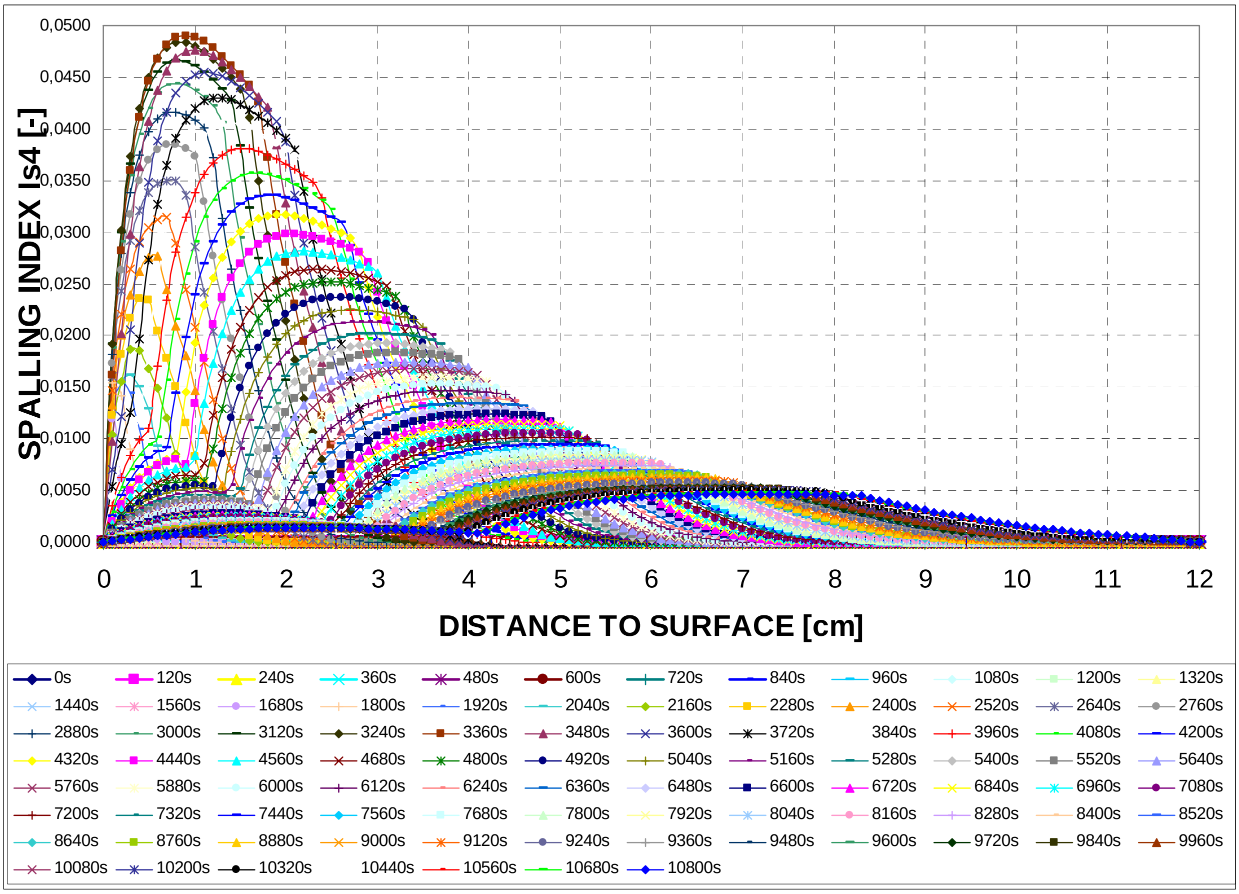

Figure 4A-50. *Spalling Index IS4 evolution for combination 50-TH12K018RH50PAR2C90*

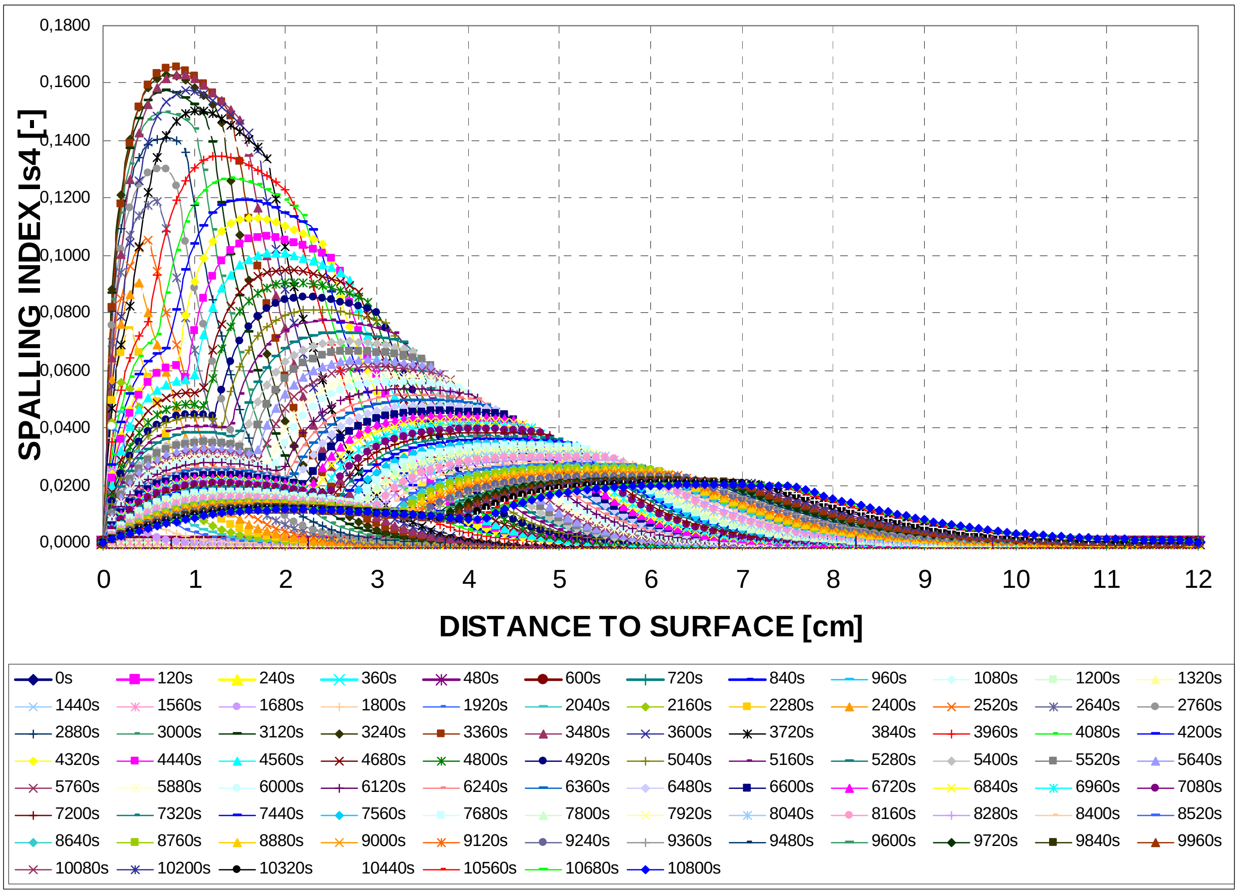

Figure 4A-51. *Spalling Index IS4 evolution for combination 51-TH12K019RH50PAR2C90*

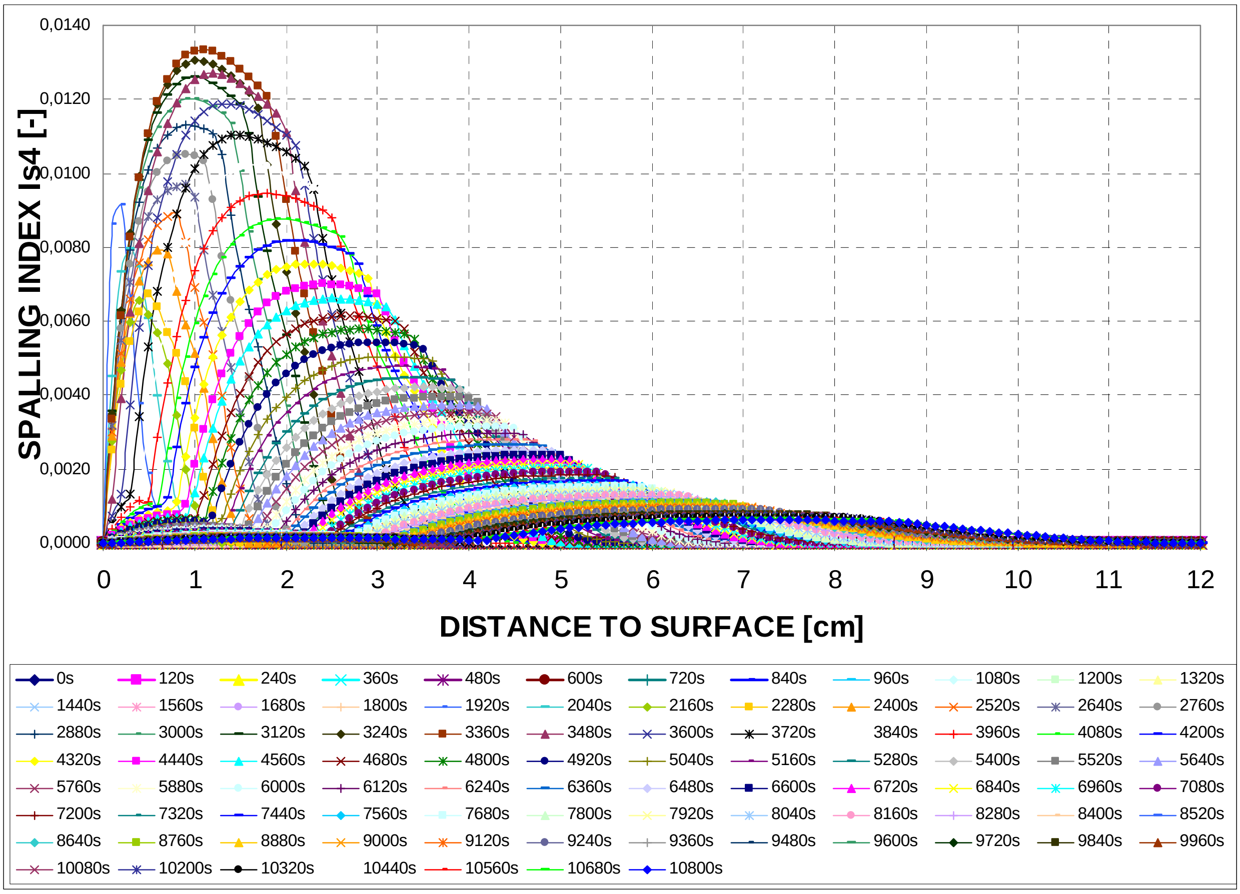

Figure 4A-52. *Spalling Index IS4 evolution for combination 52-TH12K017RH60PAR2C90*

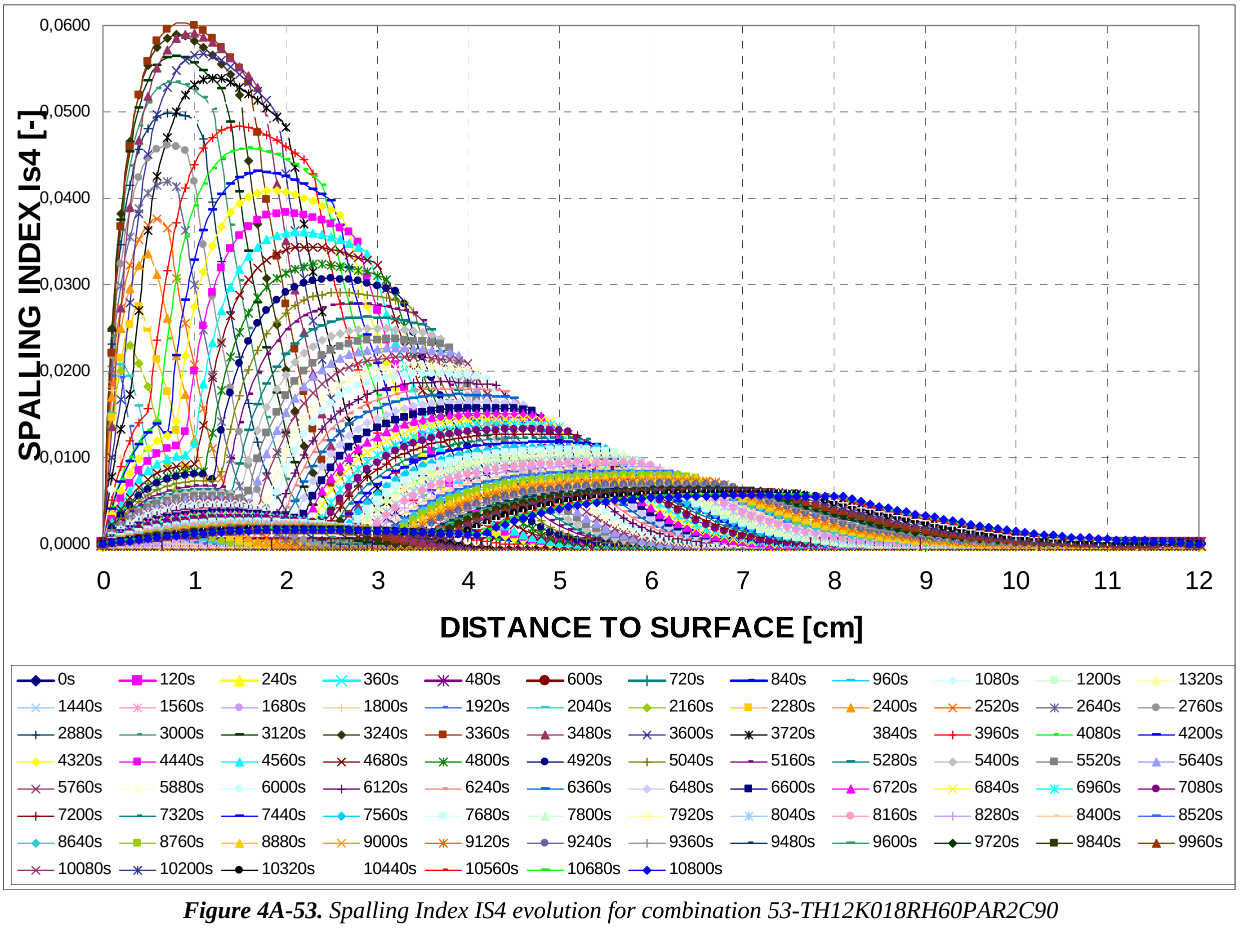

Figure 4A-53. *Spalling Index IS4 evolution for combination 53-TH12K018RH60PAR2C90*

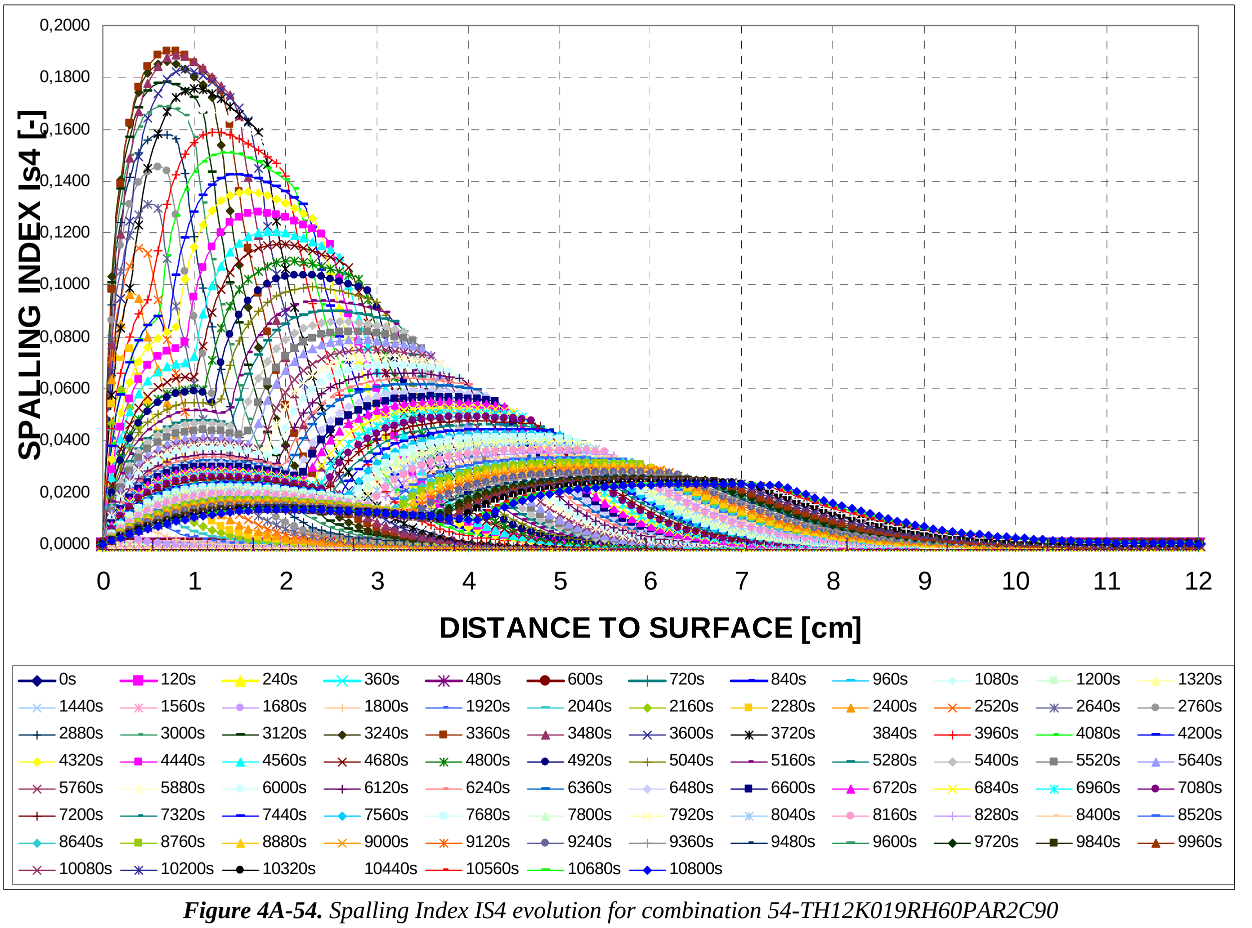

Figure 4A-54. *Spalling Index IS4 evolution for combination 54-TH12K019RH60PAR2C90*

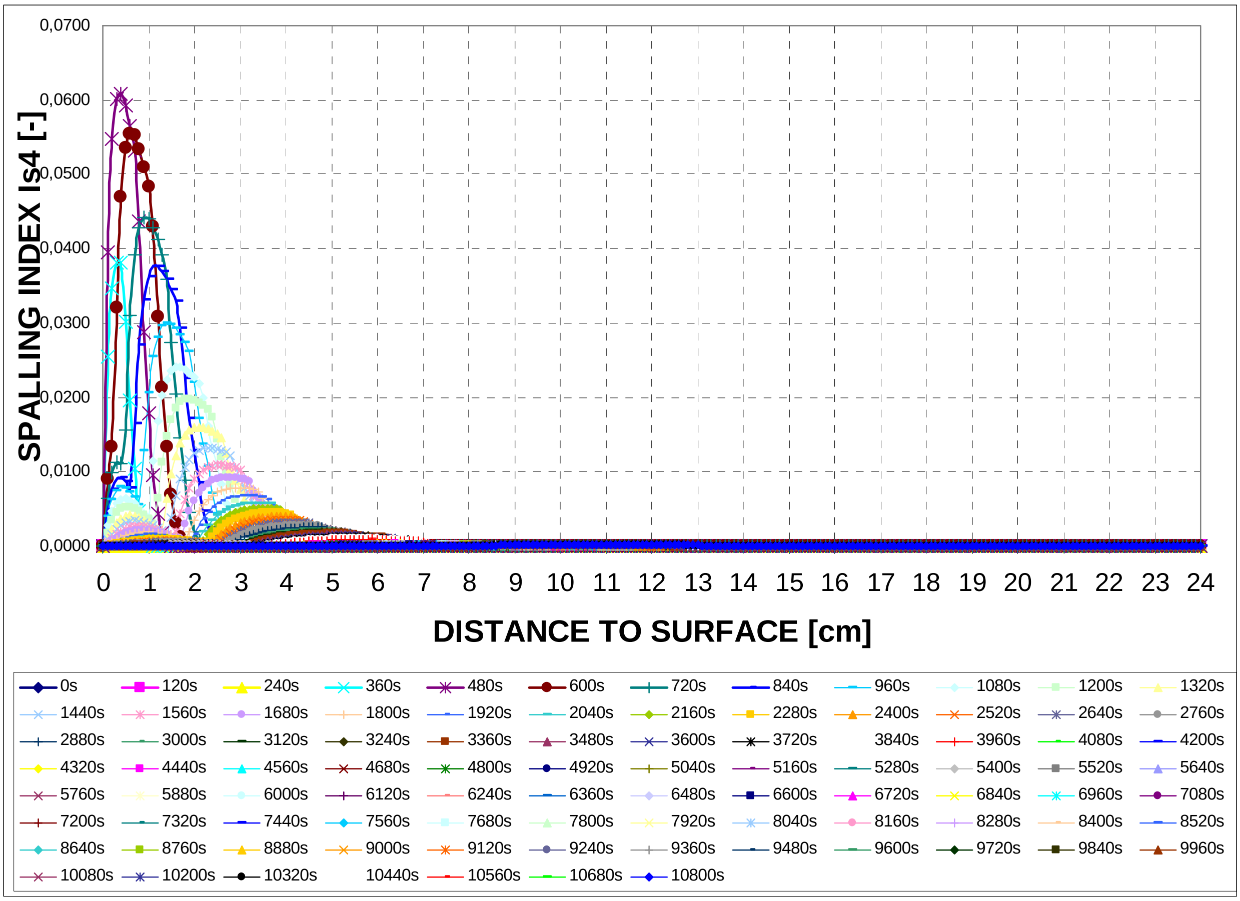

Figure 4A-55. *Spalling Index IS4 evolution for combination 55-TH24K017RH40PAR1C90*

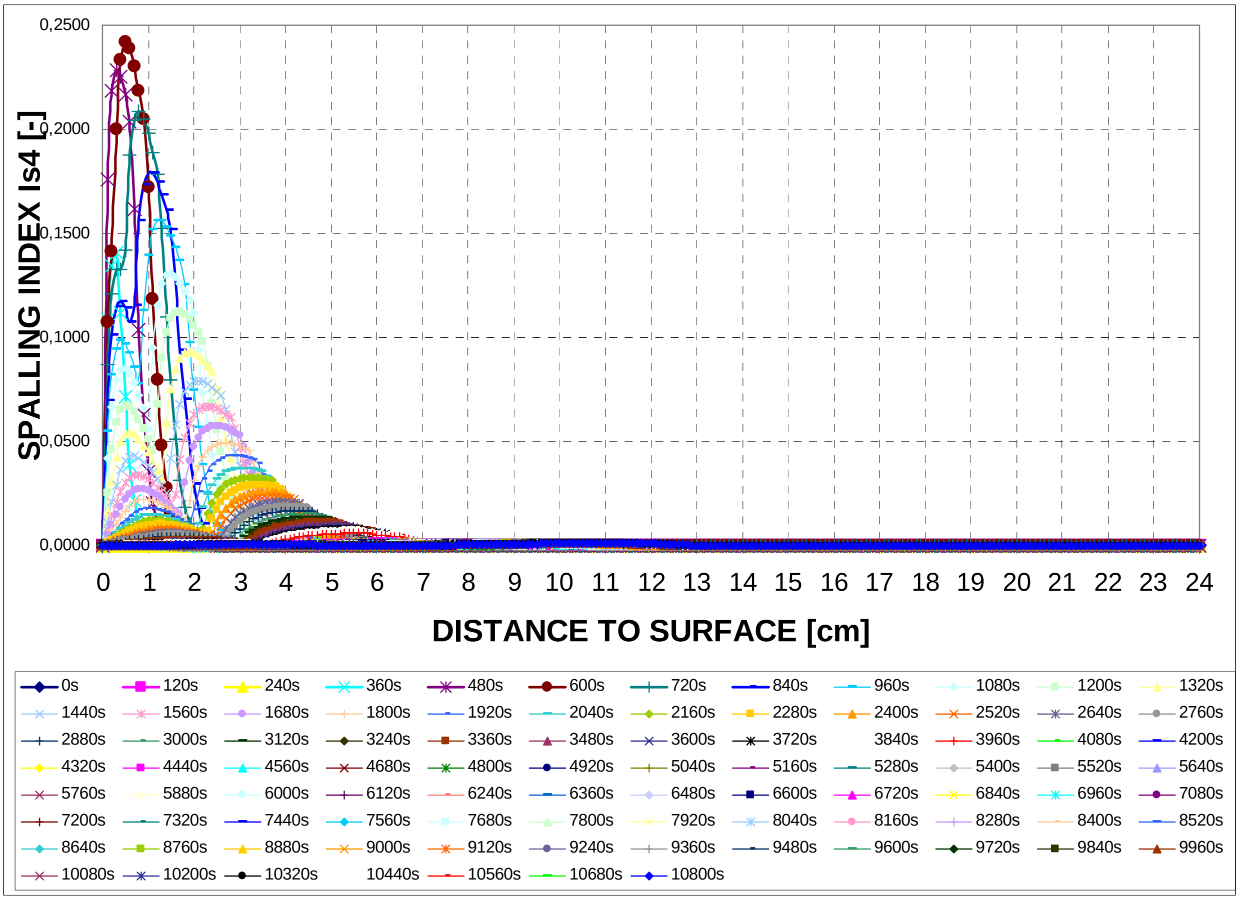

Figure 4A-56. *Spalling Index IS4 evolution for combination 56-TH24K018RH40PAR1C90*

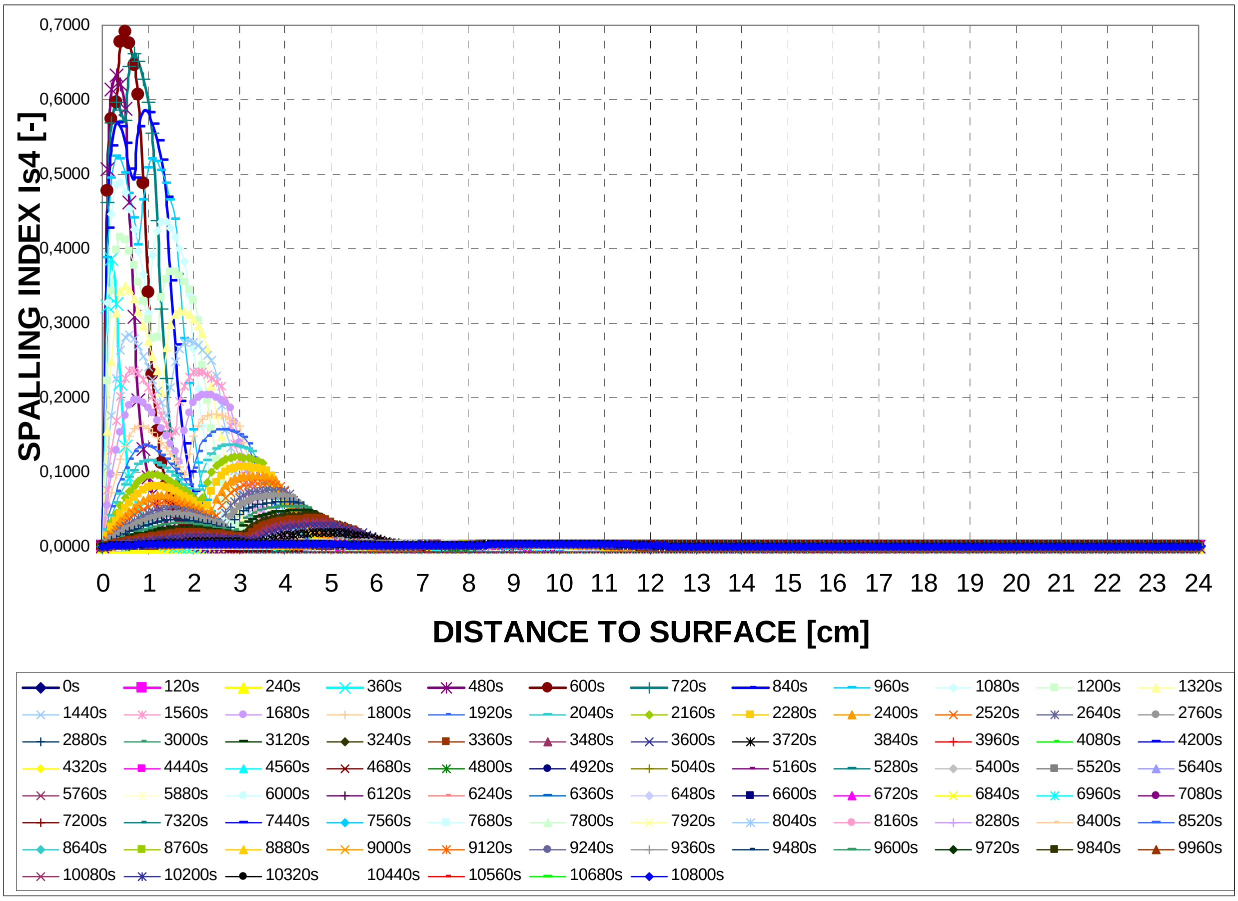

Figure 4A-57. *Spalling Index IS4 evolution for combination 57-TH24K019RH40PAR1C90*

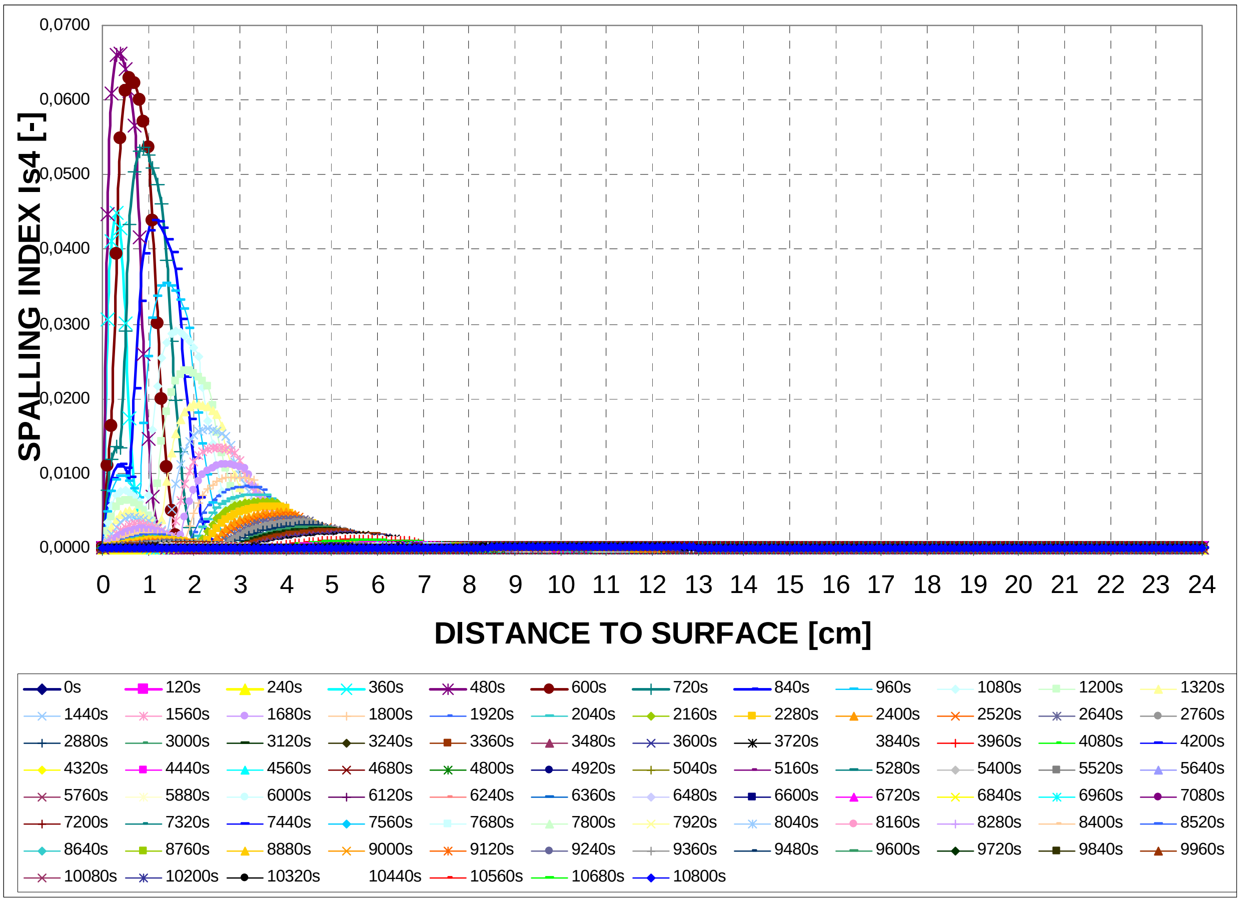

Figure 4A-58. *Spalling Index IS4 evolution for combination 58-TH24K017RH50PAR1C90*

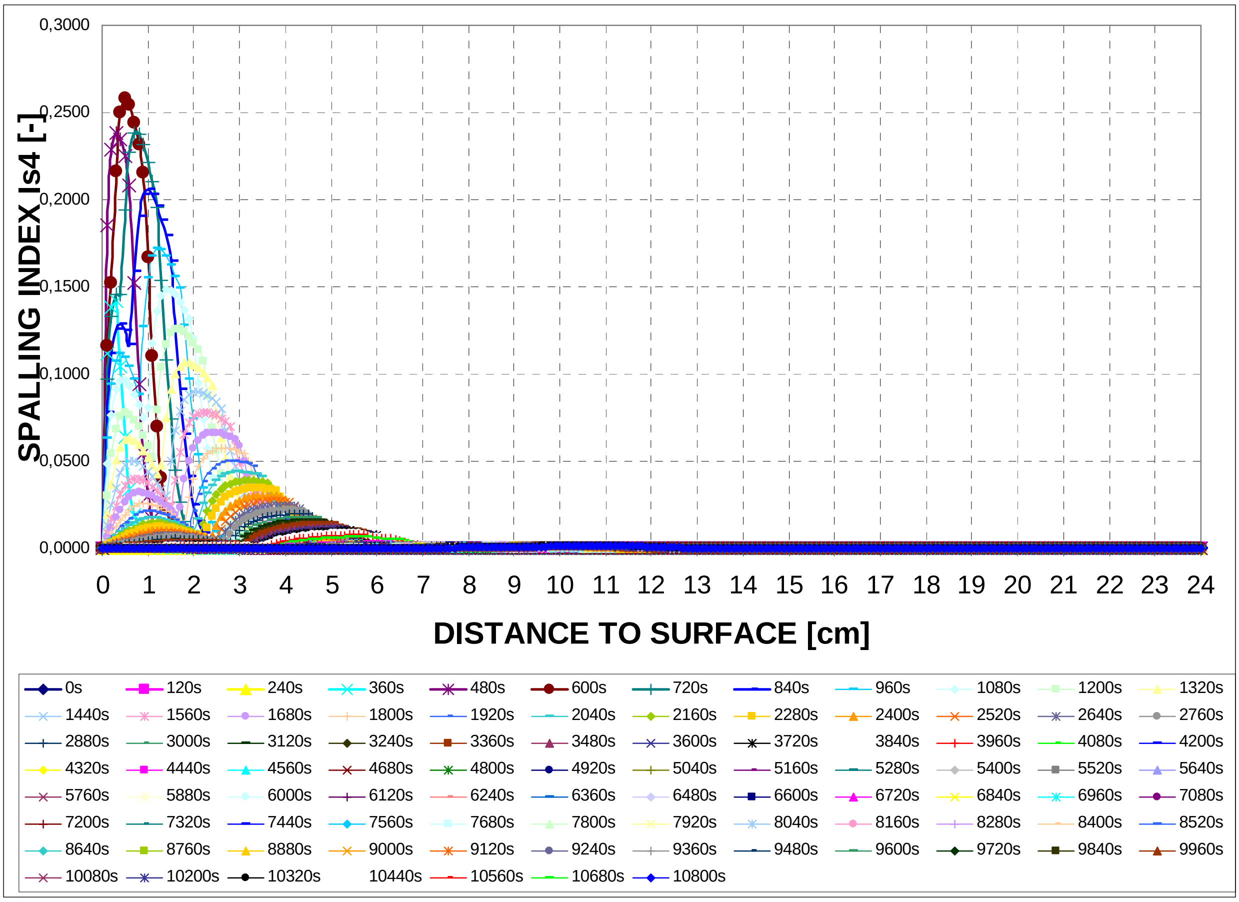

Figure 4A-59. *Spalling Index IS4 evolution for combination 59-TH24K018RH50PAR1C90*

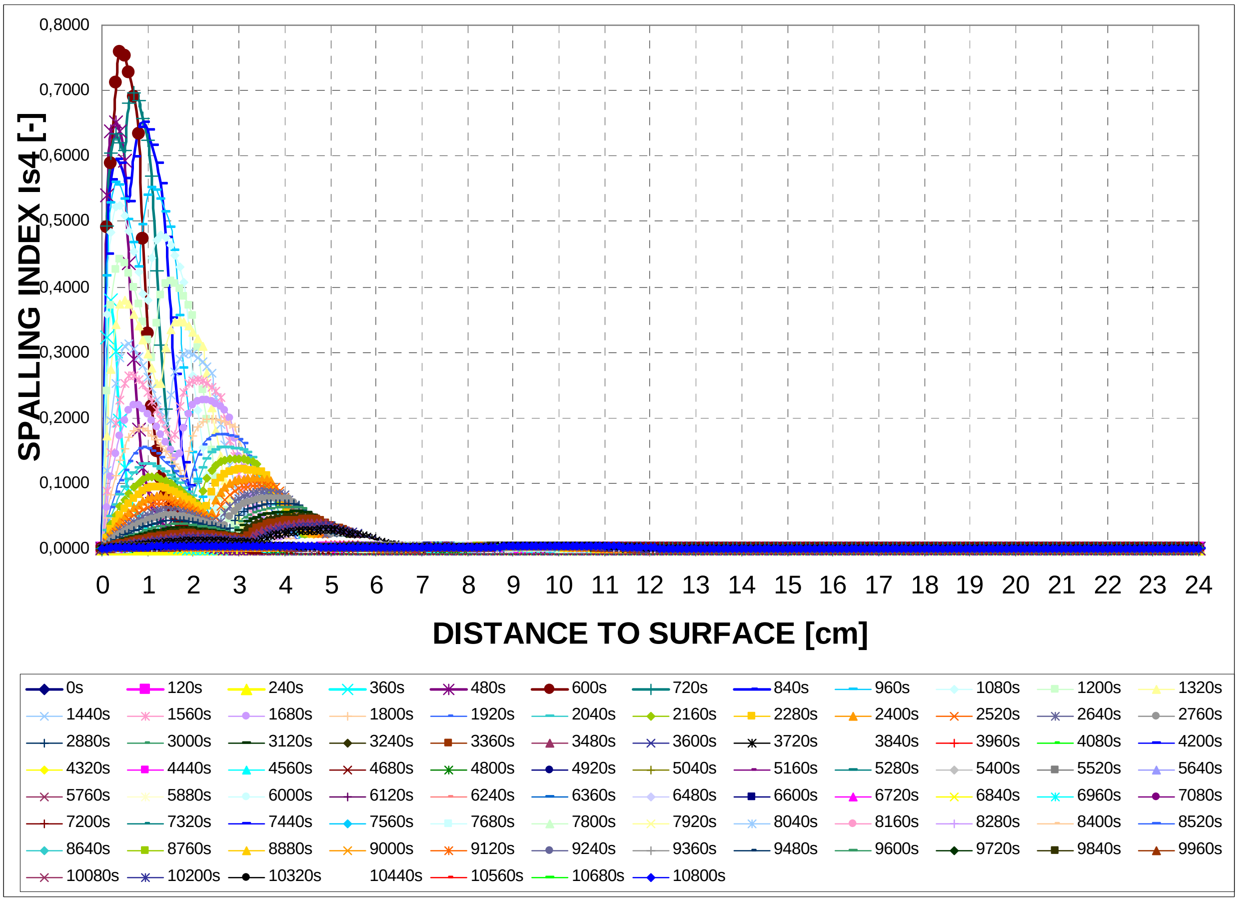

Figure 4A-60. *Spalling Index IS4 evolution for combination 60-TH24K019RH50PAR1C90*

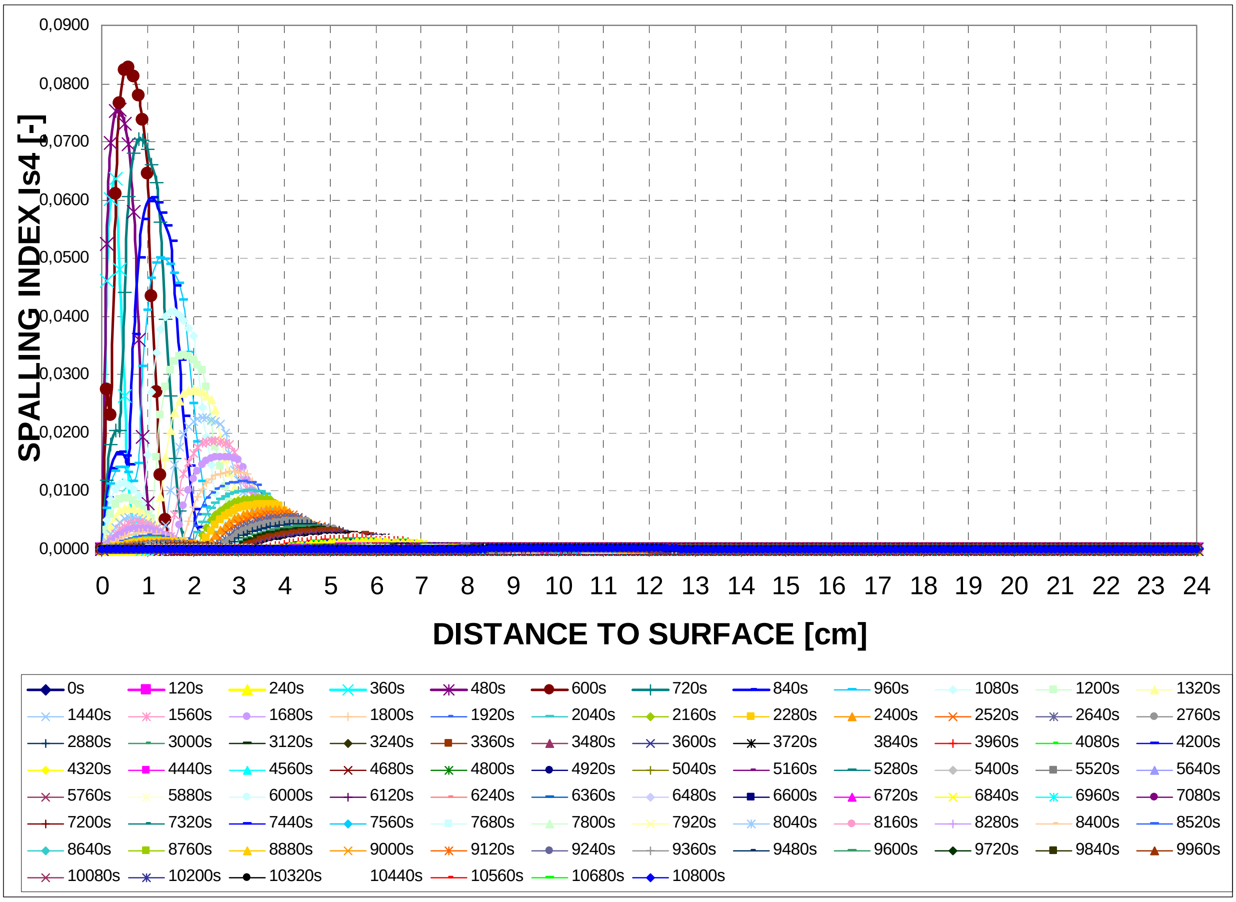

Figure 4A-61. *Spalling Index IS4 evolution for combination 61-TH24K017RH60PAR1C90*

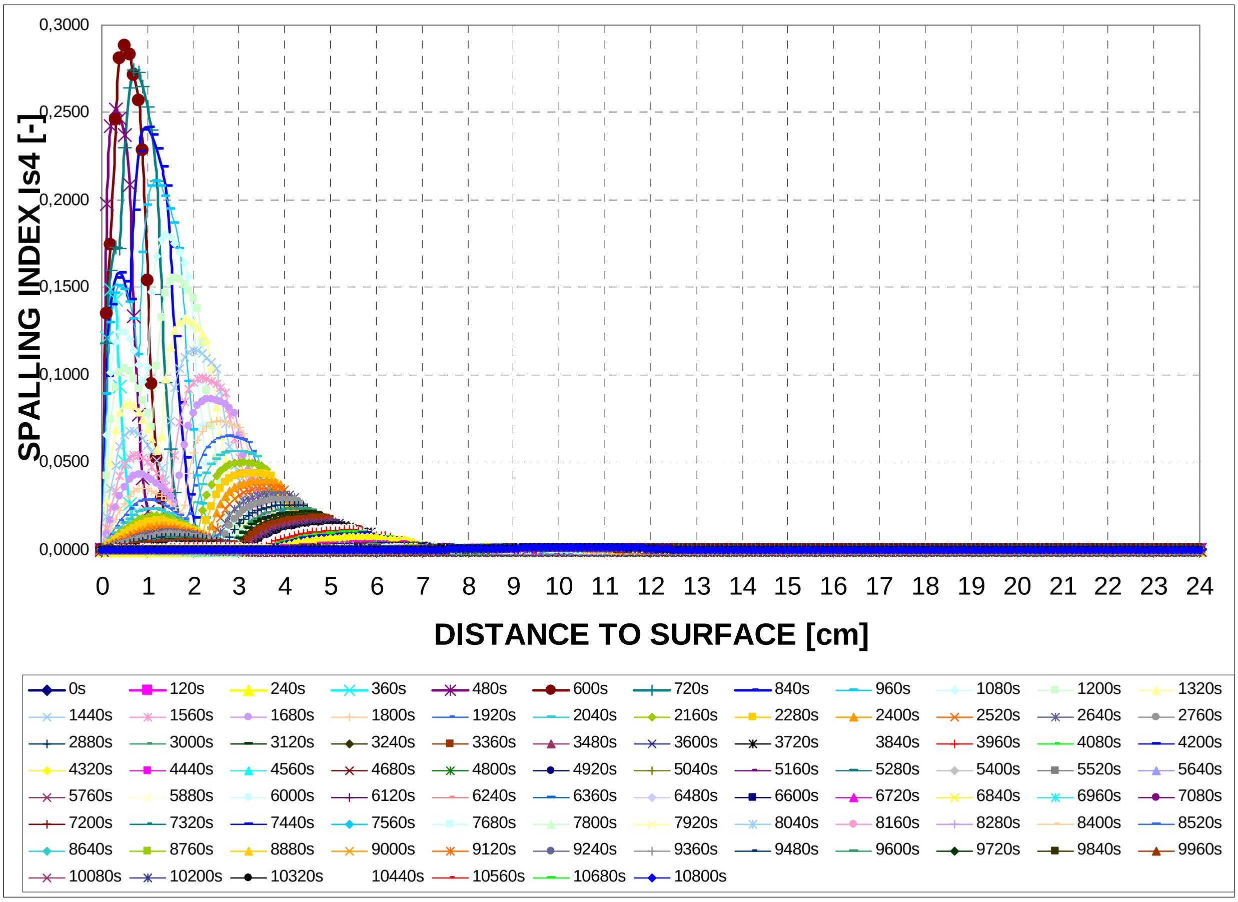

Figure 4A-62. *Spalling Index IS4 evolution for combination 62-TH24K018RH60PAR1C90*

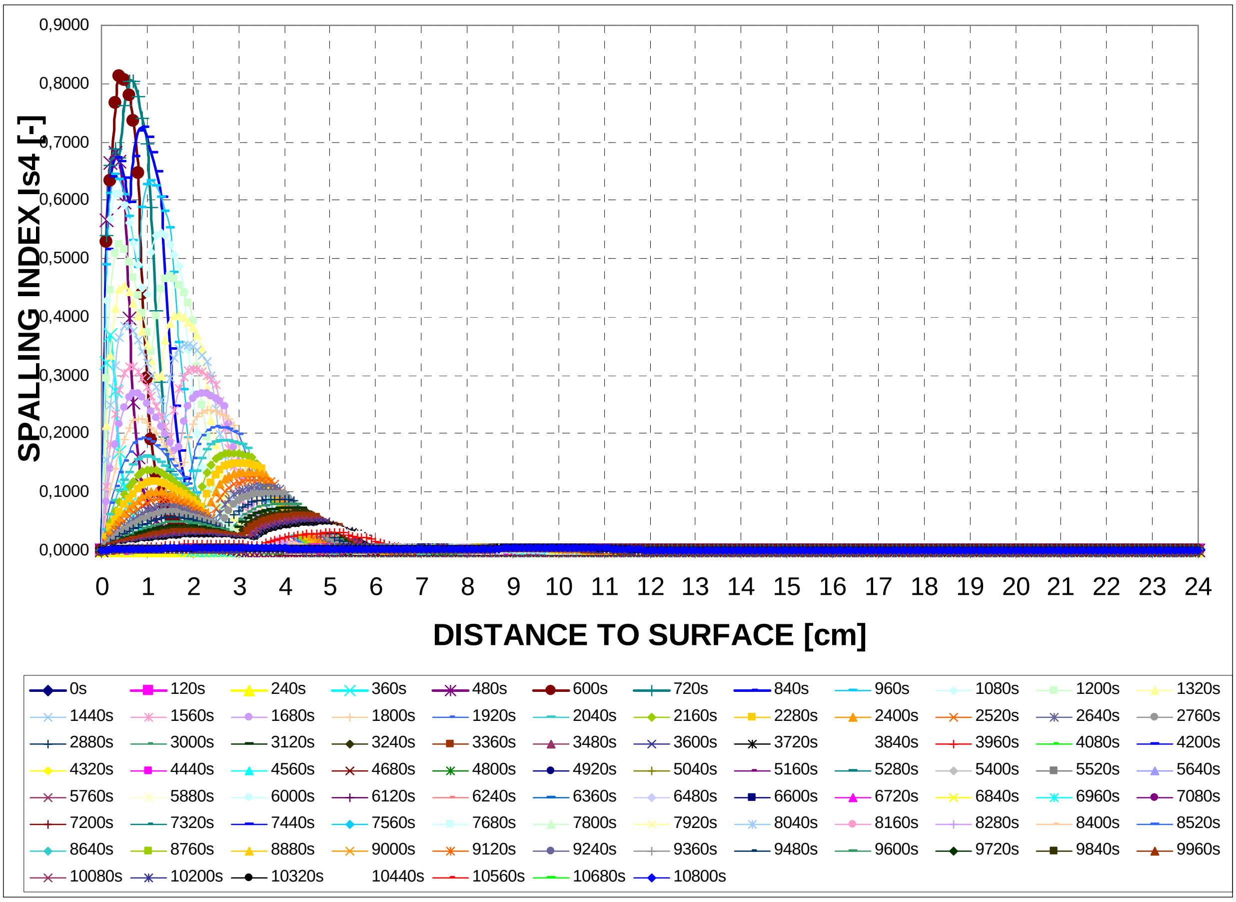

Figure 4A-63. *Spalling Index IS4 evolution for combination 63-TH24K019RH60PAR1C90*

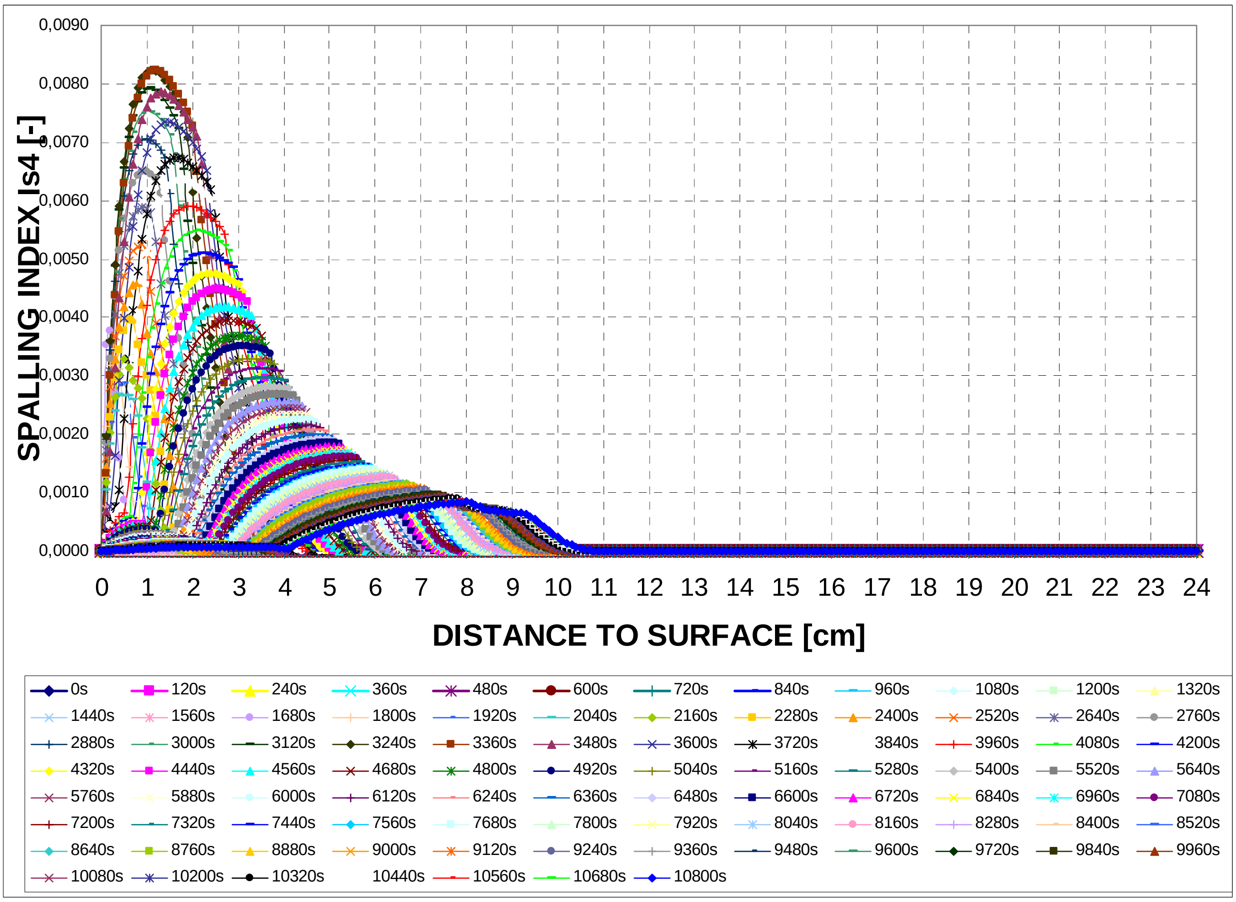

Figure 4A-64. *Spalling Index IS4 evolution for combination 64-TH24K017RH40PAR2C90*

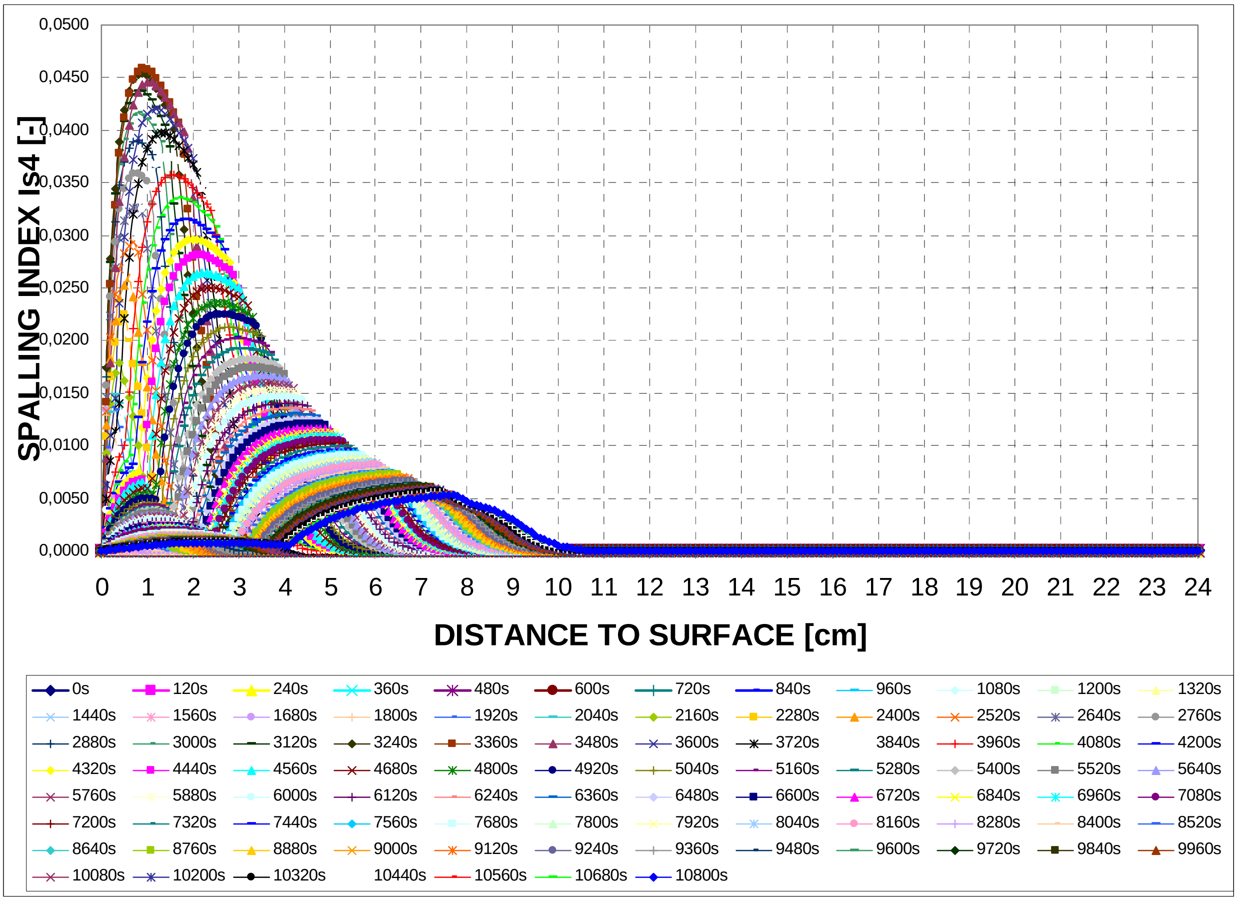

Figure 4A-65. *Spalling Index IS4 evolution for combination 65-TH24K018RH40PAR2C90*

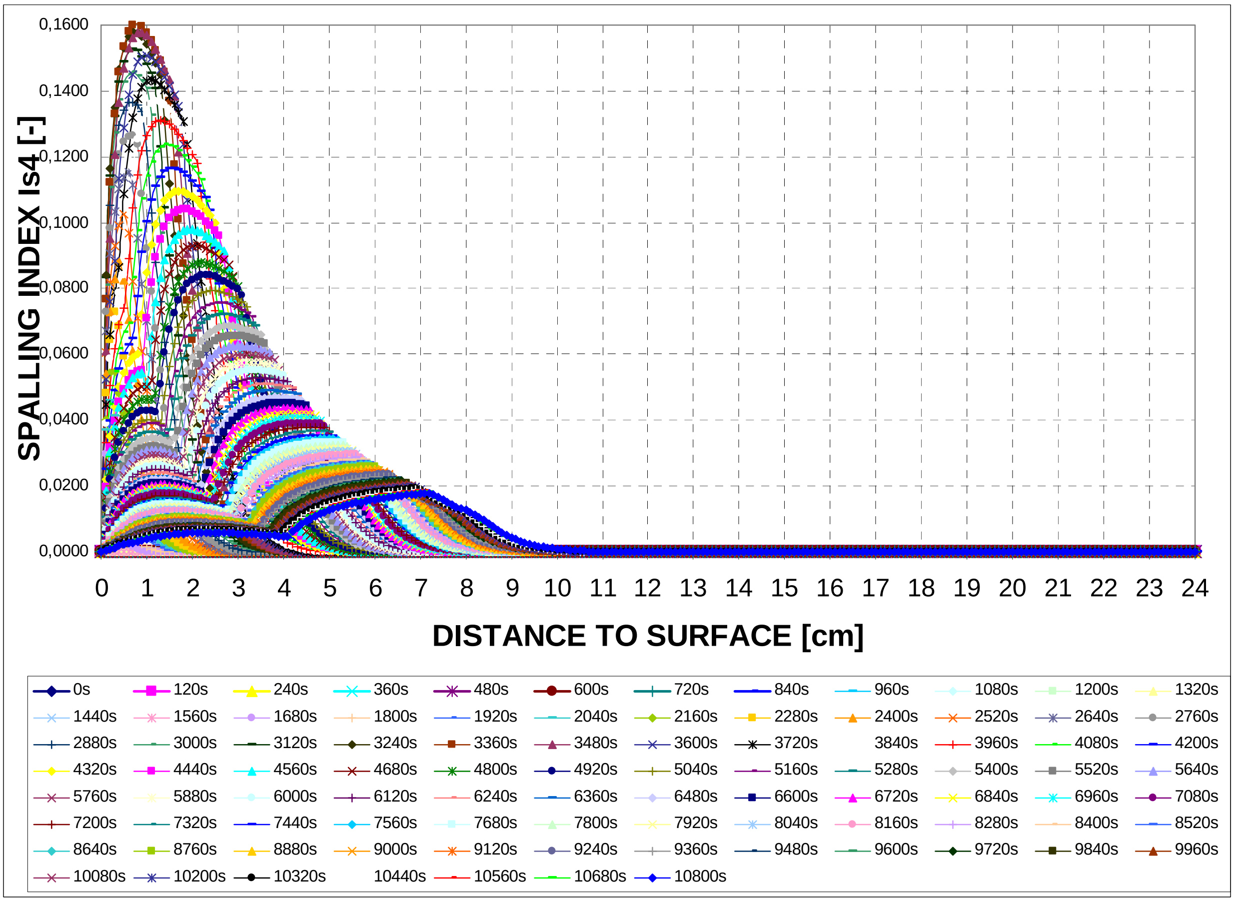

Figure 4A-66. *Spalling Index IS4 evolution for combination 66-TH24K019RH40PAR2C90*

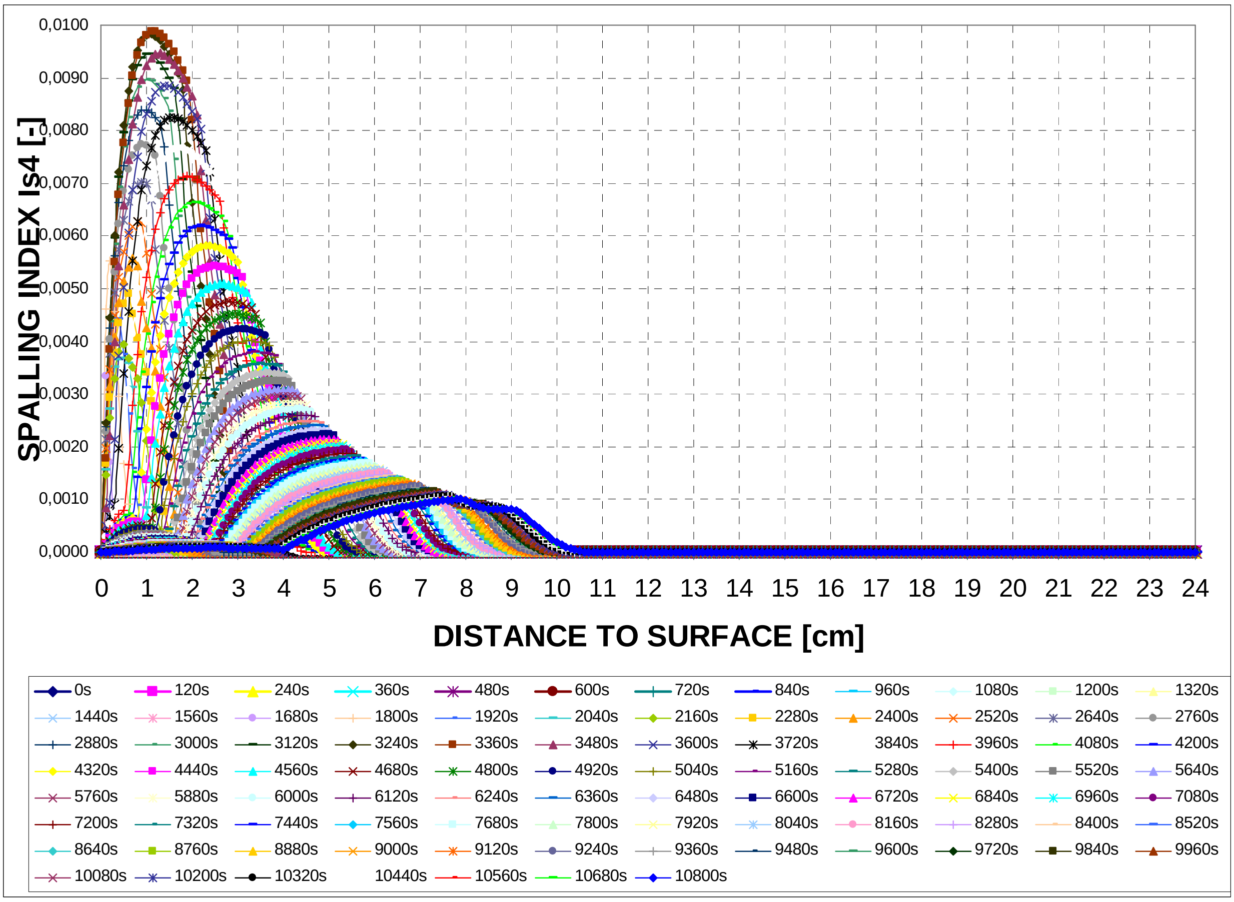

Figure 4A-67. *Spalling Index IS4 evolution for combination 67-TH24K017RH50PAR2C90*

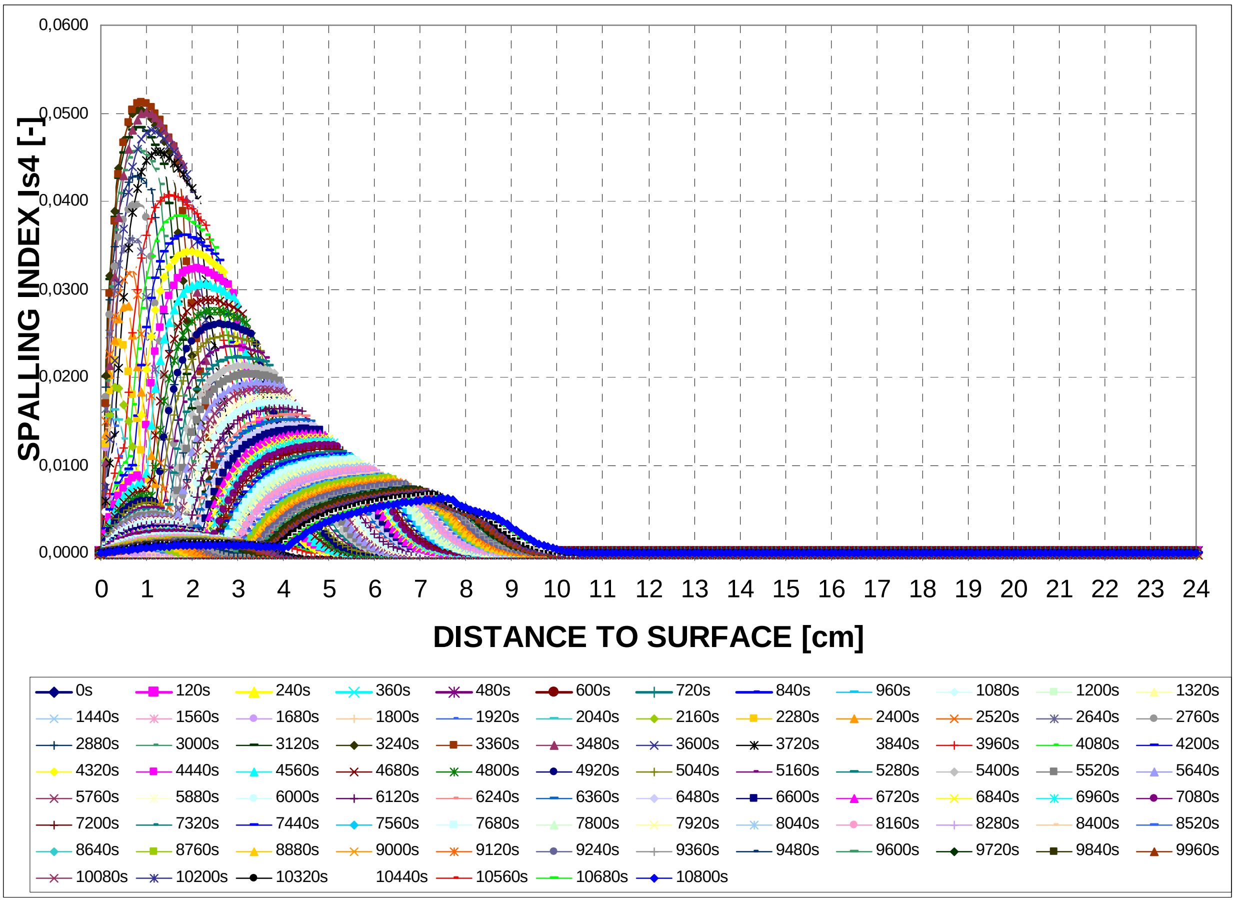

Figure 4A-68. *Spalling Index IS4 evolution for combination 68-TH24K018RH50PAR2C90*

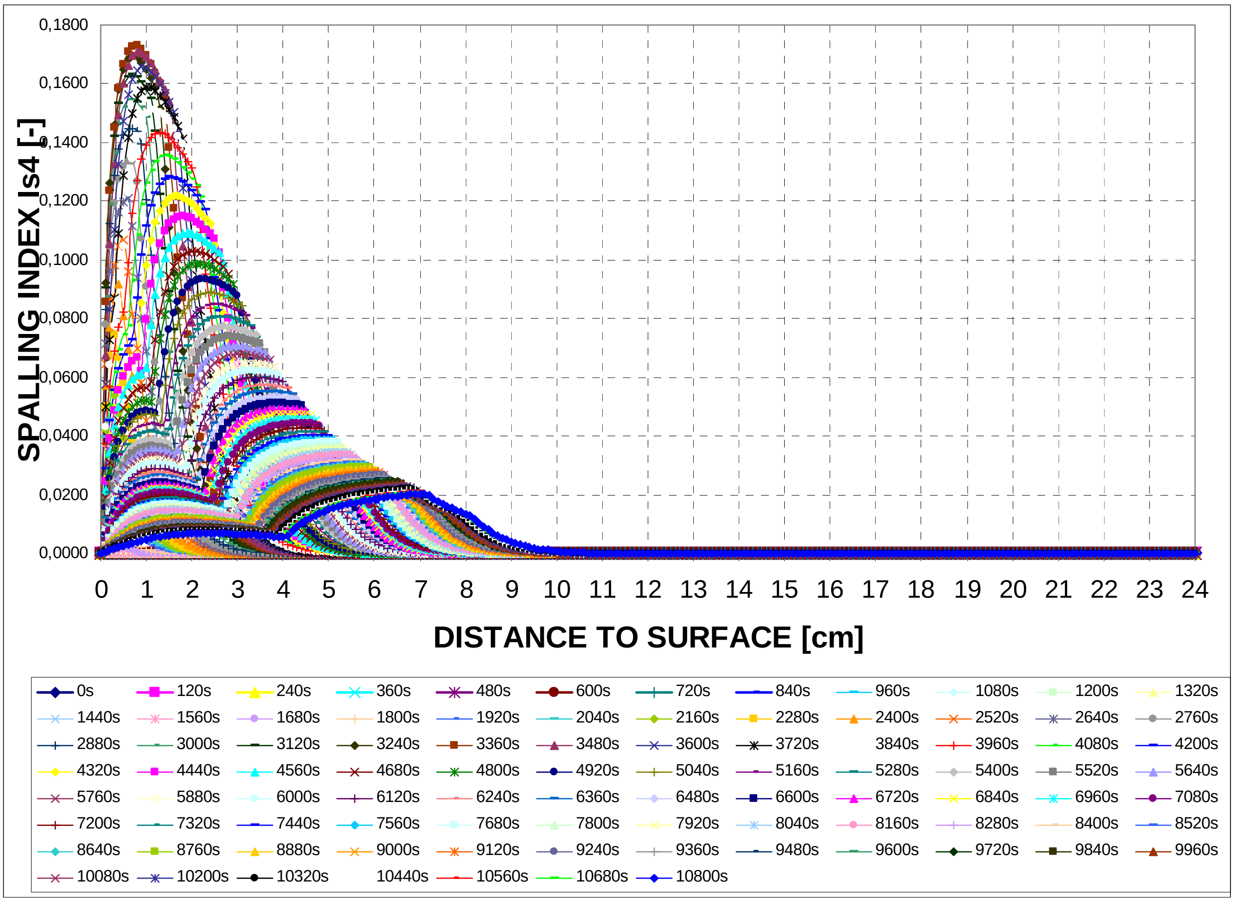

Figure 4A-69. *Spalling Index IS4 evolution for combination 69-TH24K019RH50PAR2C90*

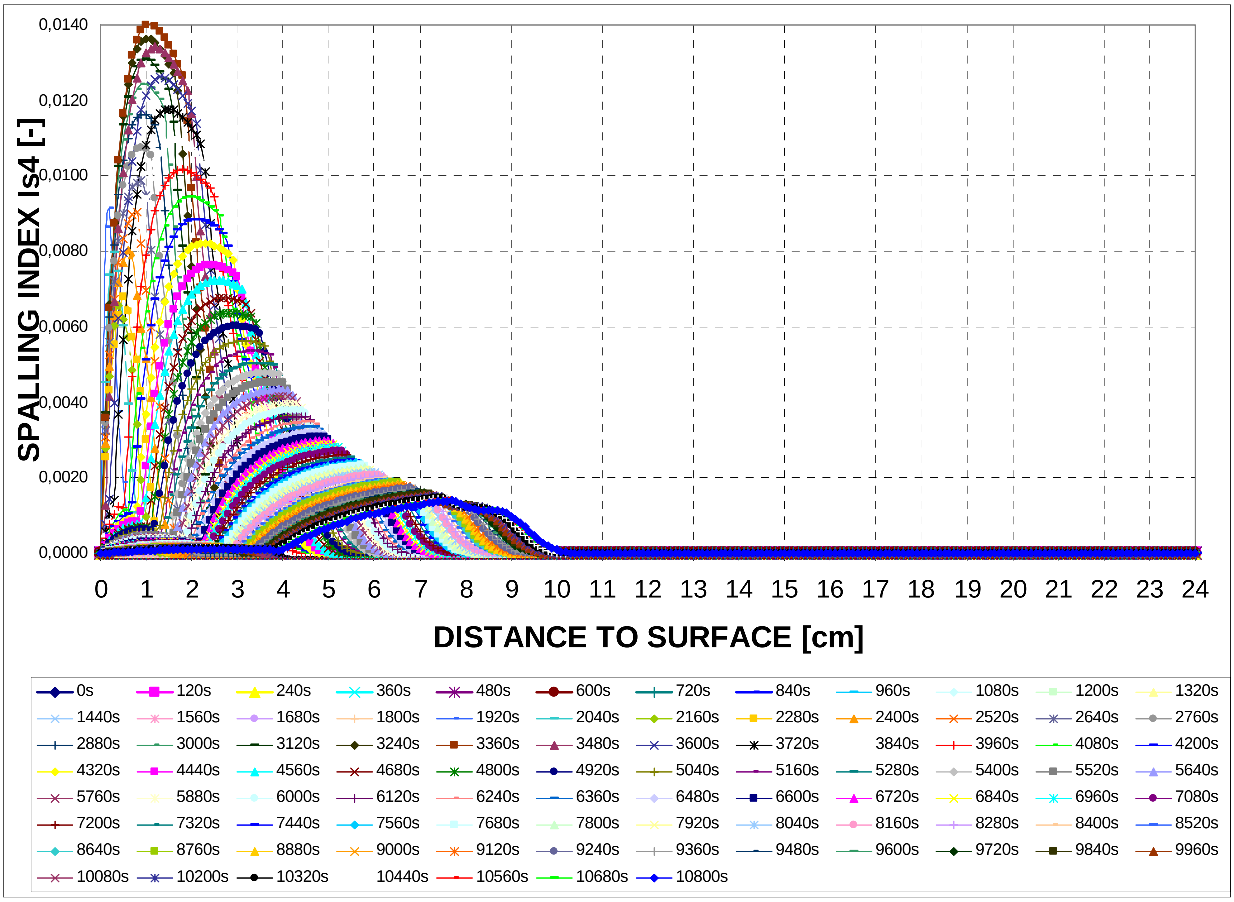

Figure 4A-70. *Spalling Index IS4 evolution for combination 70-TH24K017RH60PAR2C90*

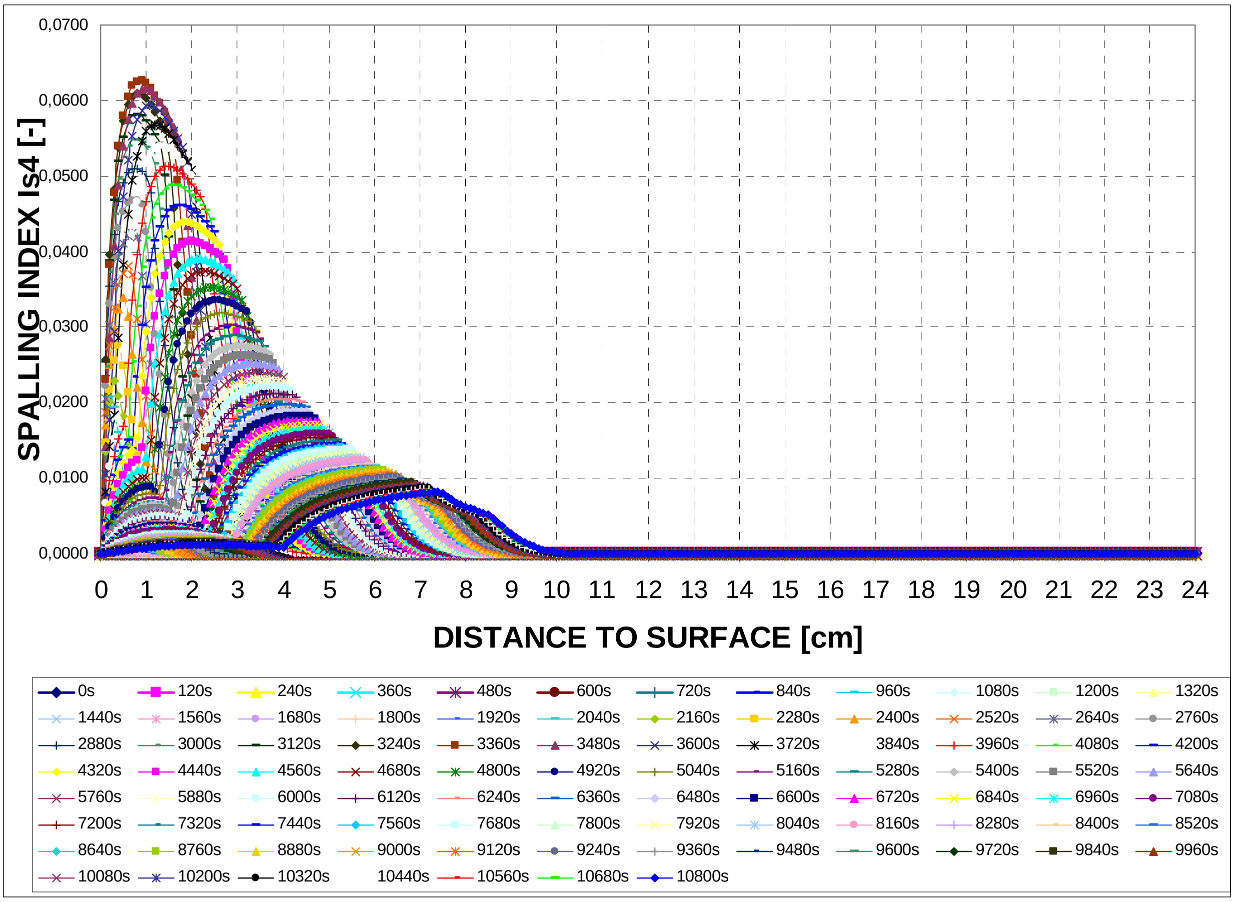

Figure 4A-71. *Spalling Index IS4 evolution for combination 71-TH24K018RH60PAR2C90*

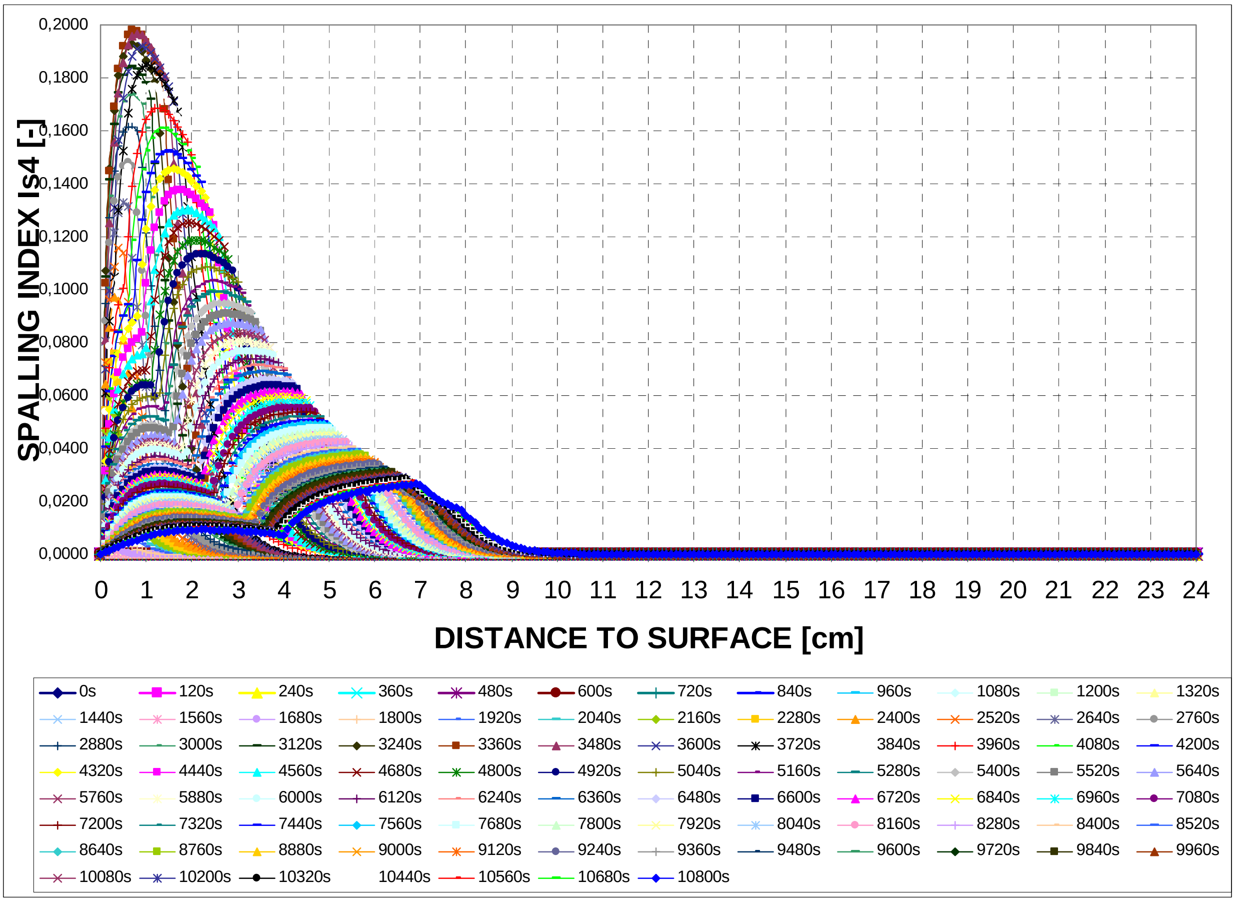

Figure 4A-72. *Spalling Index IS4 evolution for combination 72-TH24K019RH60PAR2C90*

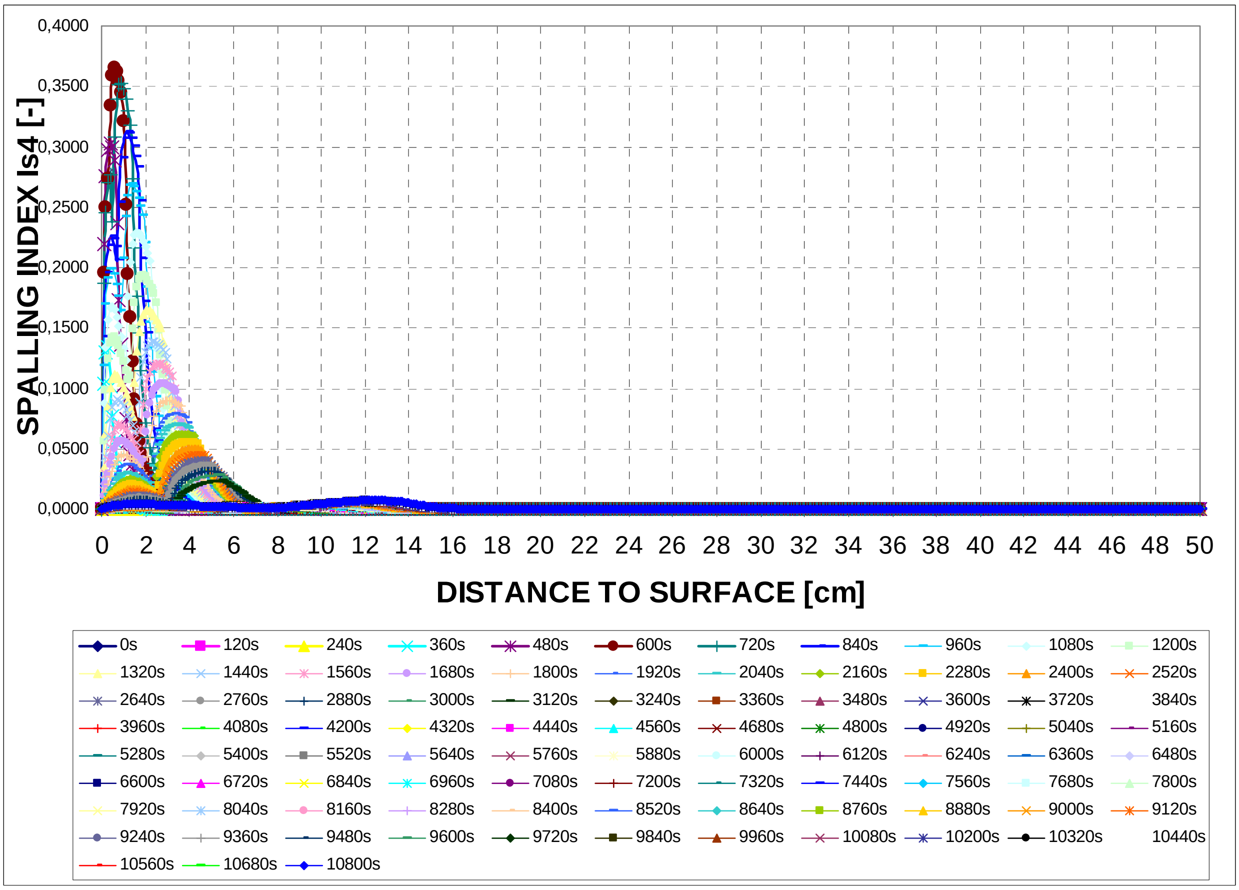

Figure 4A-73. *Spalling Index IS4 evolution for combination 73-TH50K018RH50PAR1C60*

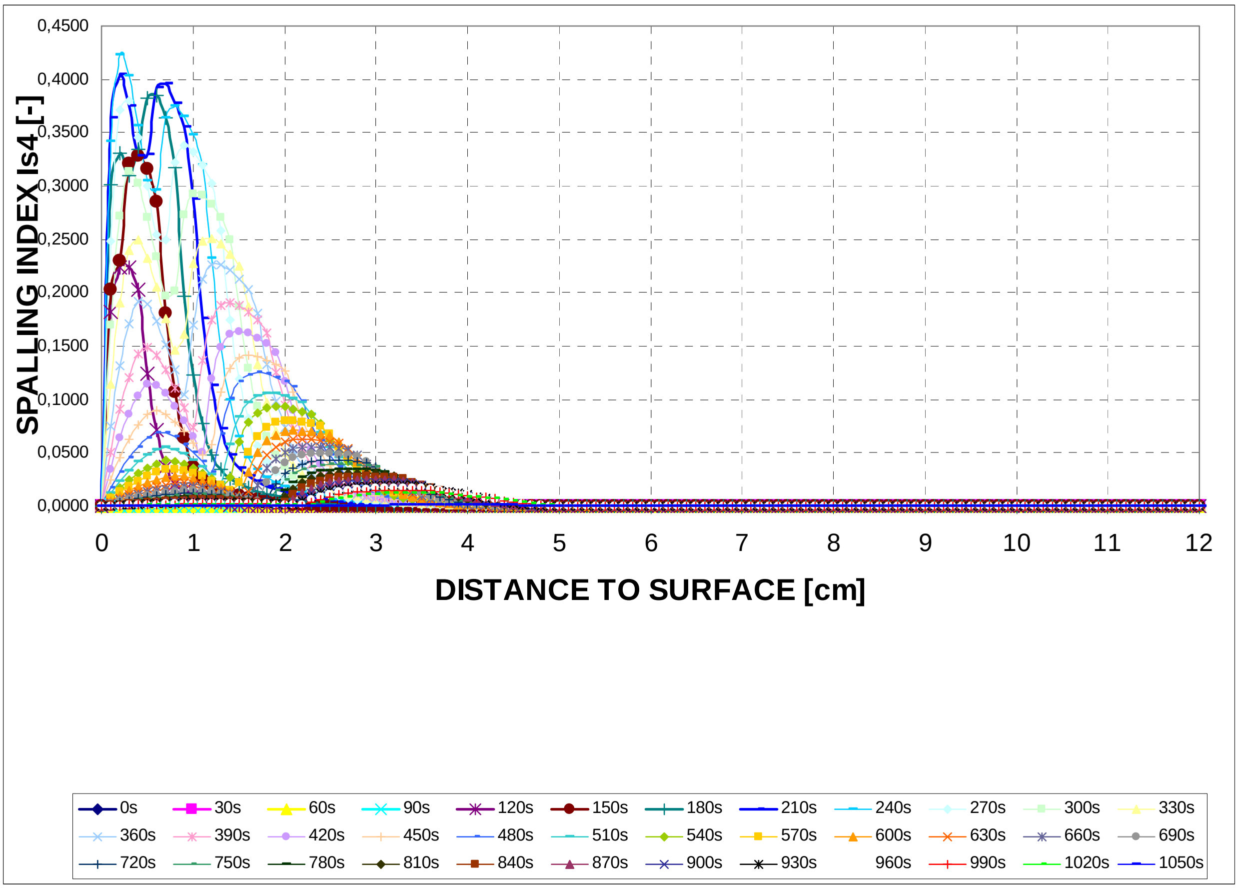

Figure 4A-74. *Spalling Index IS4 evolution for combination 74-TH12K017RH40PAR3C60*

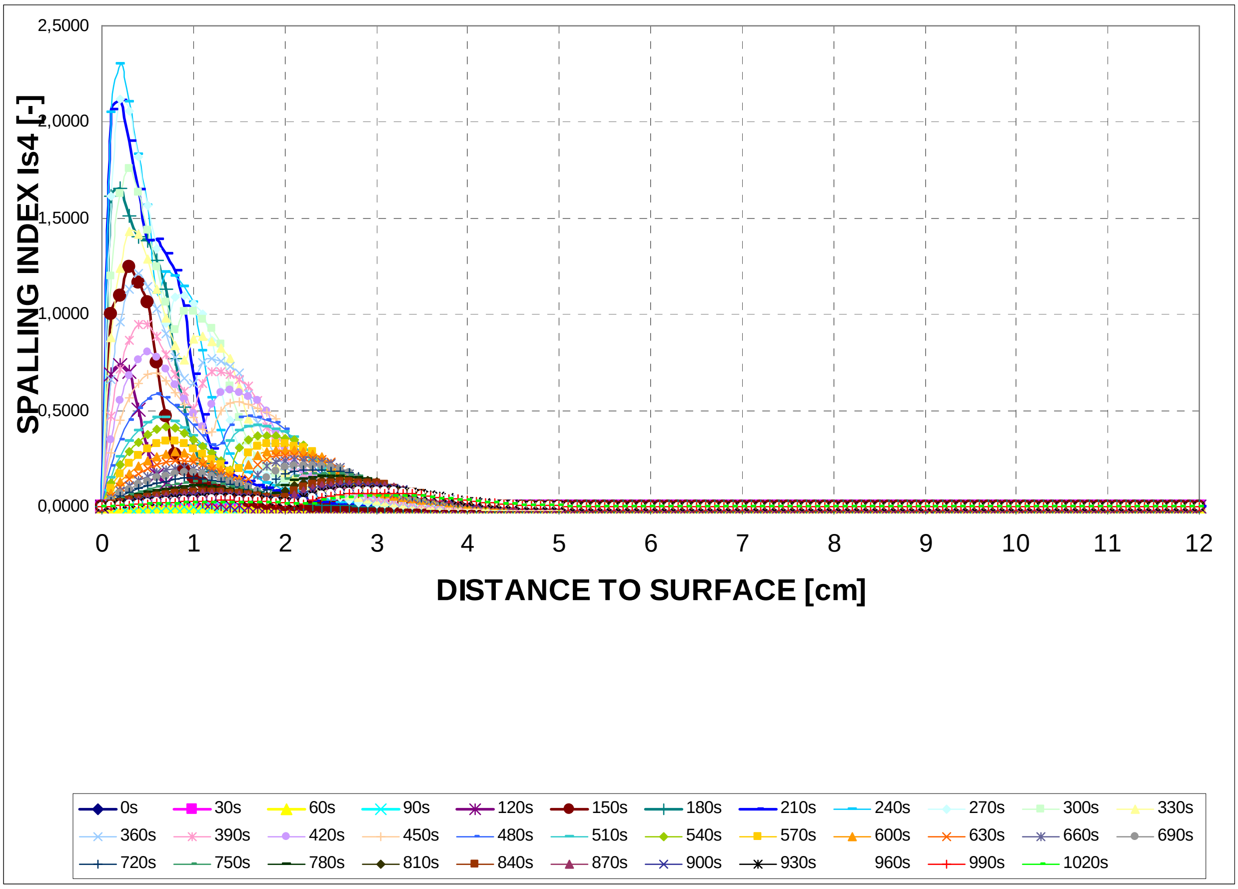

Figure 4A-75. *Spalling Index IS4 evolution for combination 75-TH12K018RH40PAR3C60*

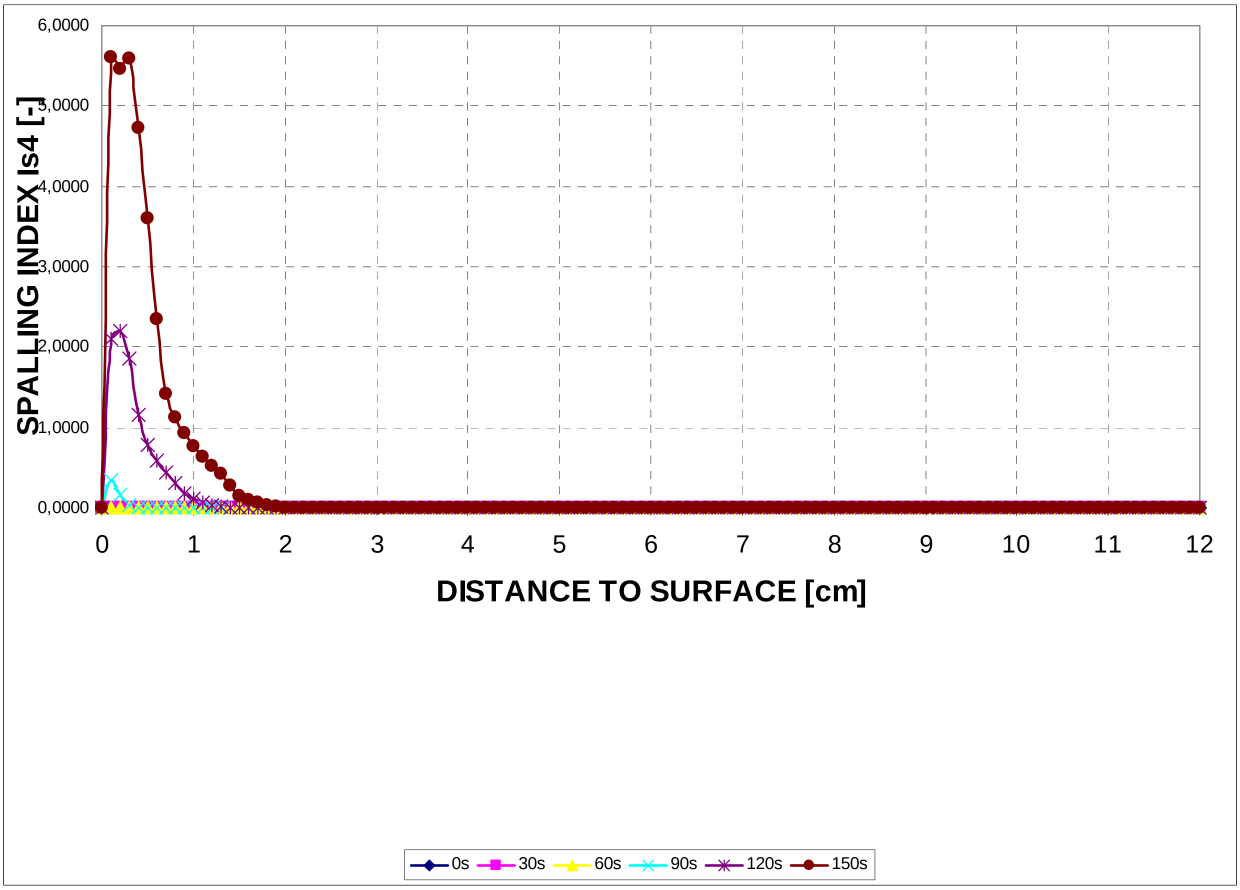

Figure 4A-76. *Spalling Index IS4 evolution for combination 76-TH12K019RH40PAR3C60*

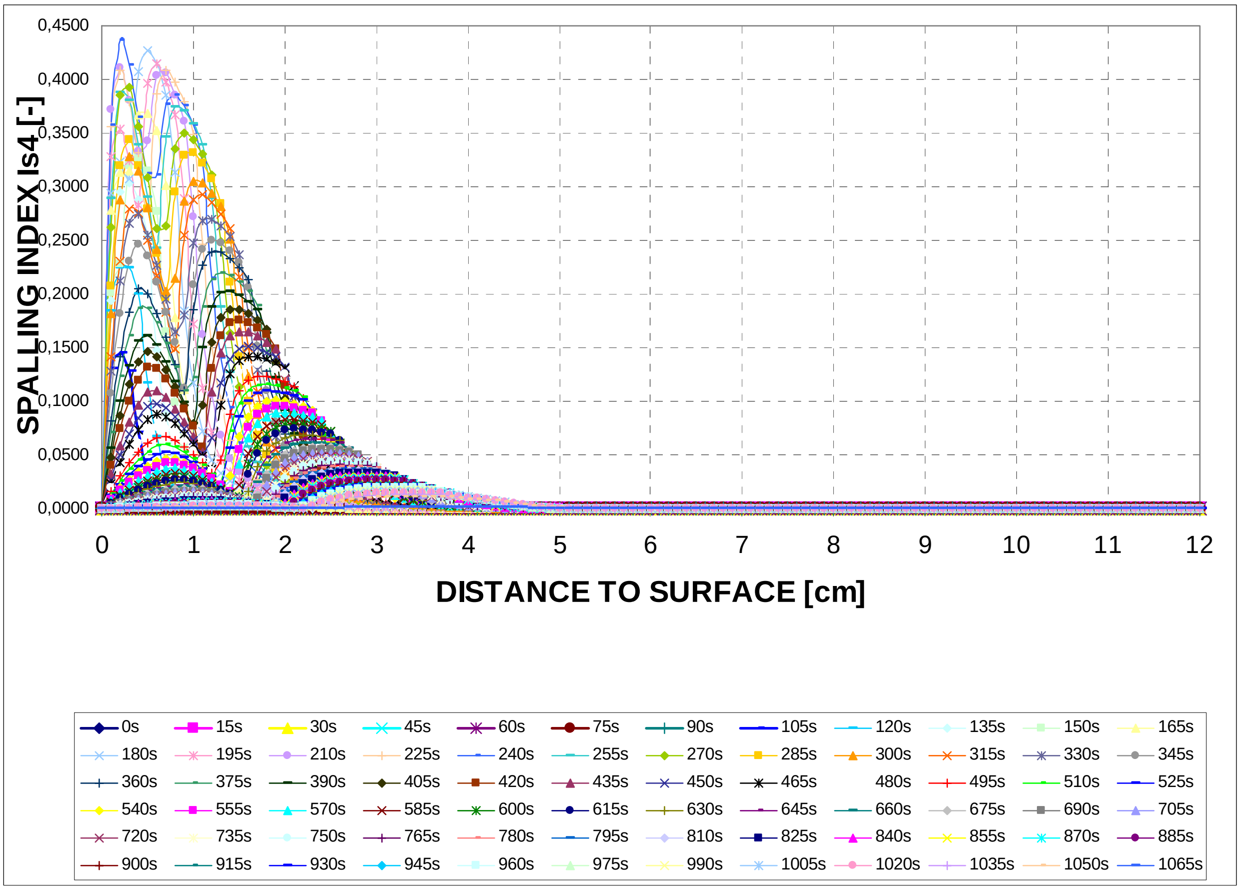

Figure 4A-77. *Spalling Index IS4 evolution for combination 77-TH12K017RH50PAR3C60*

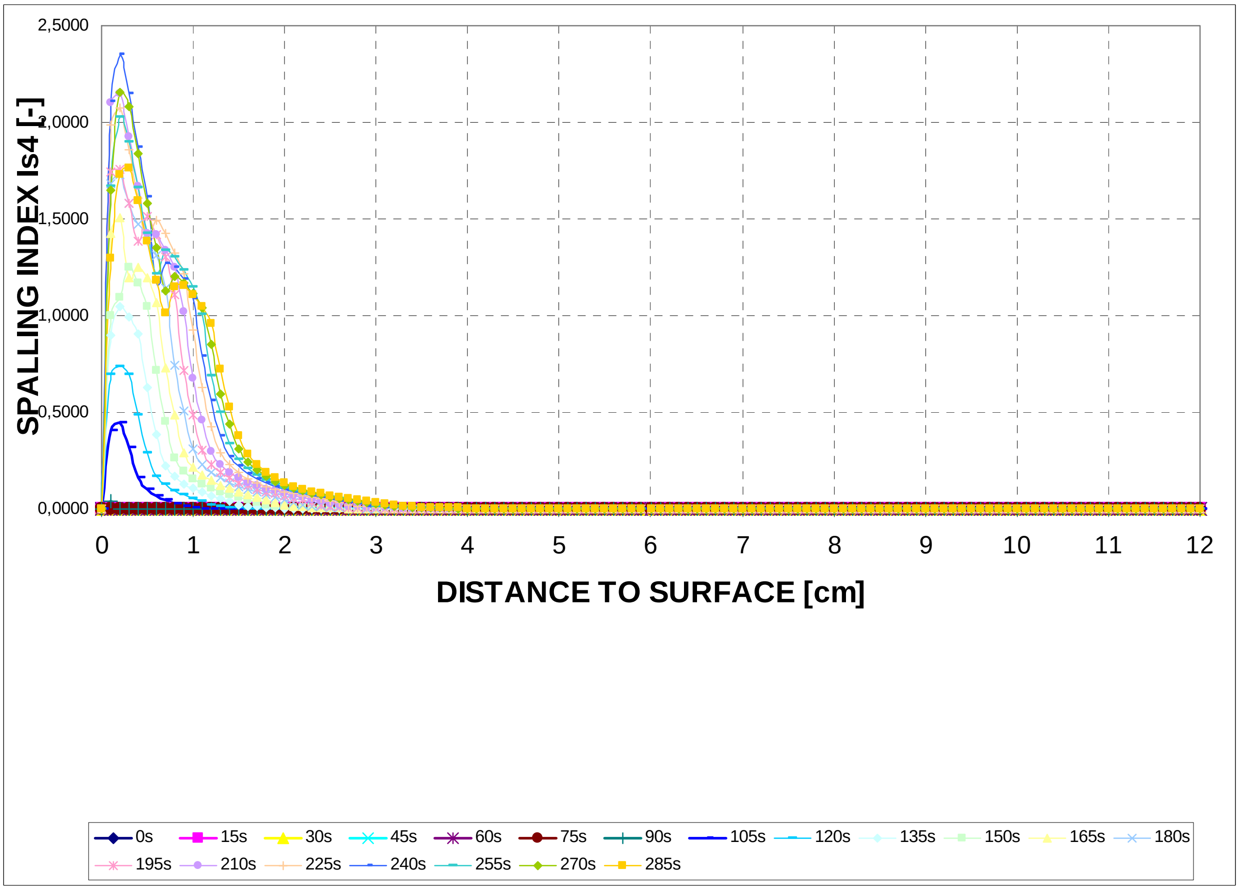

Figure 4A-78. *Spalling Index IS4 evolution for combination 78-TH12K018RH50PAR3C60*

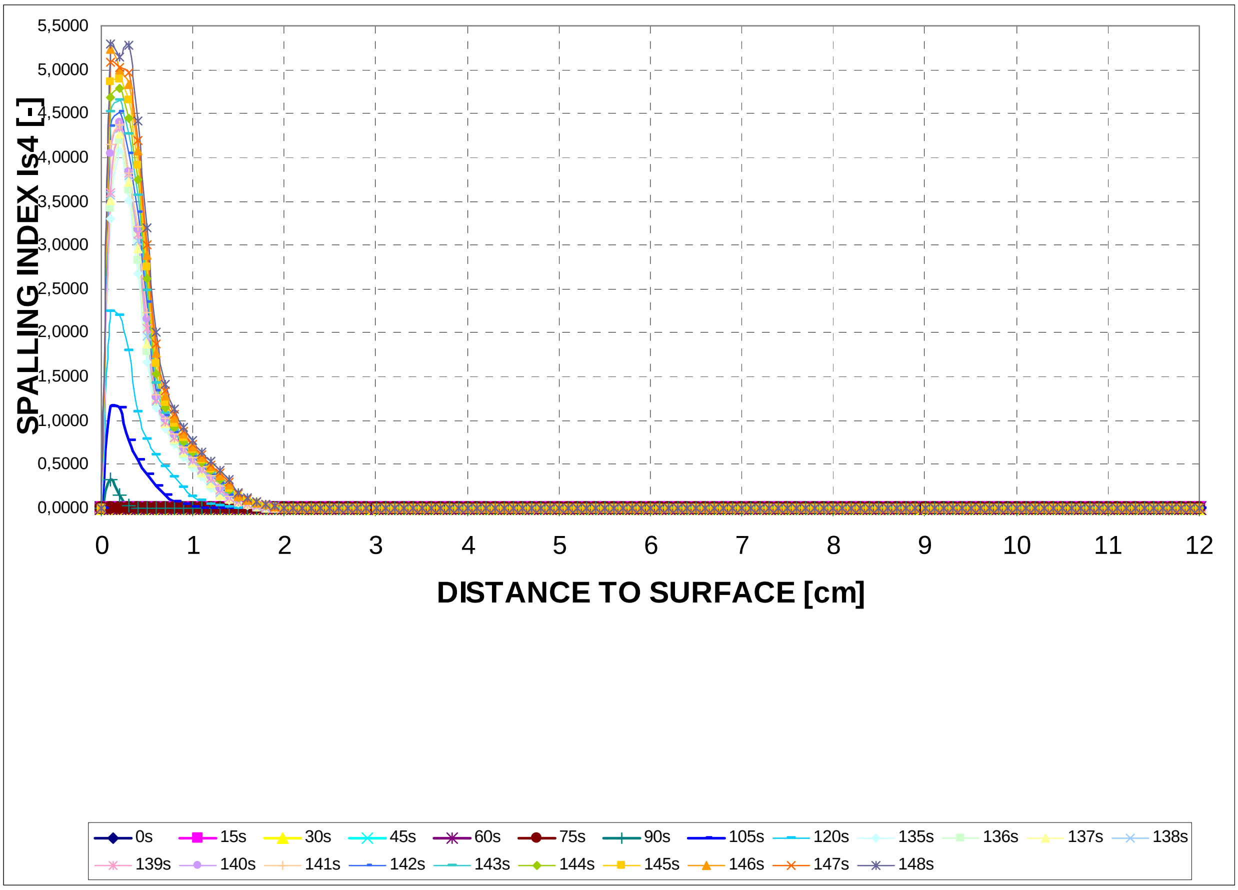

Figure 4A-79. *Spalling Index IS4 evolution for combination 79-TH12K019RH50PAR3C60*

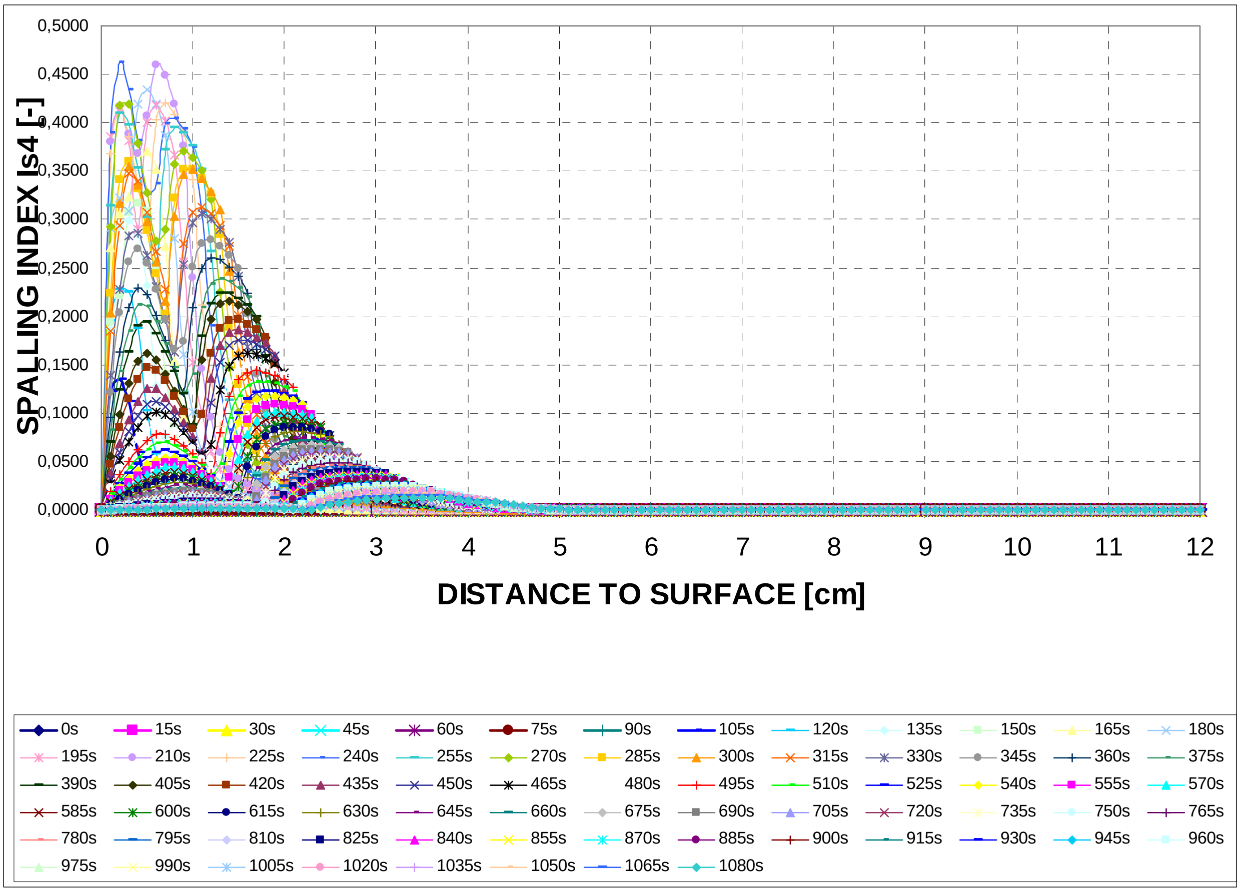

Figure 4A-80. *Spalling Index IS4 evolution for combination 80-TH12K017RH60PAR3C60*

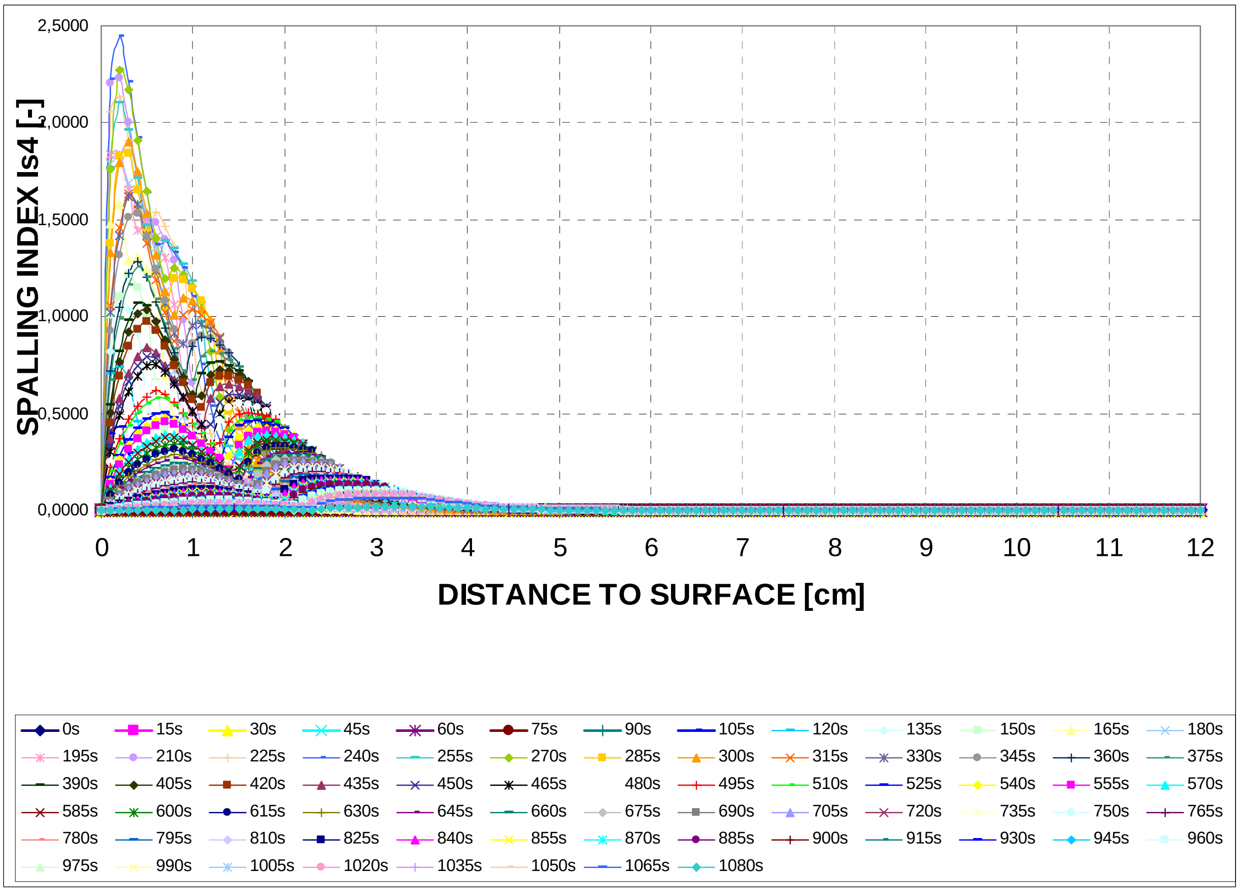

Figure 4A-81. *Spalling Index IS4 evolution for combination 81-TH12K018RH60PAR3C60*

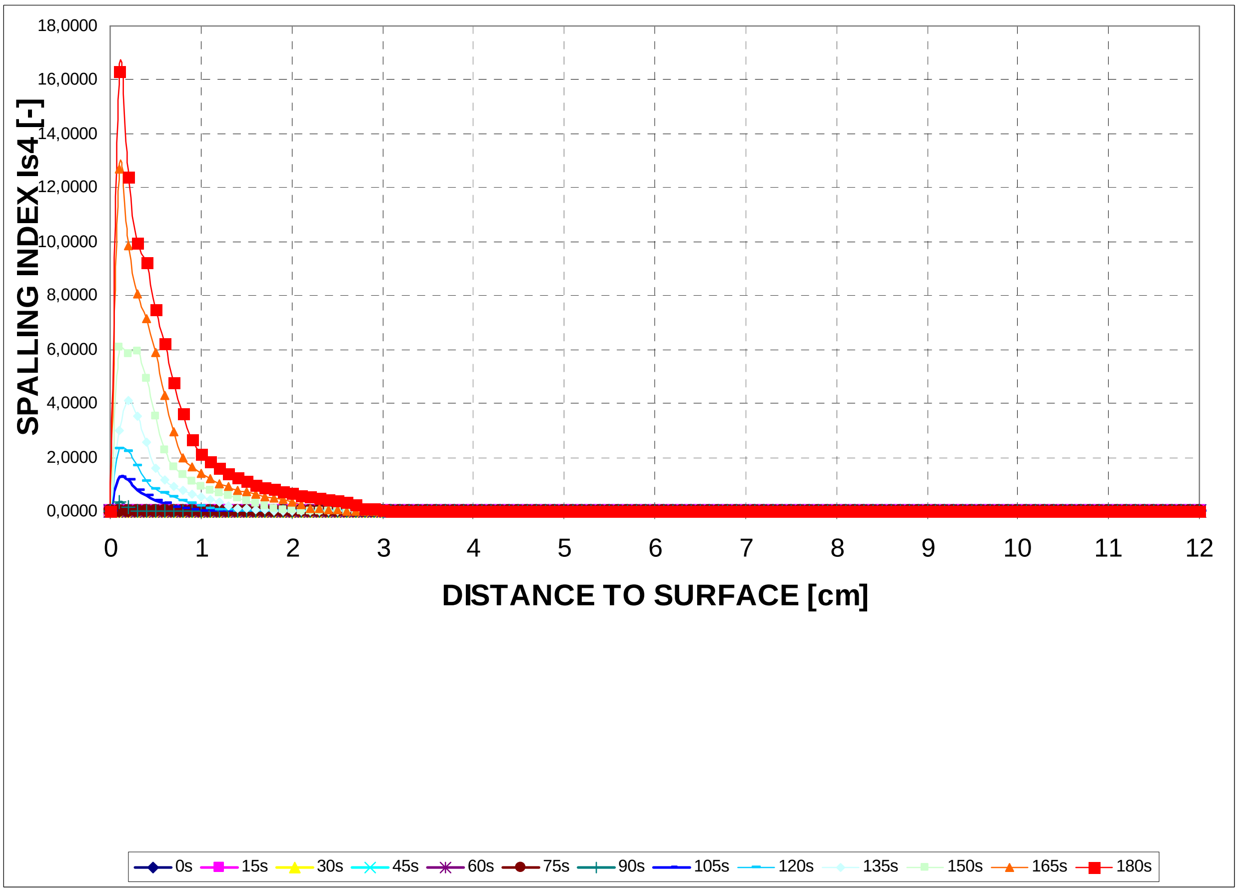

Figure 4A-82. *Spalling Index IS4 evolution for combination 82-TH12K019RH60PAR3C60*

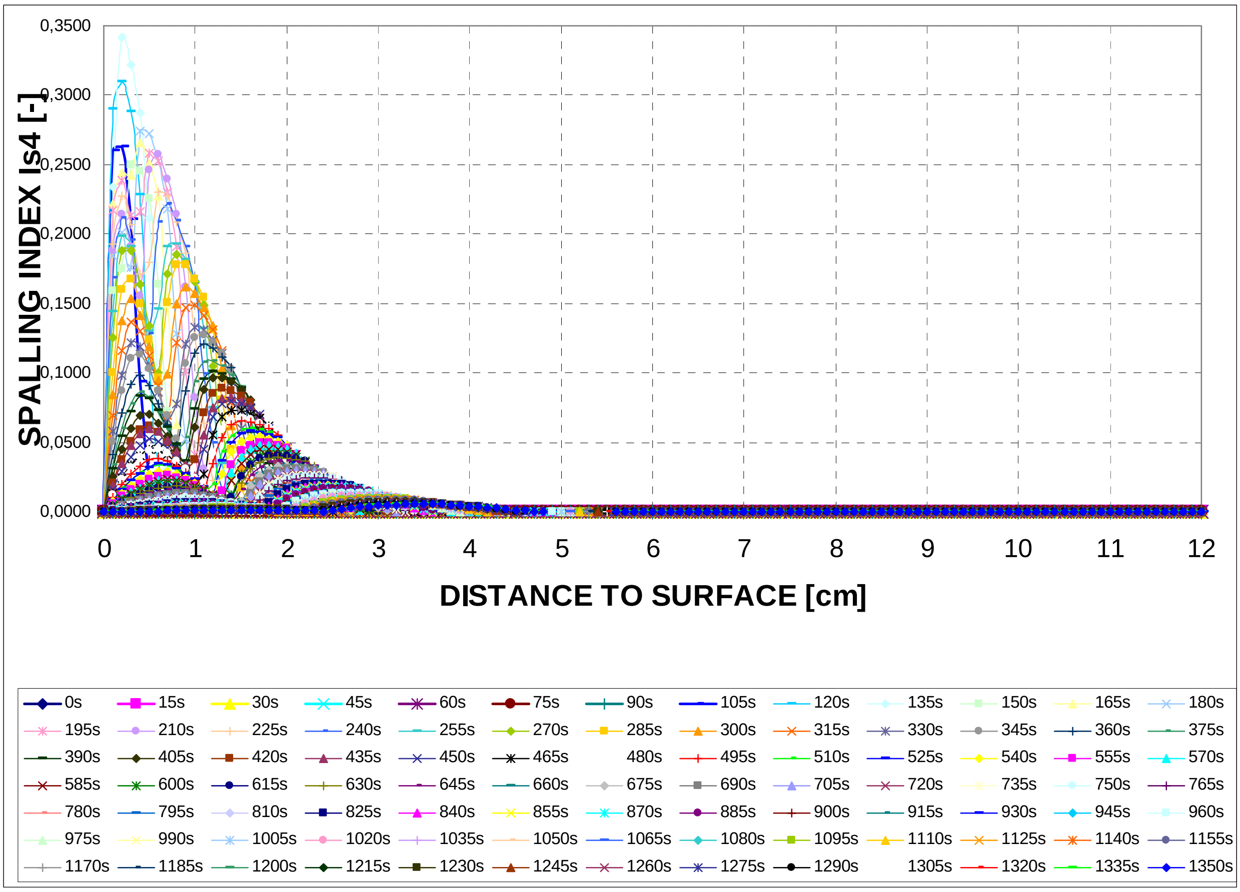

Figure 4A-83. *Spalling Index IS4 evolution for combination 83-TH12K017RH40PAR3C90*

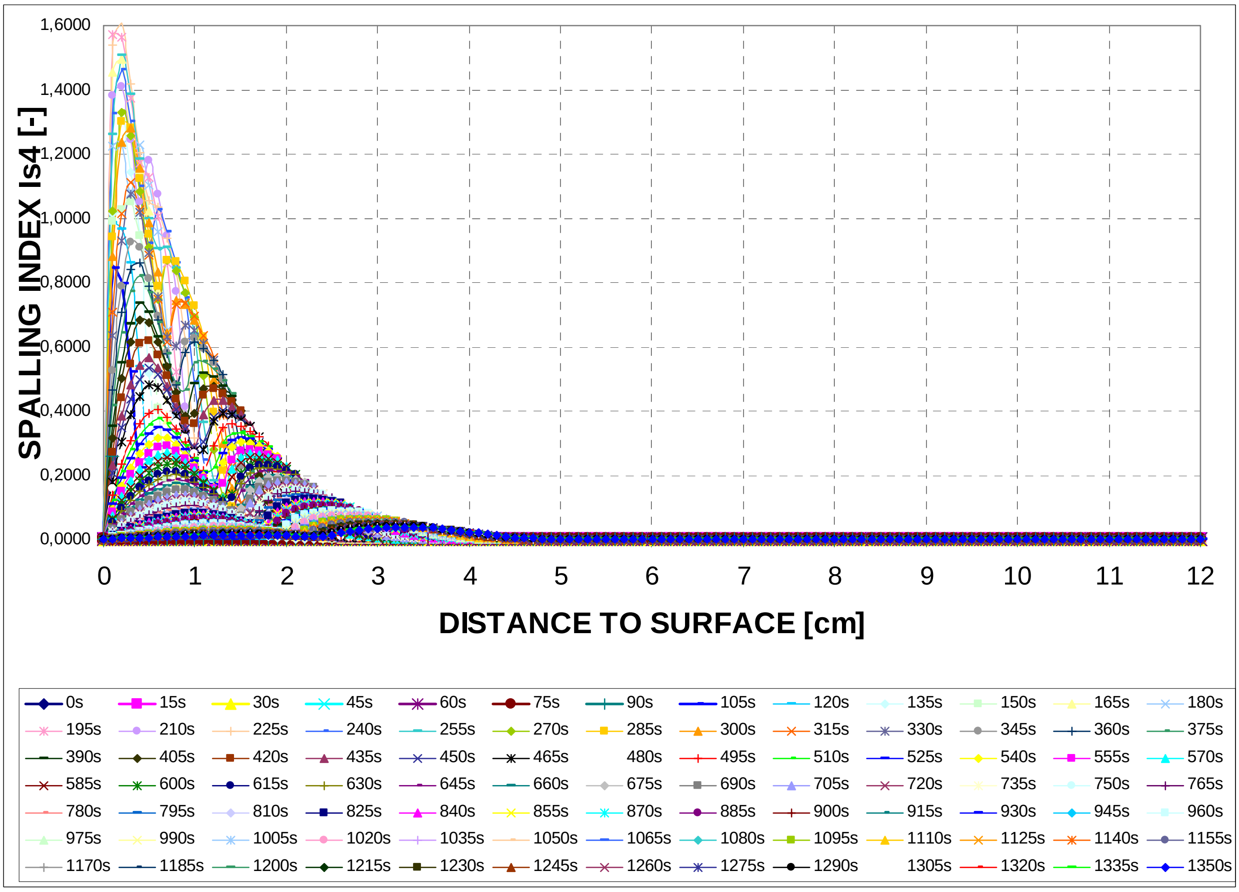

Figure 4A-84. *Spalling Index IS4 evolution for combination 84-TH12K018RH40PAR3C90*

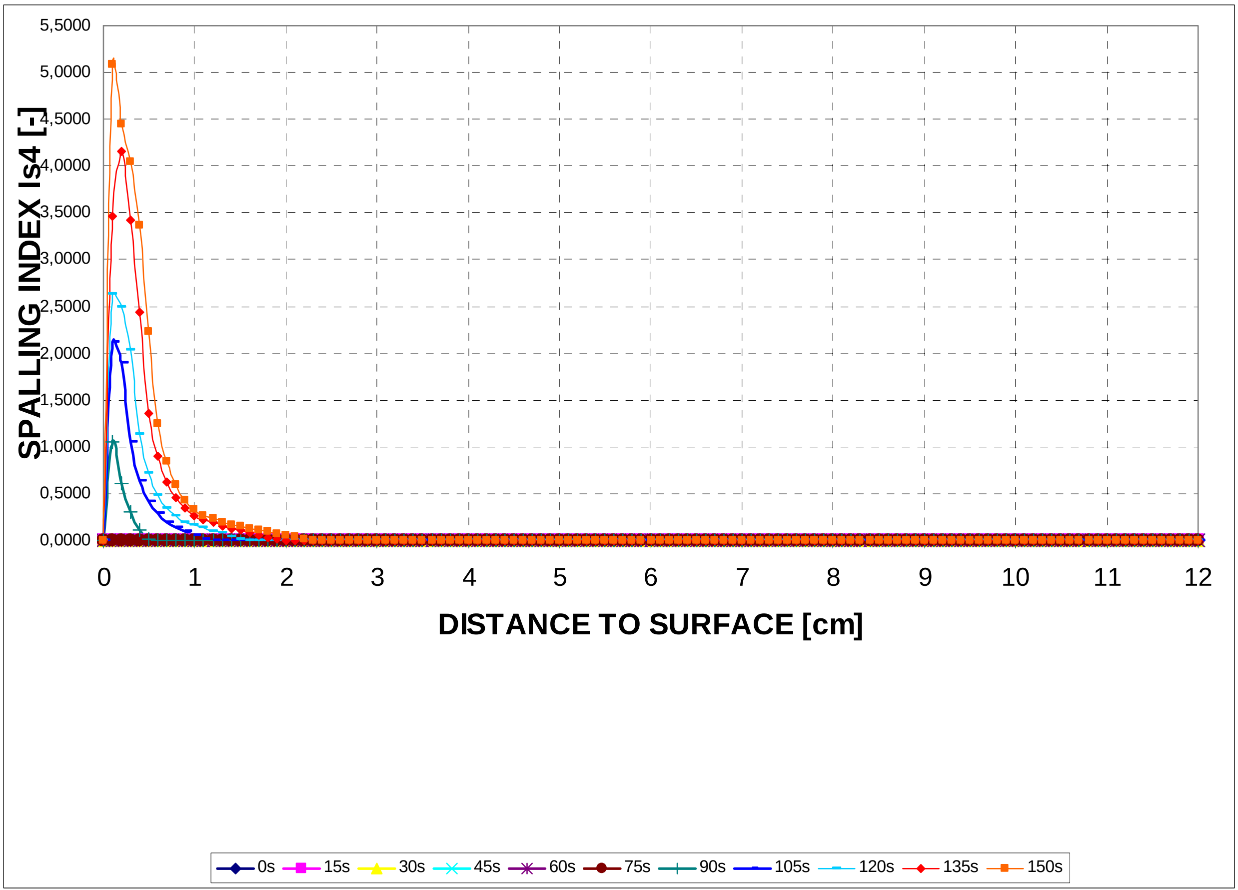

Figure 4A-85. *Spalling Index IS4 evolution for combination 85-TH12K019RH40PAR3C90*

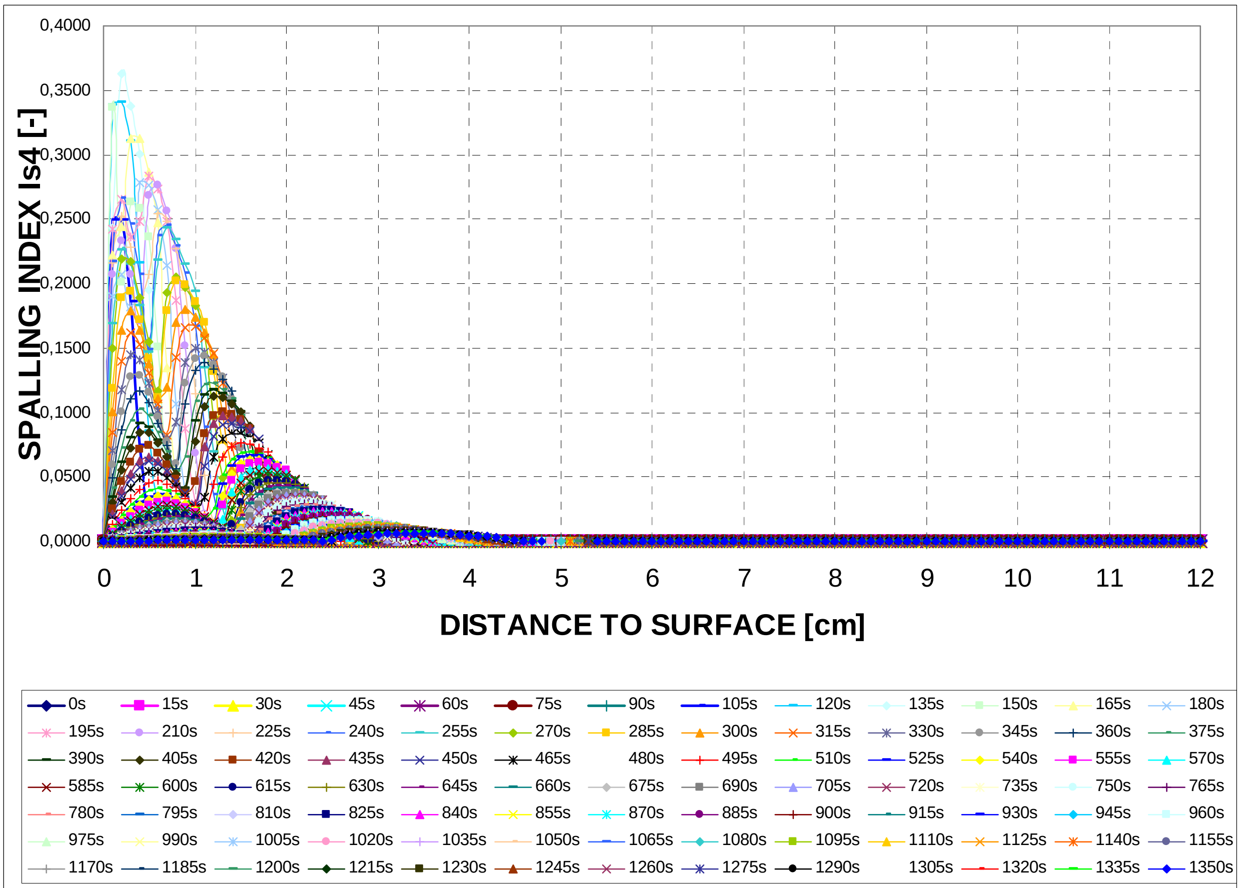

Figure 4A-86. *Spalling Index IS4 evolution for combination 86-TH12K017RH50PAR3C90*

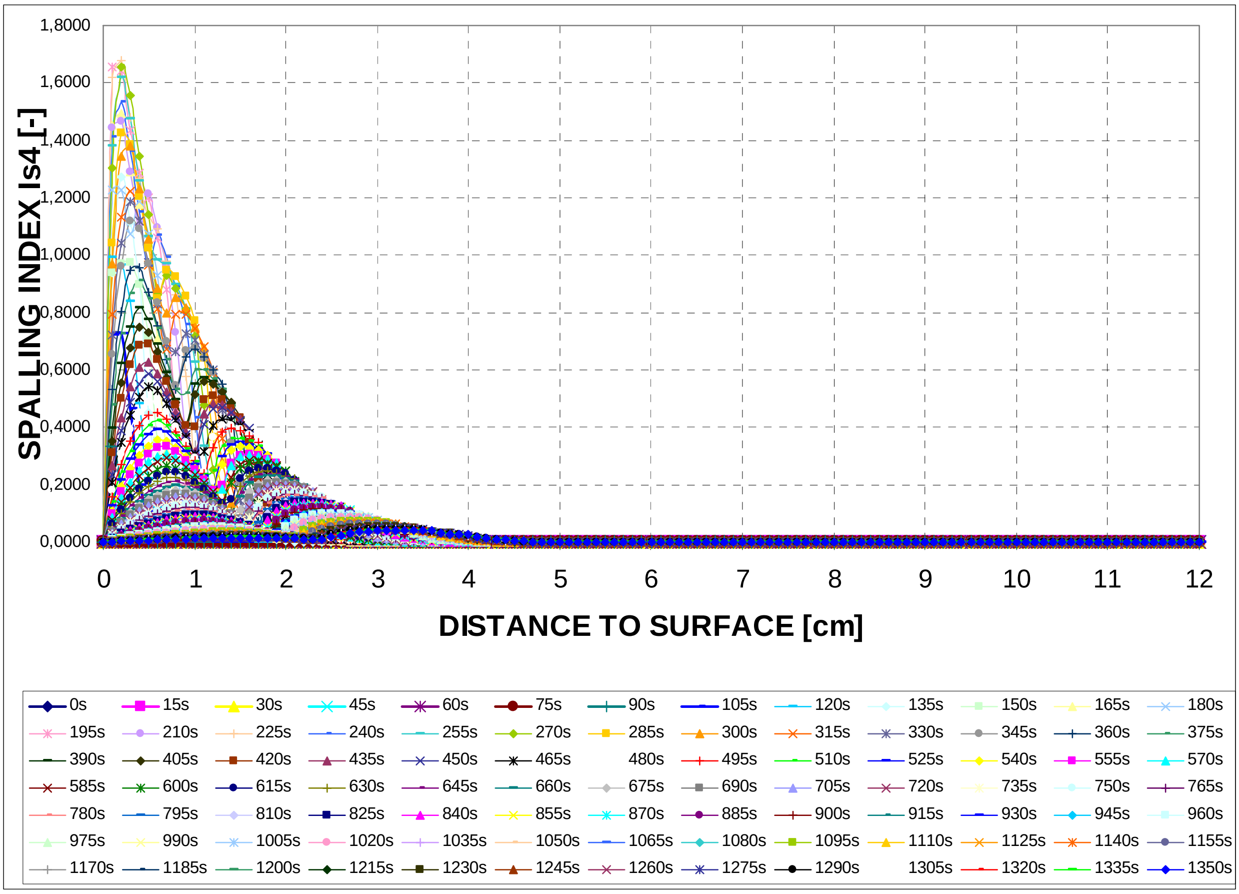

Figure 4A-87. *Spalling Index IS4 evolution for combination 87-TH12K018RH50PAR3C90*

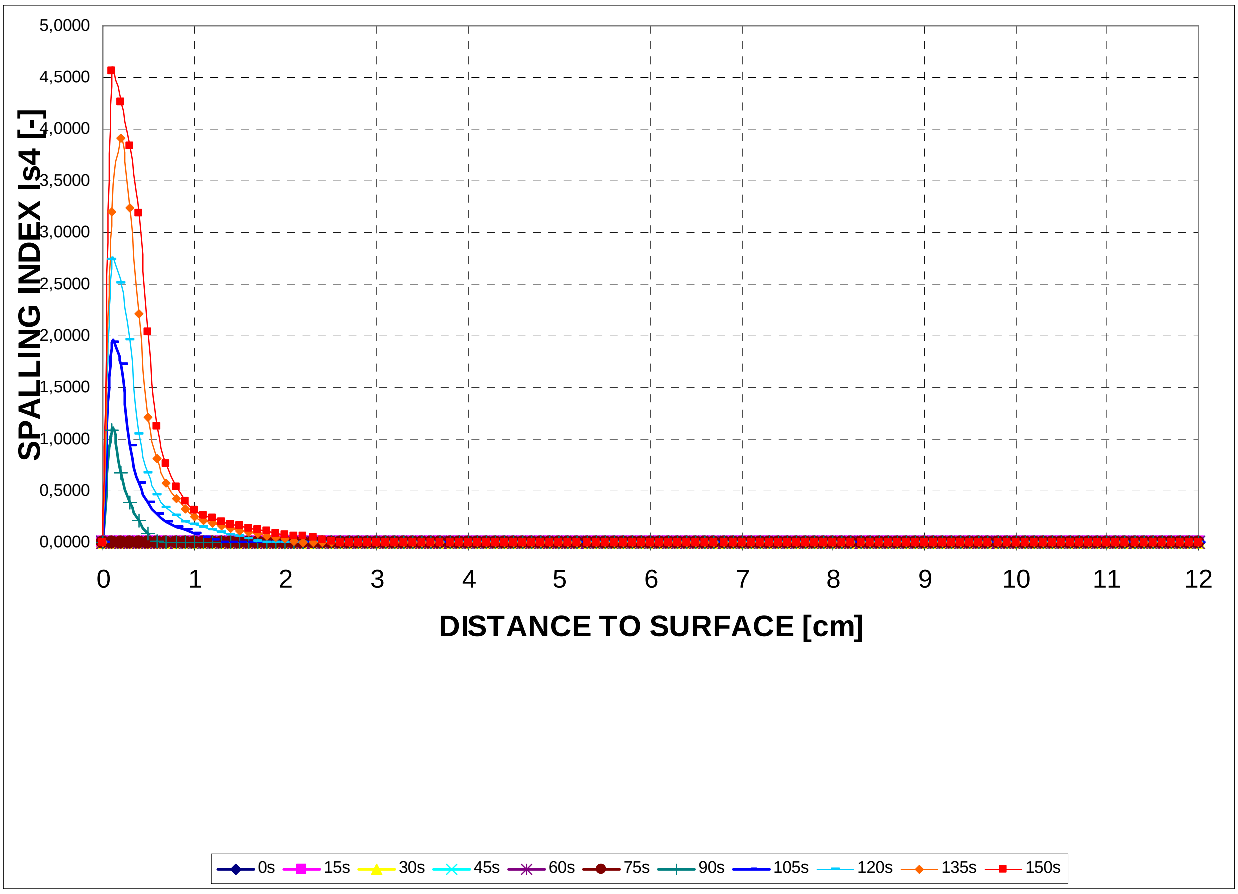

Figure 4A-88. *Spalling Index IS4 evolution for combination 88-TH12K019RH50PAR3C90*

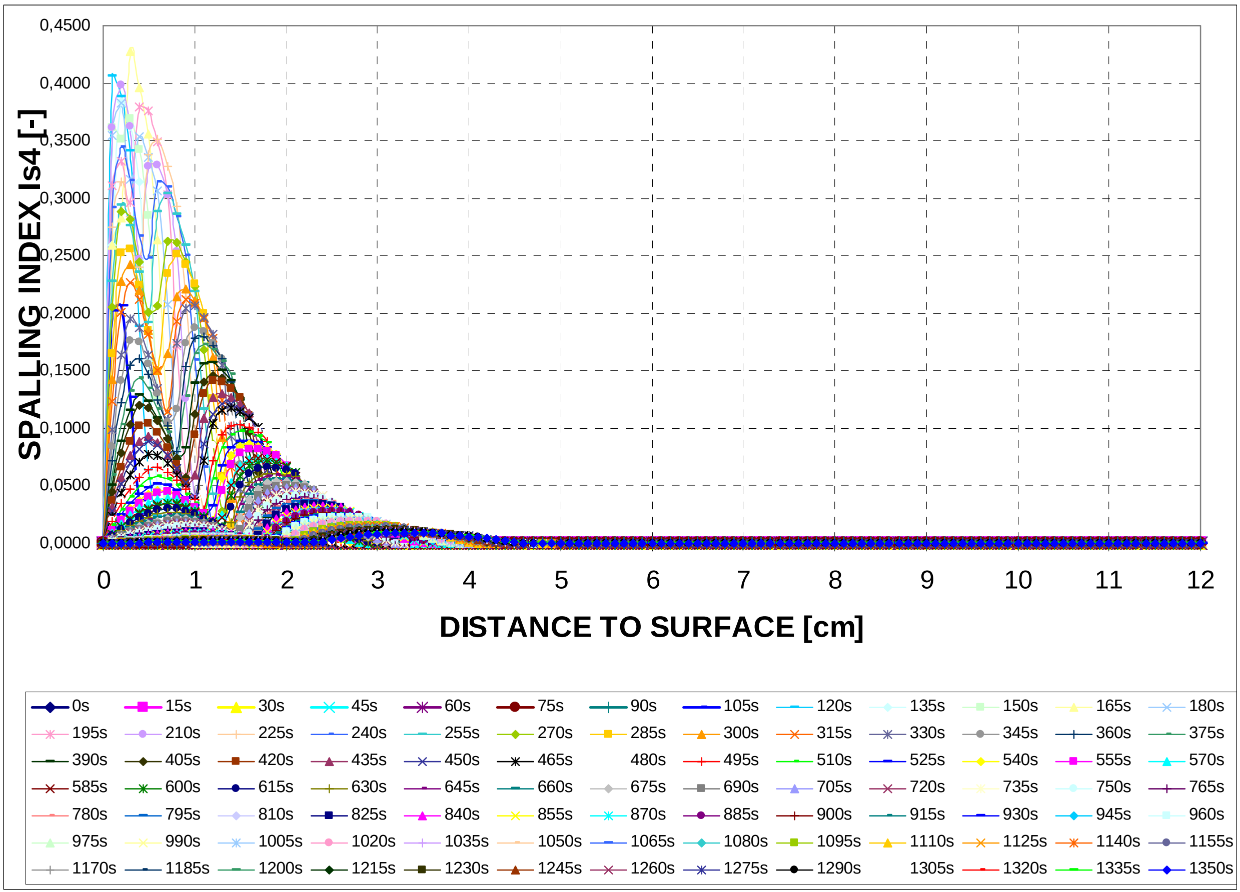

Figure 4A-89. *Spalling Index IS4 evolution for combination 89-TH12K017RH60PAR3C90*

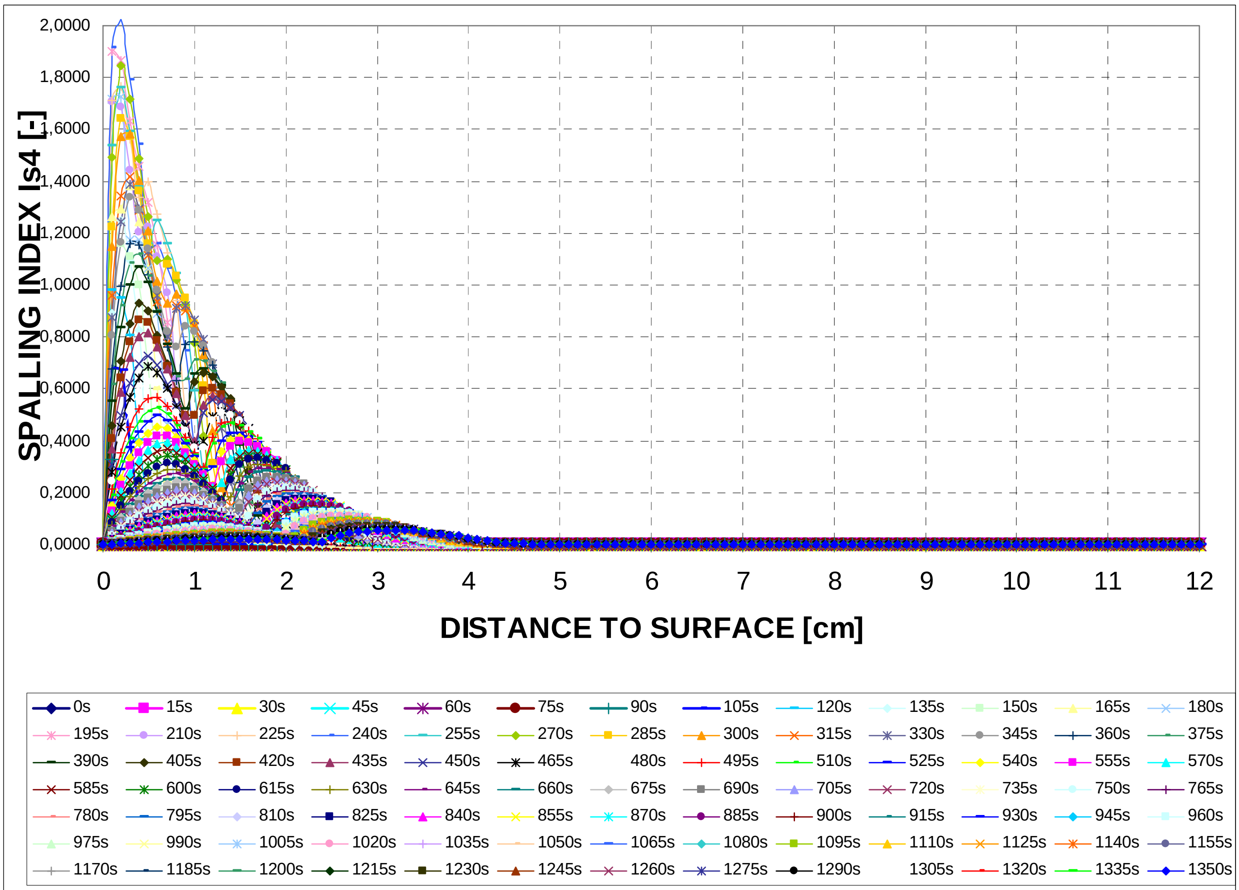

Figure 4A-90. *Spalling Index IS4 evolution for combination 90-TH12K018RH60PAR3C90*

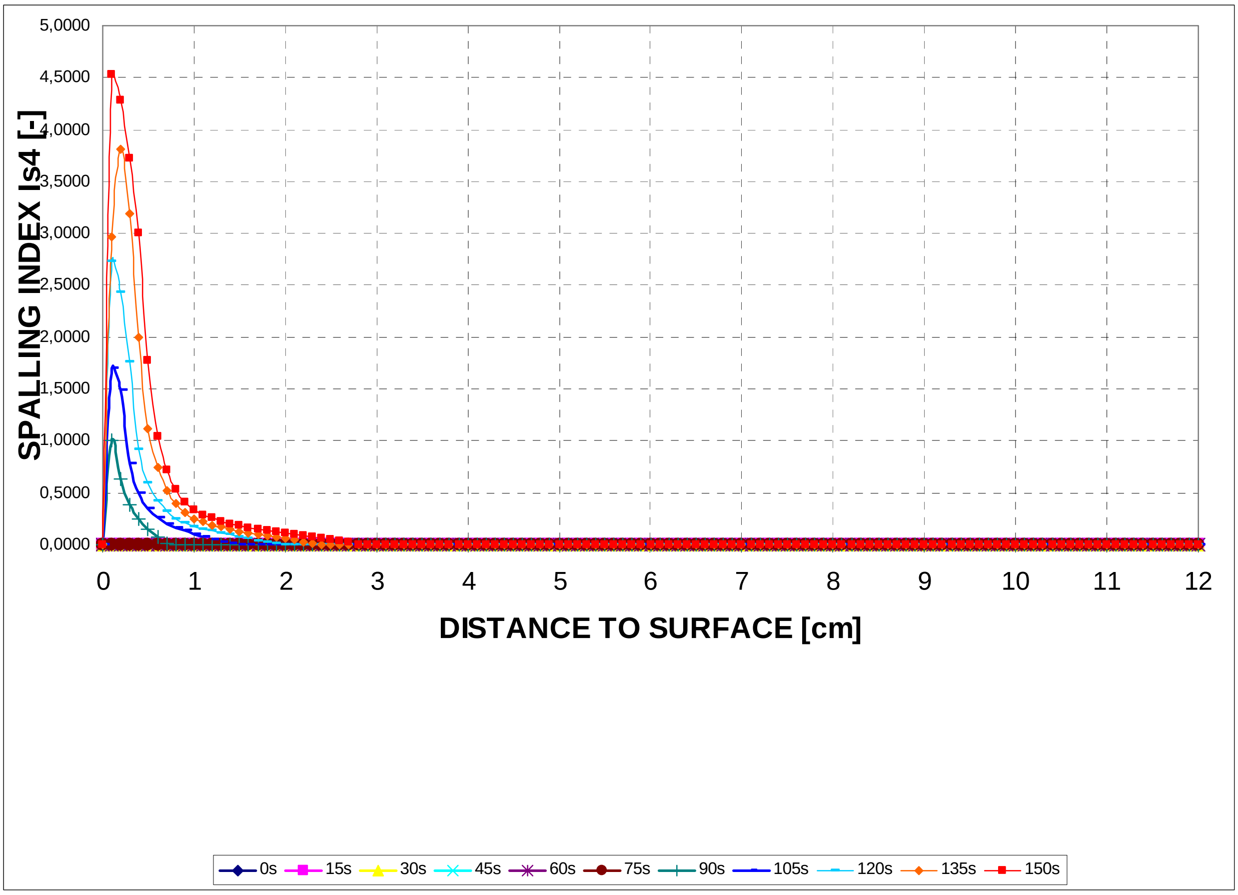

Figure 4A-91. *Spalling Index IS4 evolution for combination 91-TH12K019RH60PAR3C90*

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