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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

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PROGRAMA DE DOCTORADO DE ANÁLISIS ESTRUCTURAL

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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, $\bar{\sigma}_{th}$, and constrained elastic energy \bar{U} . The considered factors impeding thermal spalling are high average values of traction strength, \bar{f}_t , and specific fracture energy, \bar{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:

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

Herein,

- The values of $\bar{\sigma}_{th}$, d , \bar{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 \bar{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):

#	Combination	PC1 (RH) [%]			PC2 (K) [m ²]			PC3 (TH) [cm]			PC4 (Heating curve)			PC5 (Mat)	
		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

<i>(continued)</i>		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
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)

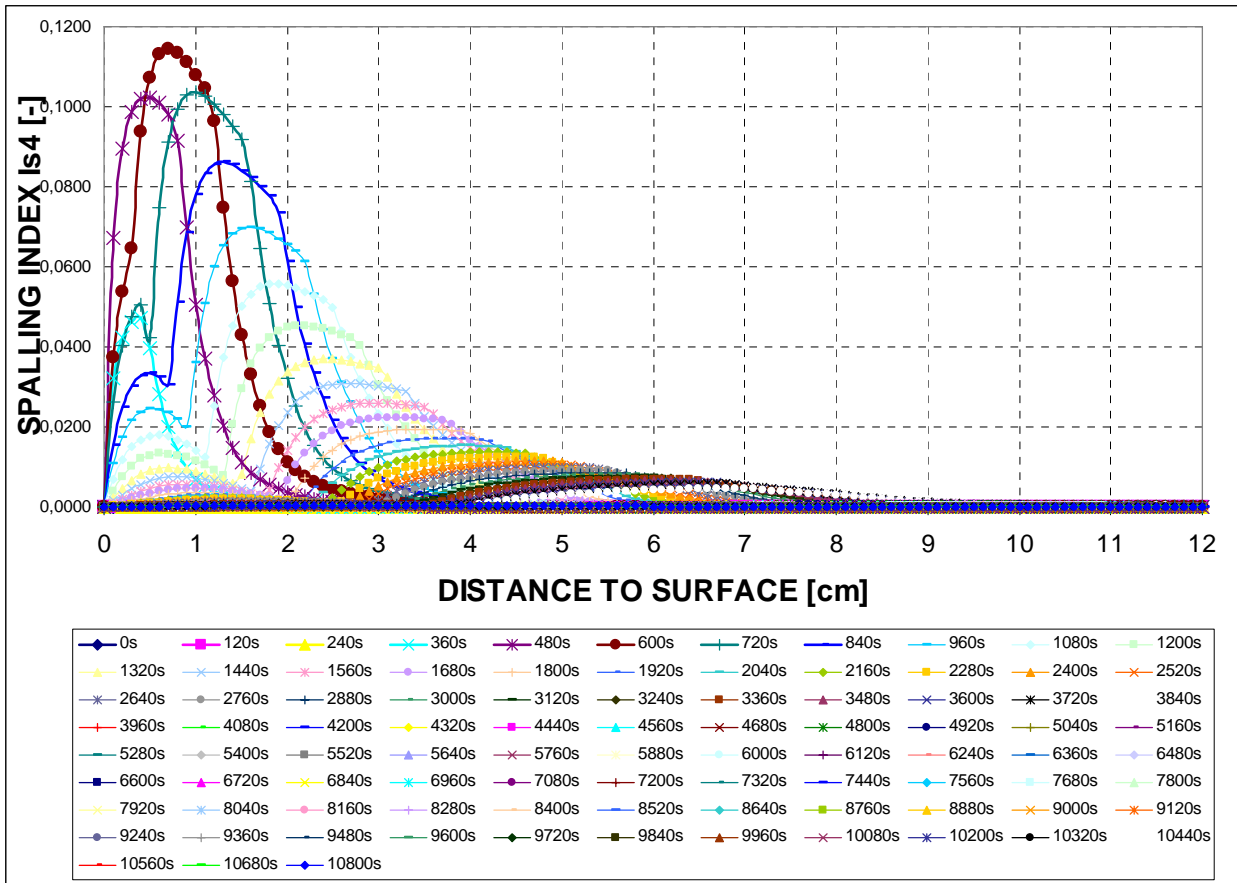


Figure 4A-1. Spalling Index IS_4 evolution for combination 1-TH12K017RH40PAR1C60

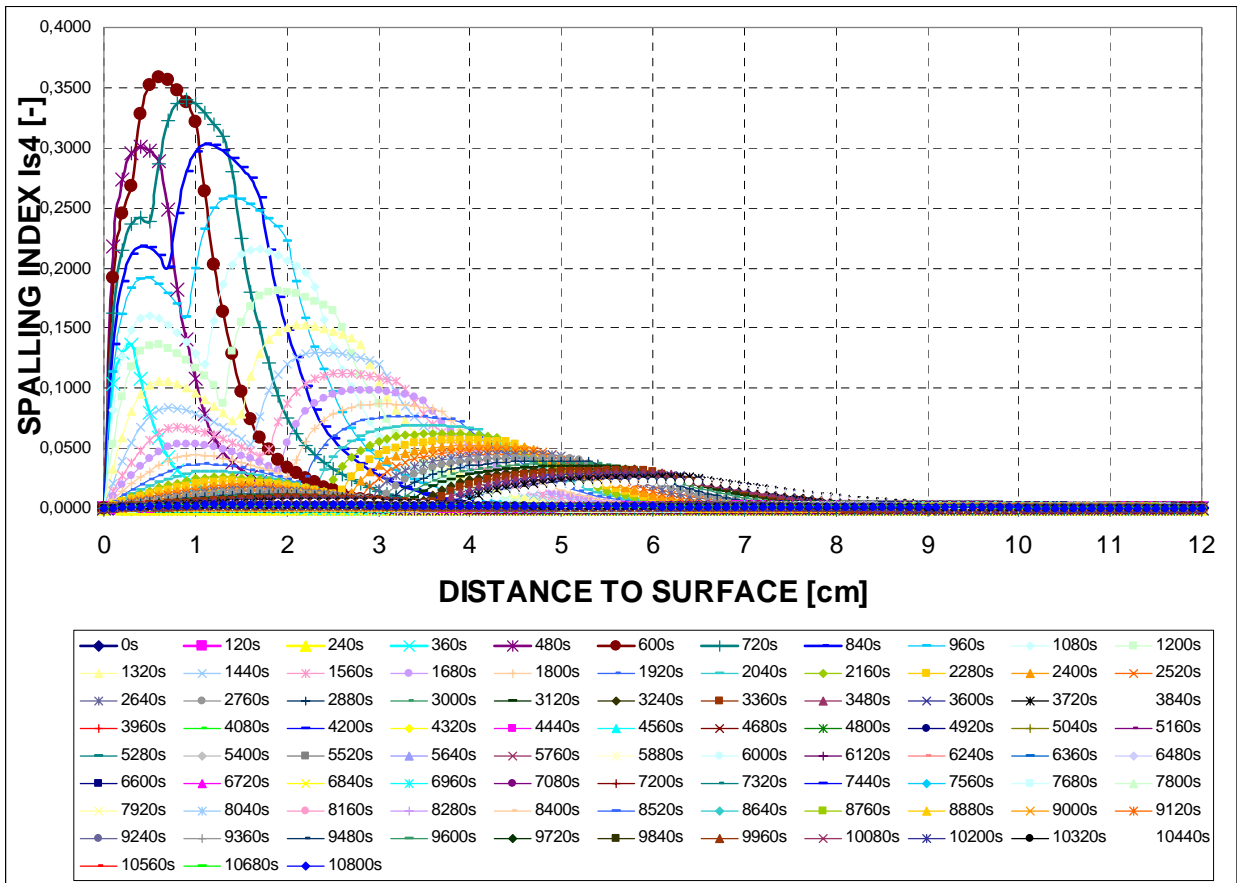


Figure 4A-2. Spalling Index IS_4 evolution for combination 2-TH12K018RH40PAR1C60

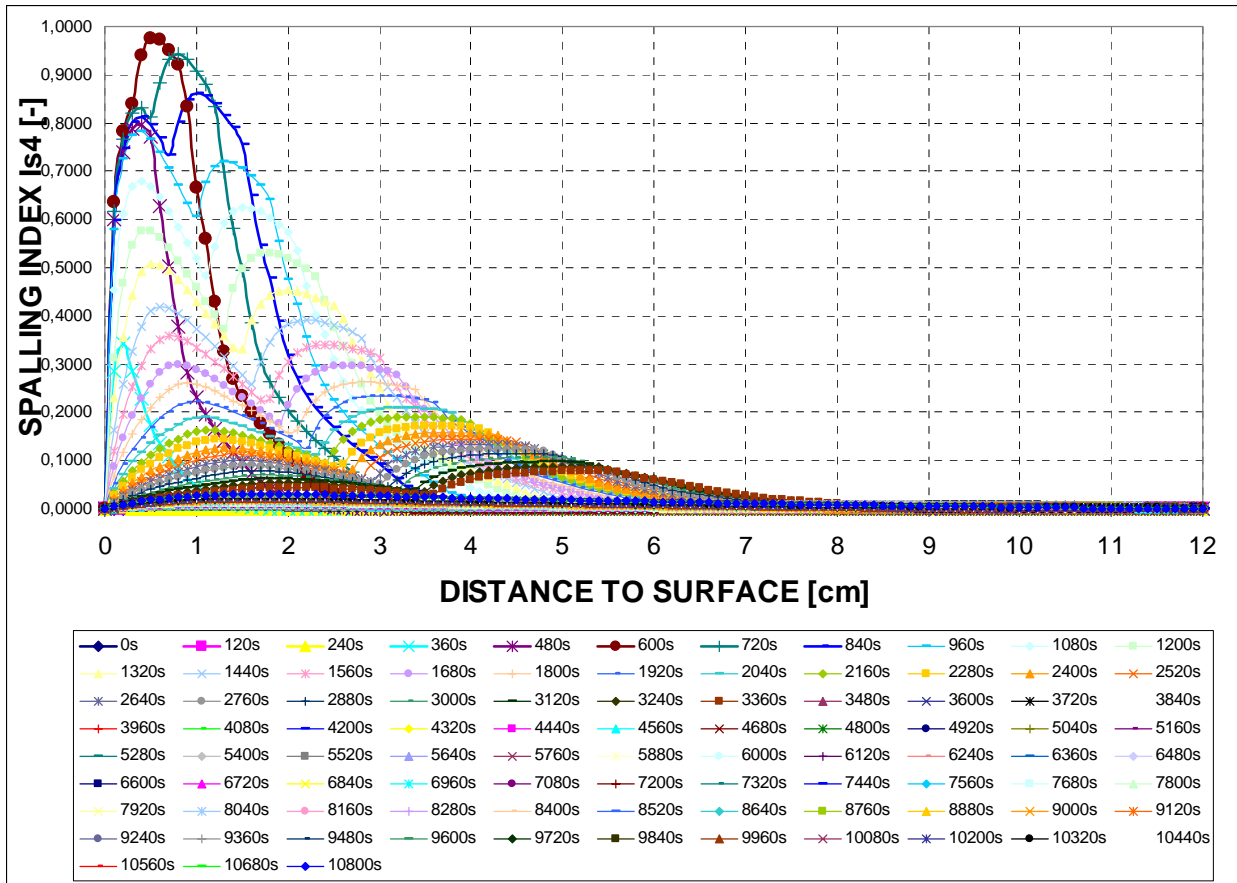


Figure 4A-3. Spalling Index IS4 evolution for combination 3-TH12K019RH40PAR1C60

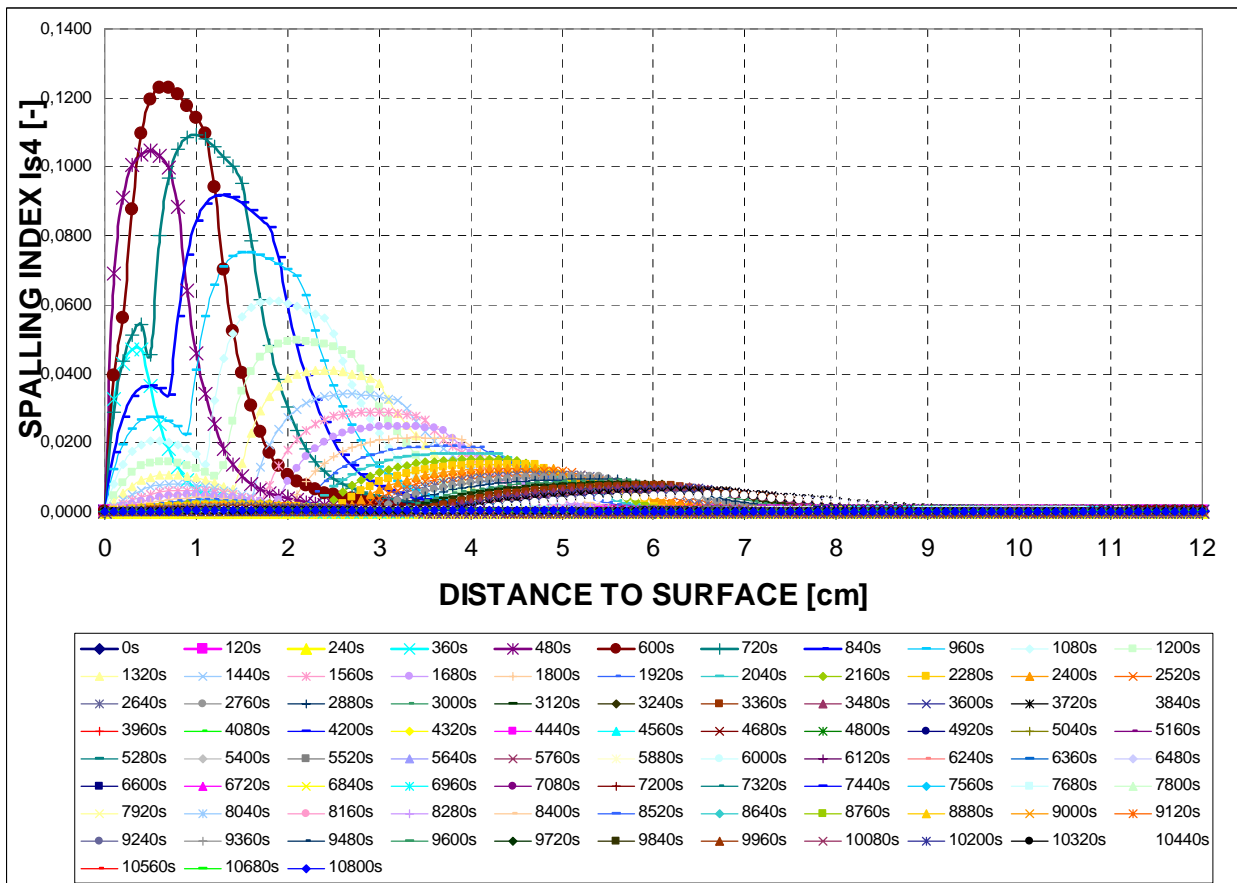


Figure 4A-4. Spalling Index IS4 evolution for combination 4-TH12K017RH50PAR1C60

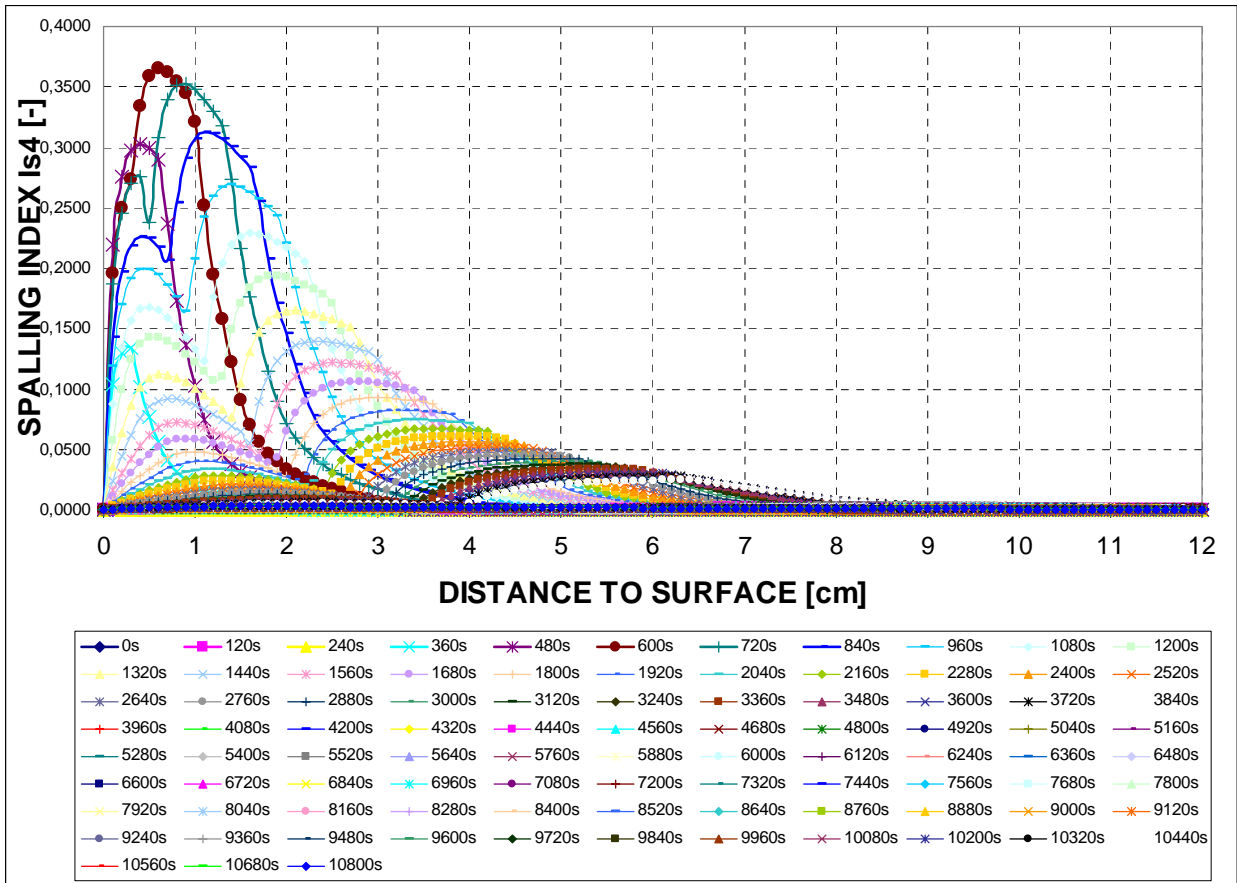


Figure 4A-5. Spalling Index IS4 evolution for combination 5-TH12K018RH50PAR1C60

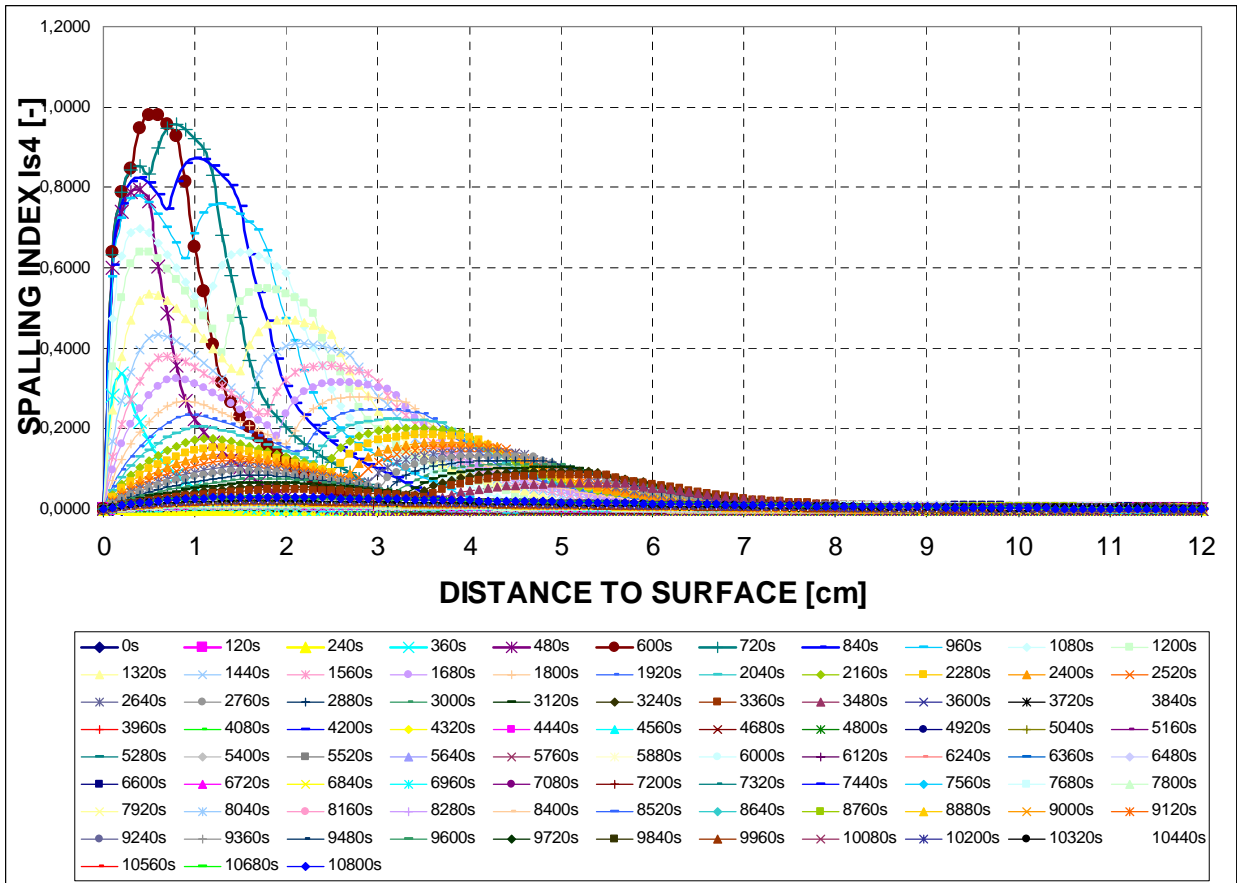


Figure 4A-6. Spalling Index IS4 evolution for combination 6-TH12K019RH50PAR1C60

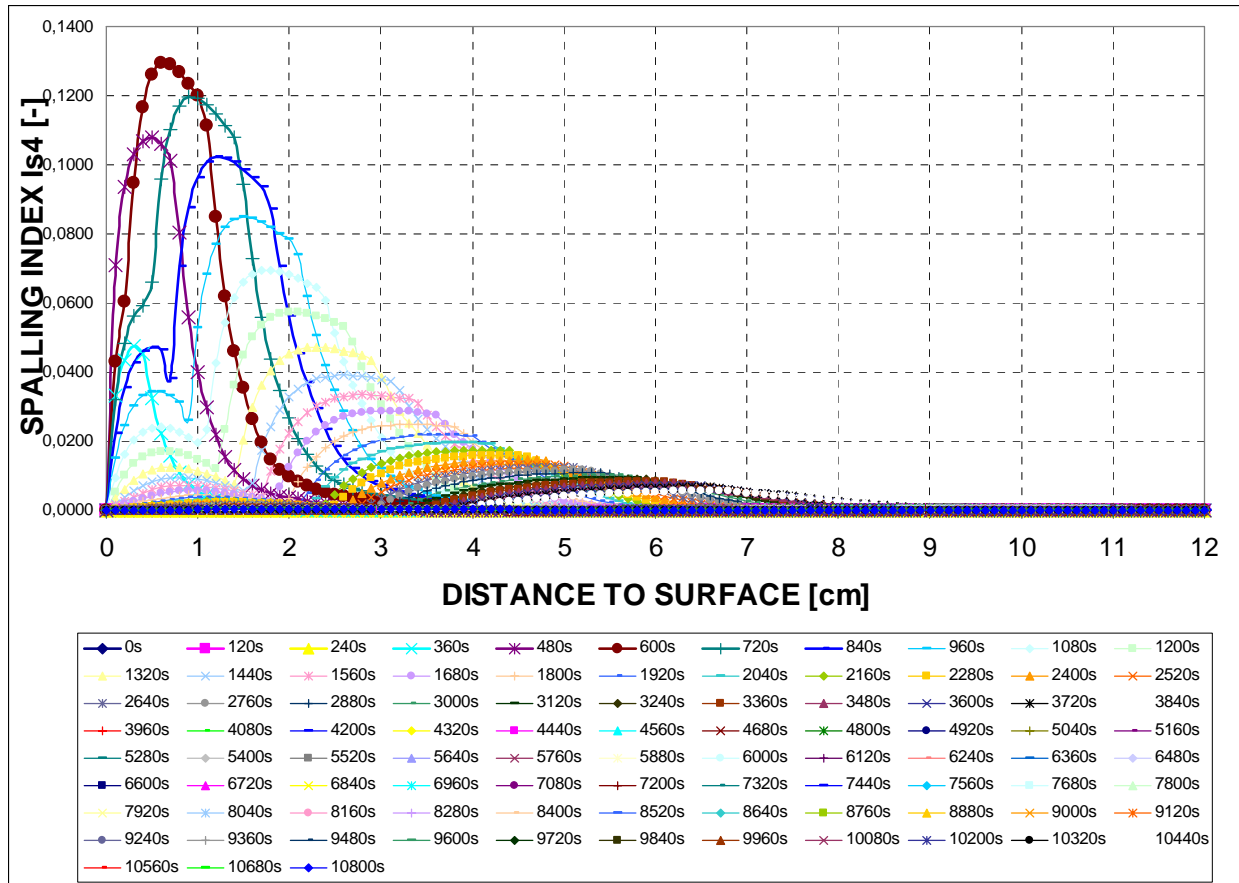


Figure 4A-7. Spalling Index IS_4 evolution for combination 7-TH12K017RH60PAR1C60

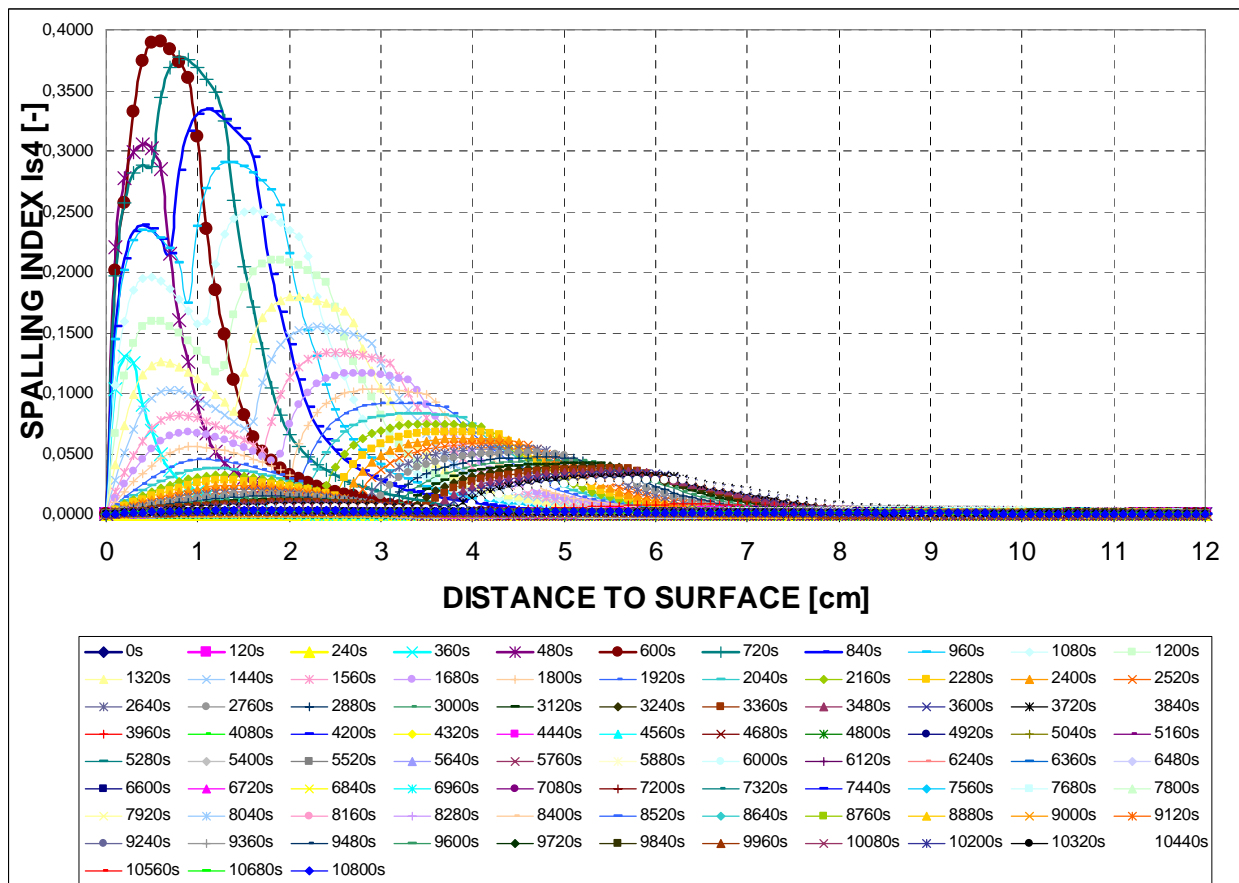


Figure 4A-8. Spalling Index IS_4 evolution for combination 8-TH12K018RH60PAR1C60

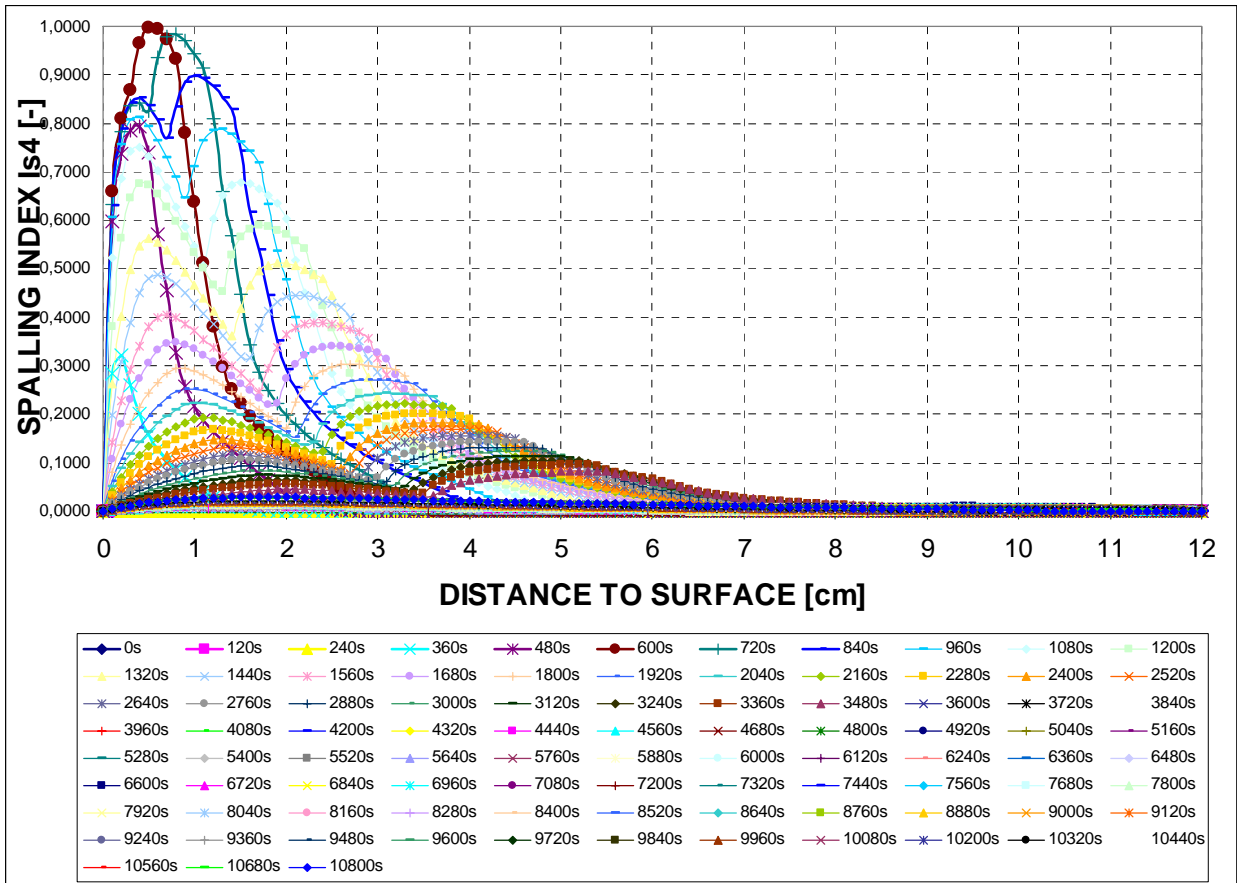


Figure 4A-9. Spalling Index IS4 evolution for combination 9-TH12K019RH60PAR1C60

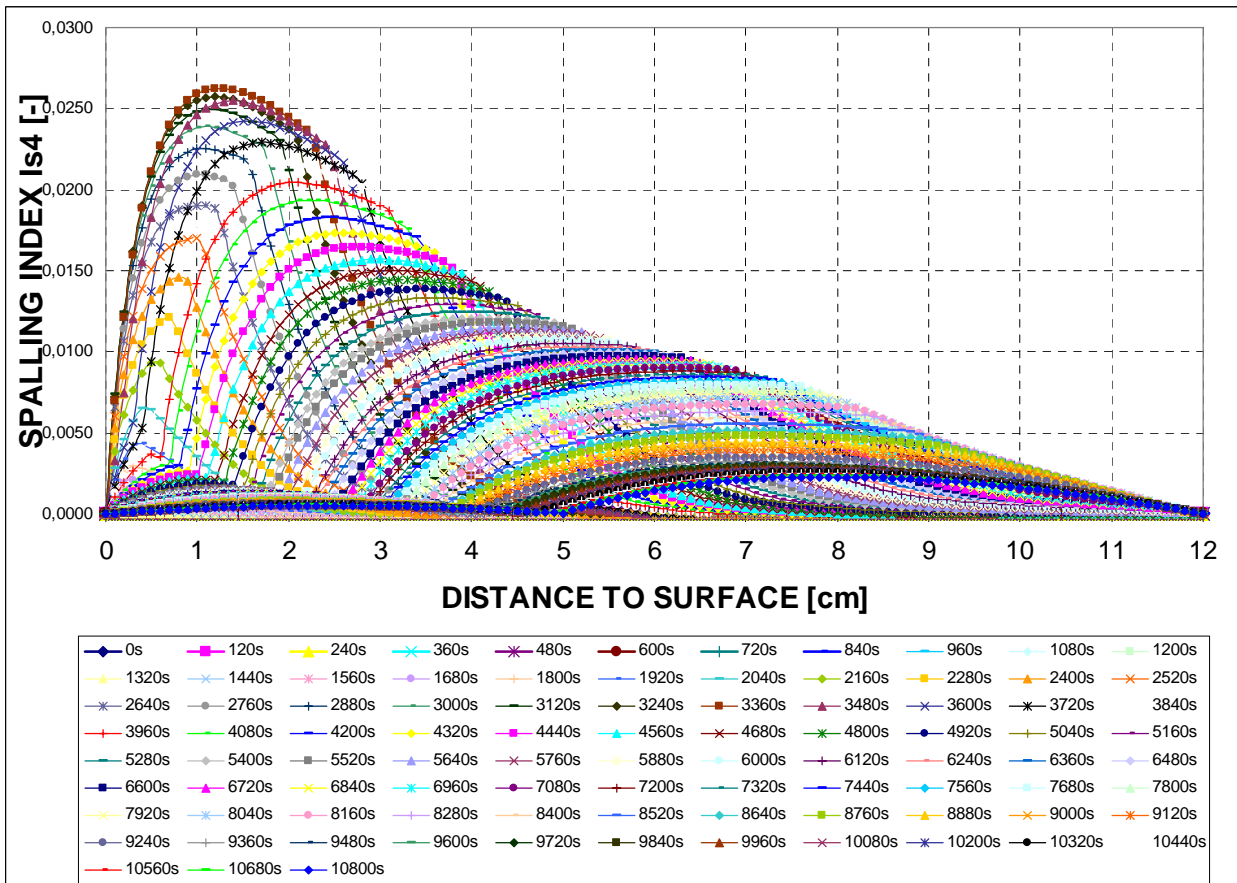


Figure 4A-10. Spalling Index IS4 evolution for combination 10-TH12K017RH40PAR2C60

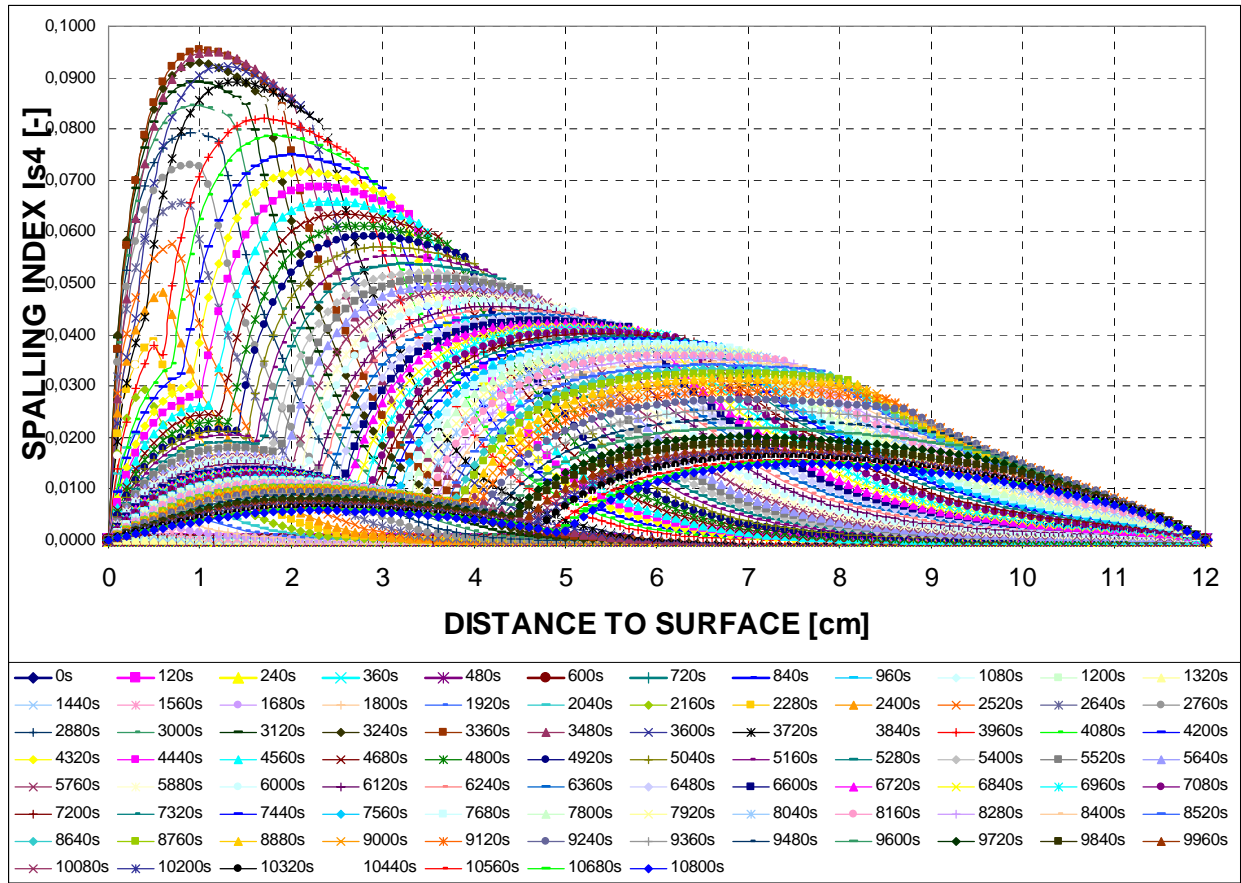


Figure 4A-11. Spalling Index IS_4 evolution for combination 11-TH12K018RH40PAR2C60

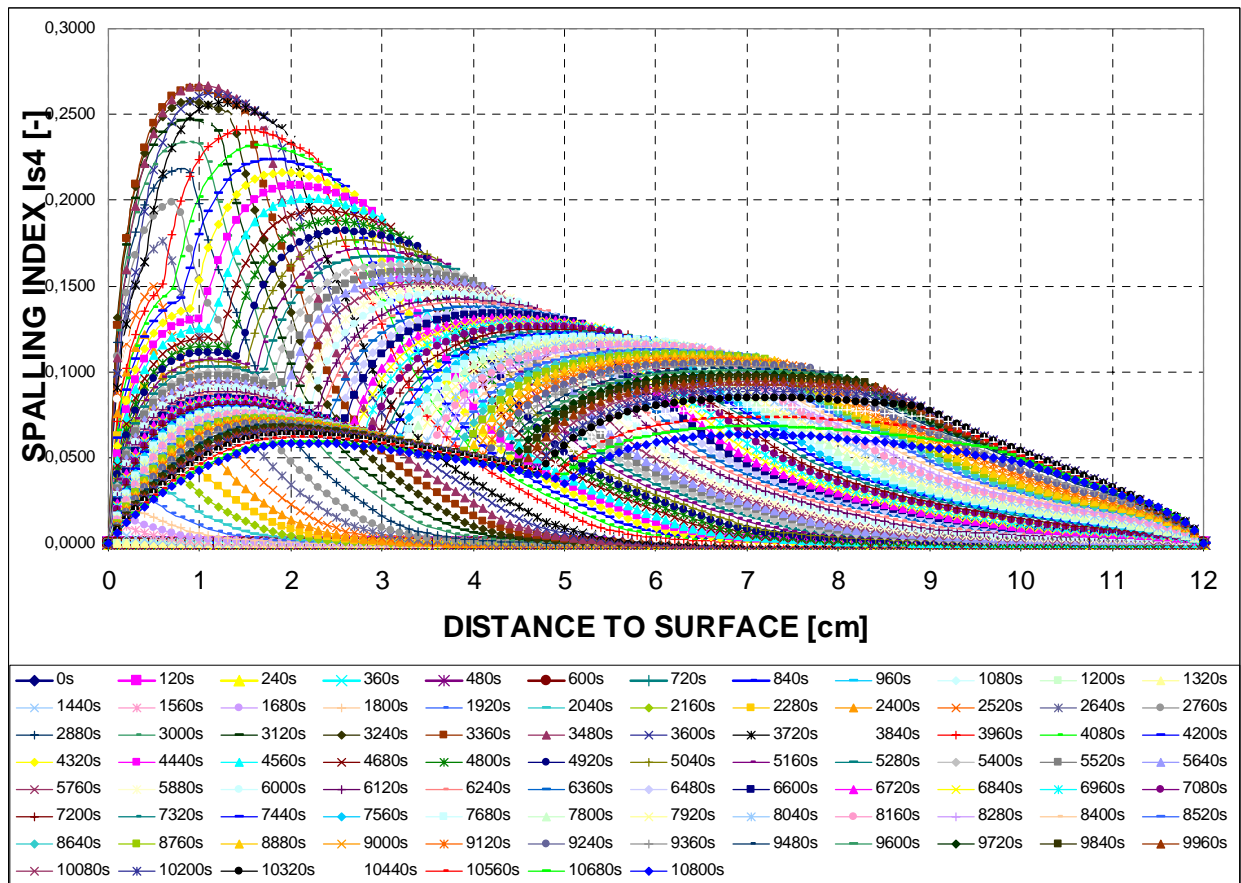


Figure 4A-12. Spalling Index IS_4 evolution for combination 12-TH12K019RH40PAR2C60

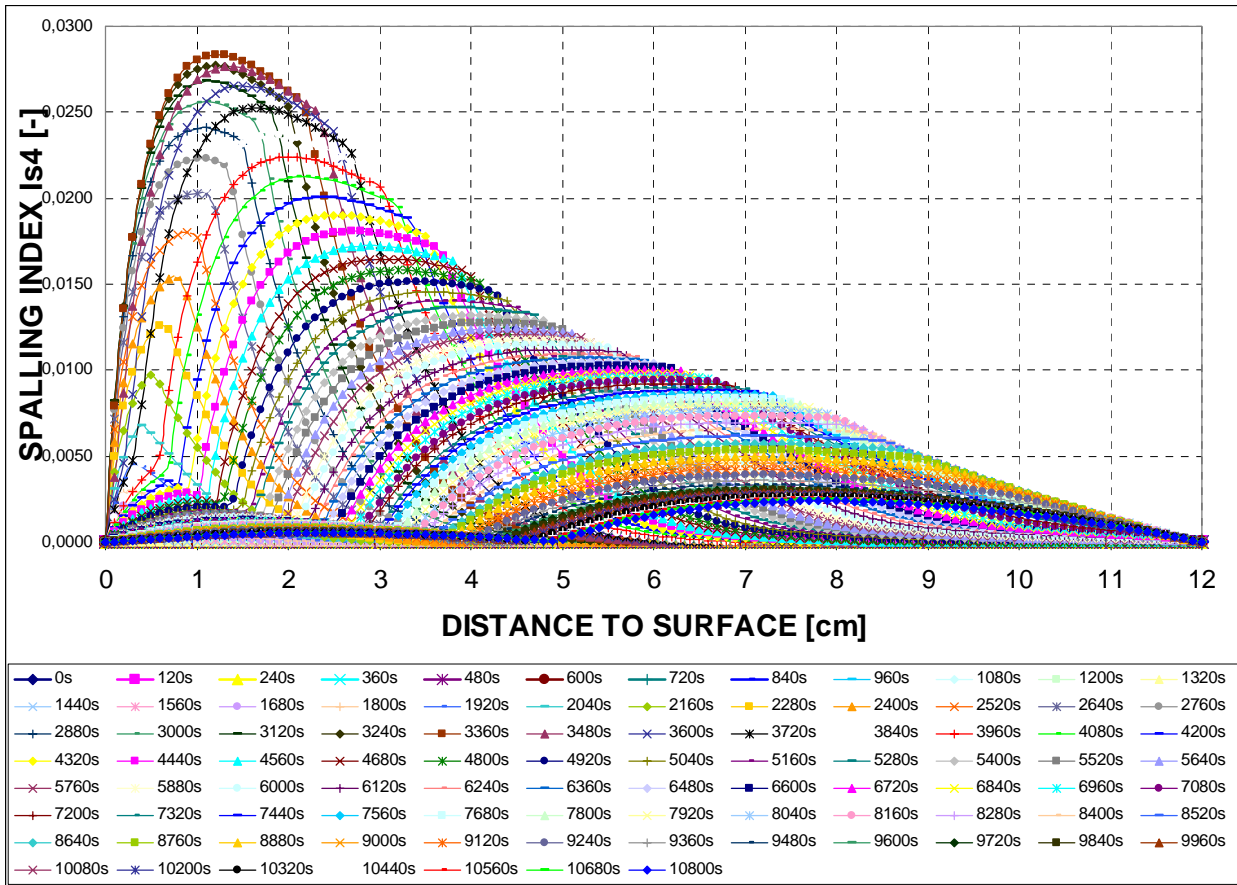


Figure 4A-13. Spalling Index IS4 evolution for combination 13-TH12K017RH50PAR2C60

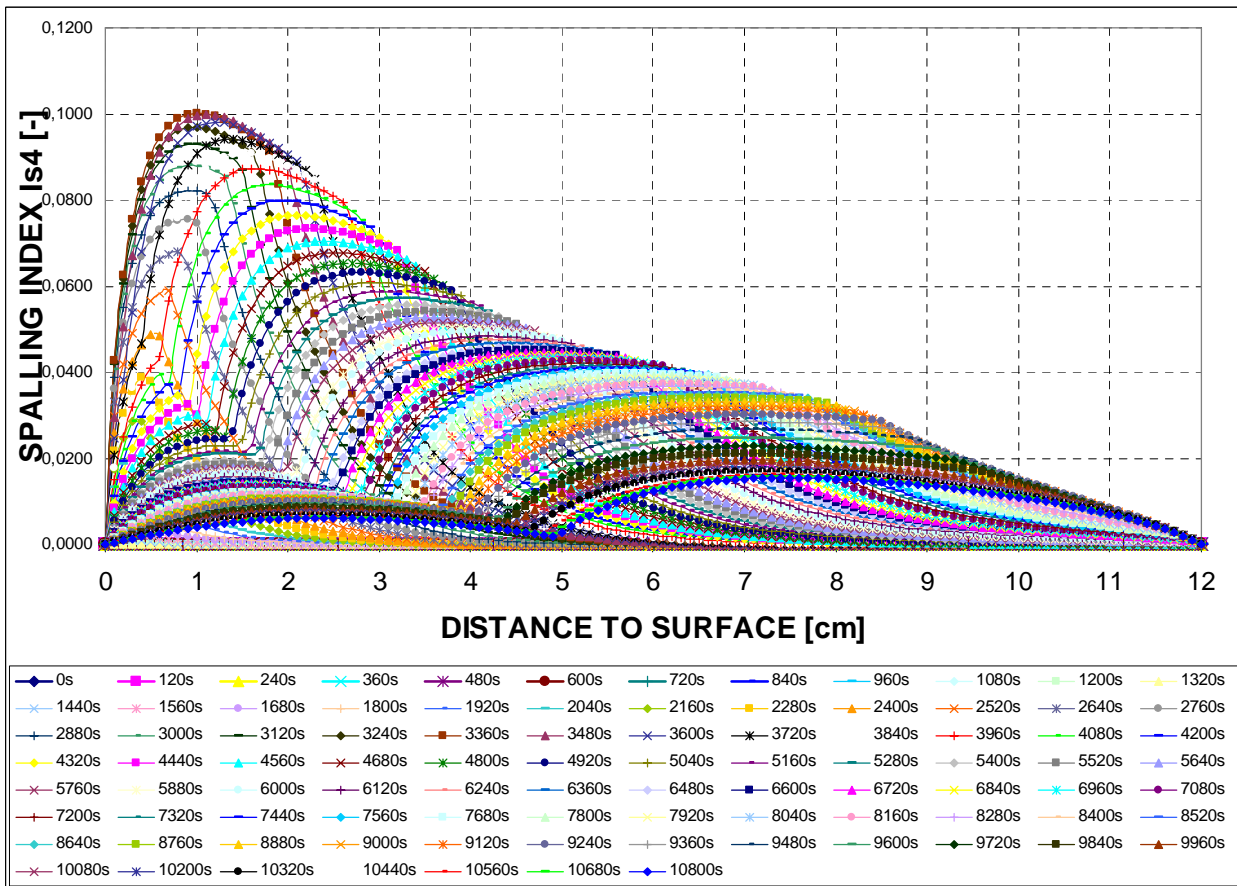


Figure 4A-14. Spalling Index IS4 evolution for combination 14-TH12K018RH50PAR2C60

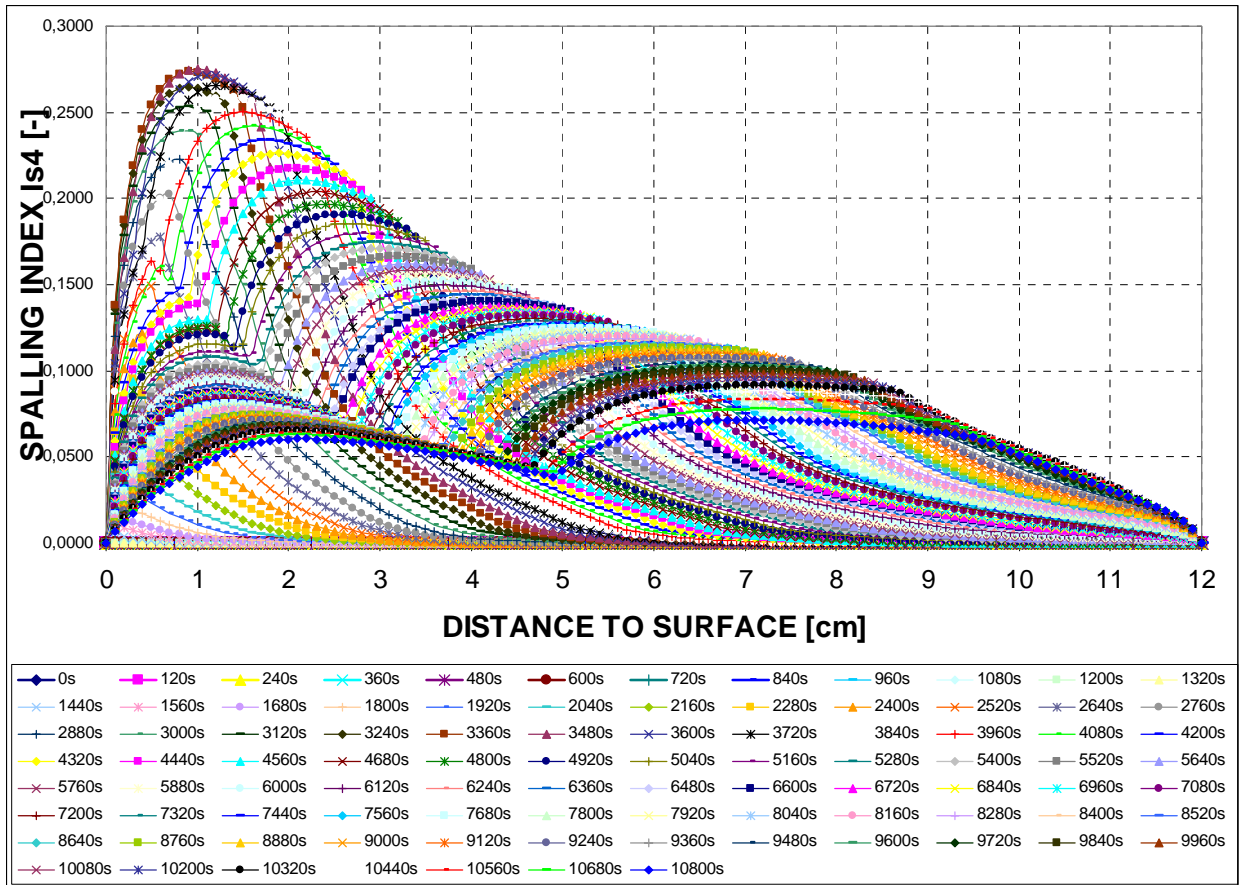


Figure 4A-15. Spalling Index IS4 evolution for combination 15-TH12K019RH50PAR2C60

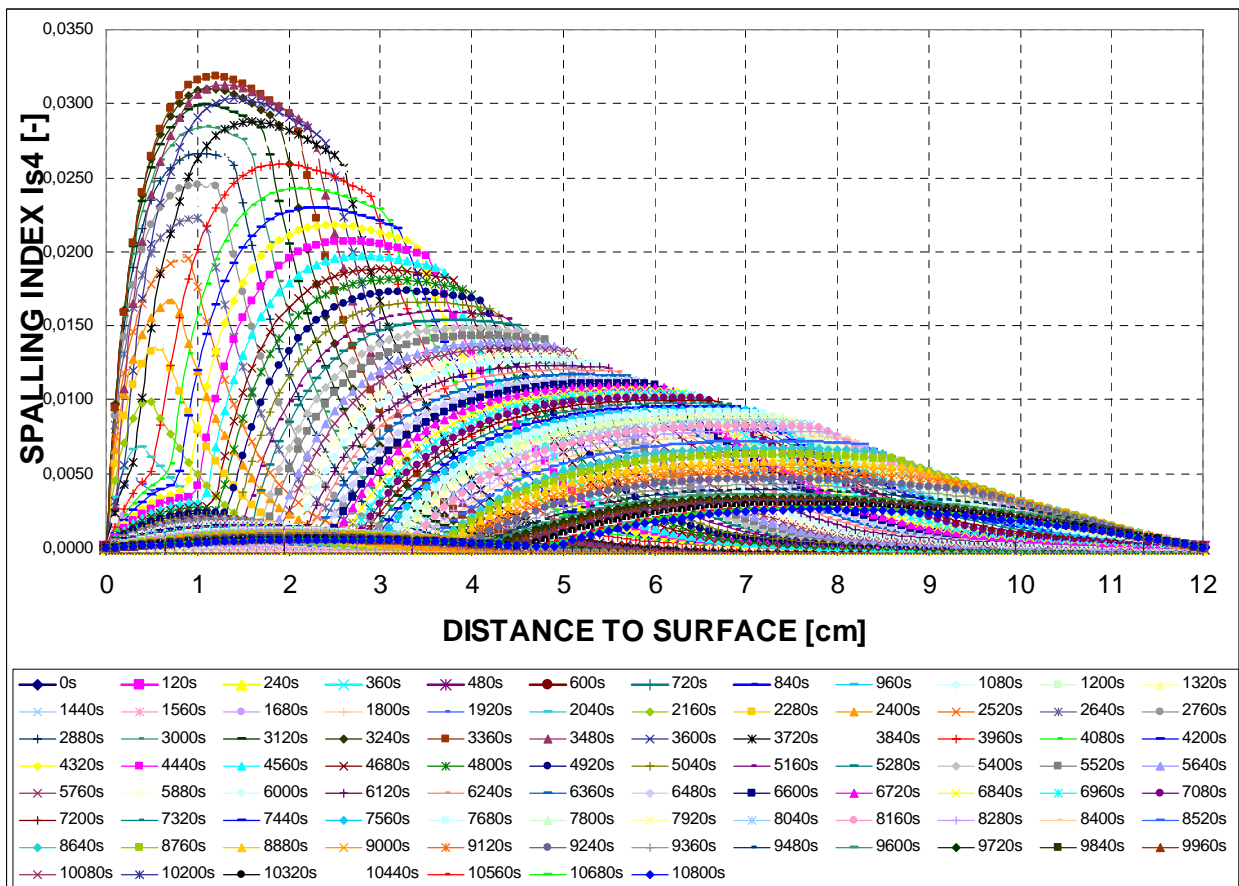


Figure 4A-16. Spalling Index IS4 evolution for combination 16-TH12K017RH60PAR2C60

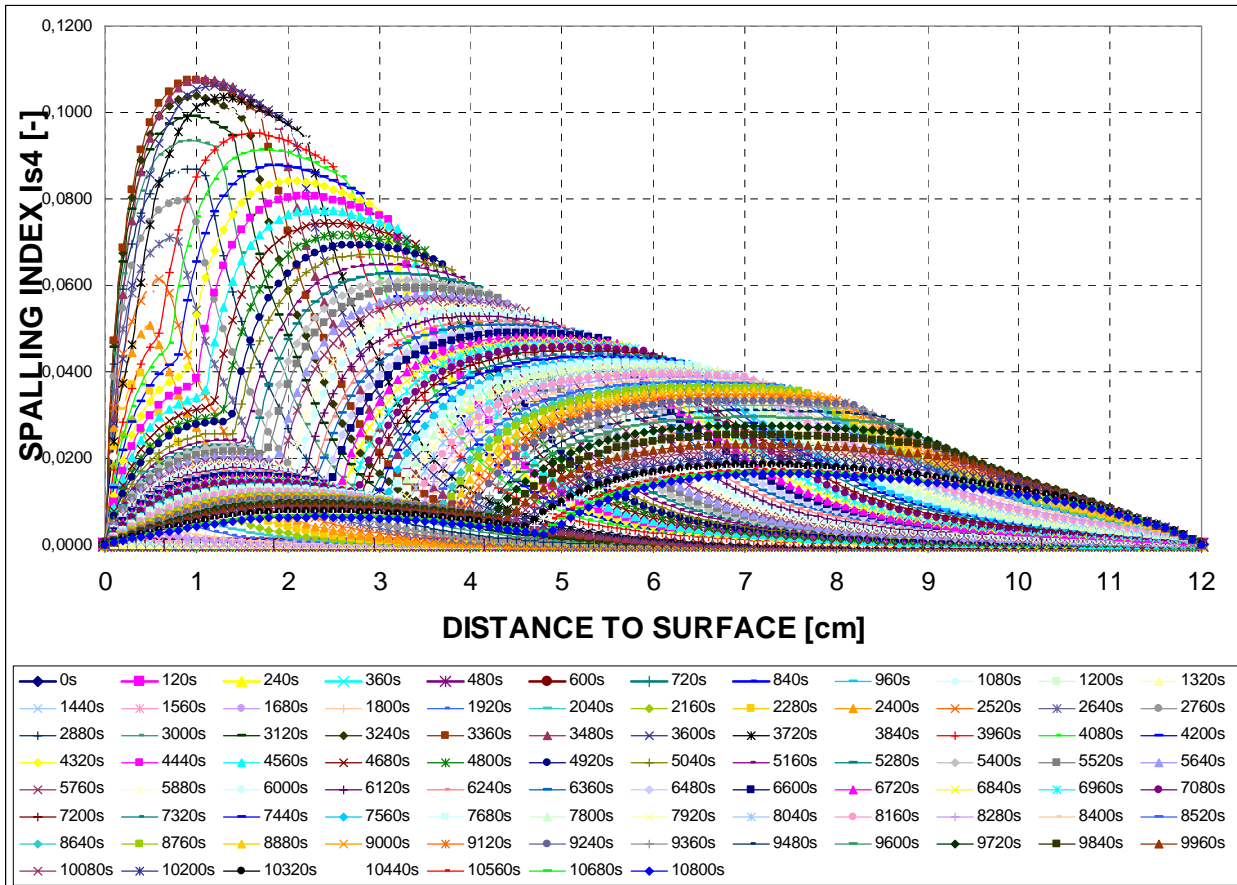


Figure 4A-17. Spalling Index IS4 evolution for combination 17-TH12K018RH60PAR2C60

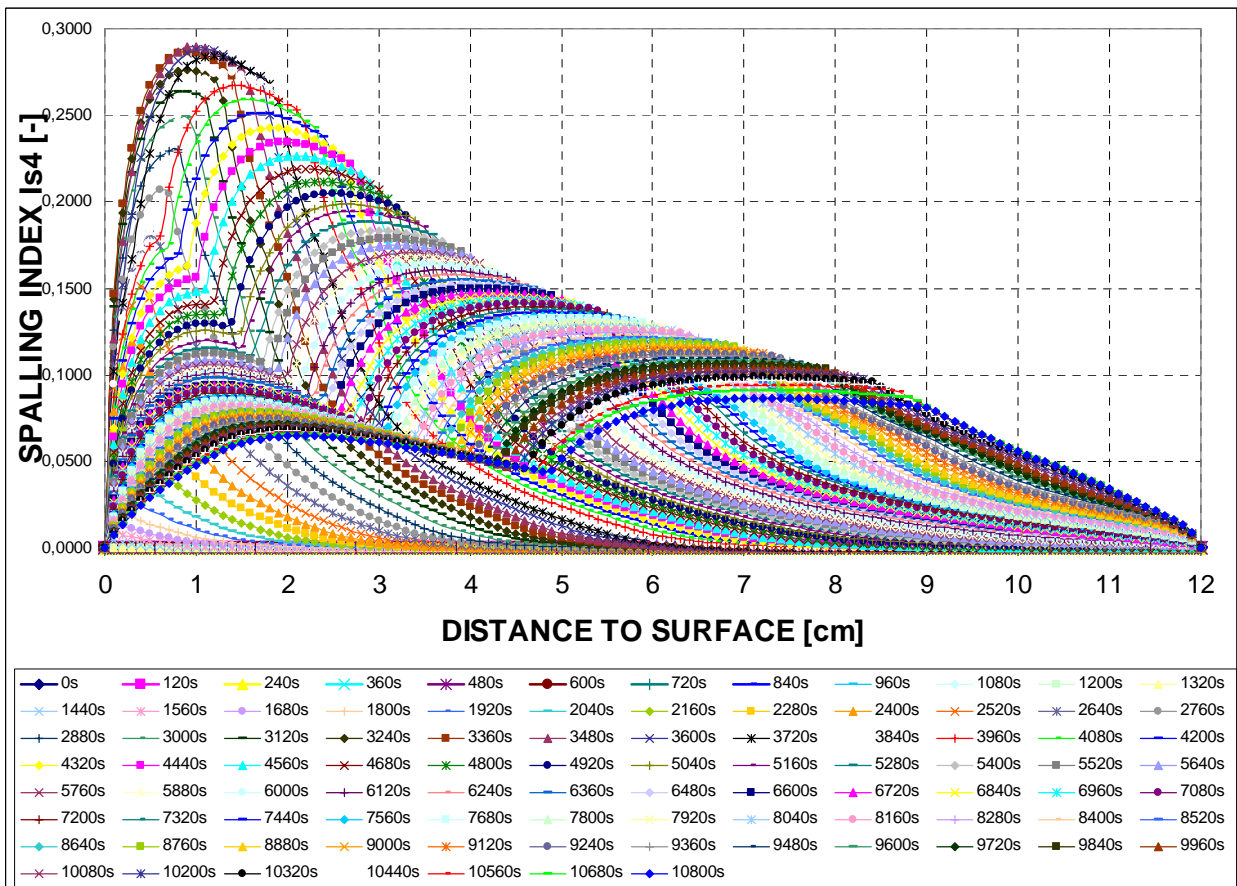


Figure 4A-18. Spalling Index IS4 evolution for combination 18-TH12K019RH60PAR2C60

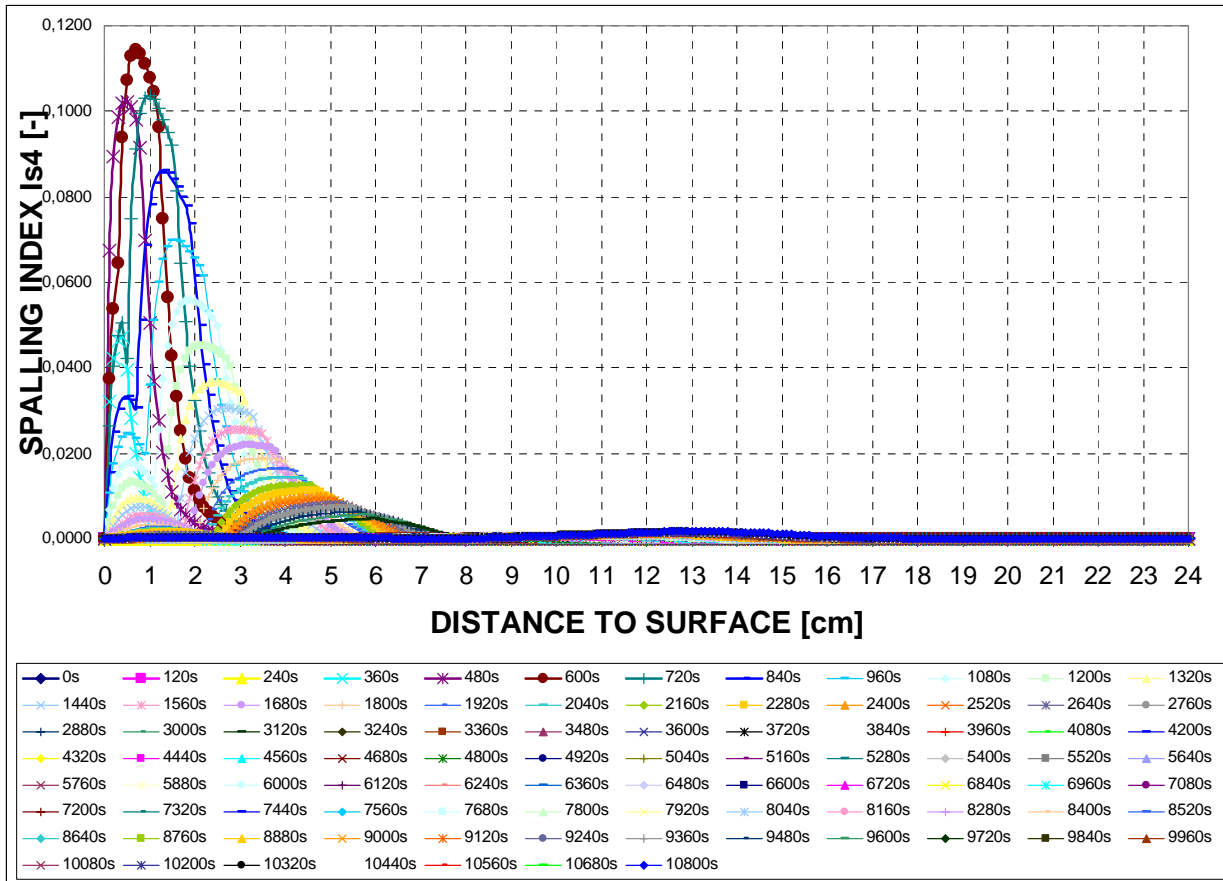


Figure 4A-19. Spalling Index IS_4 evolution for combination 19-TH24K017RH40PAR1C60

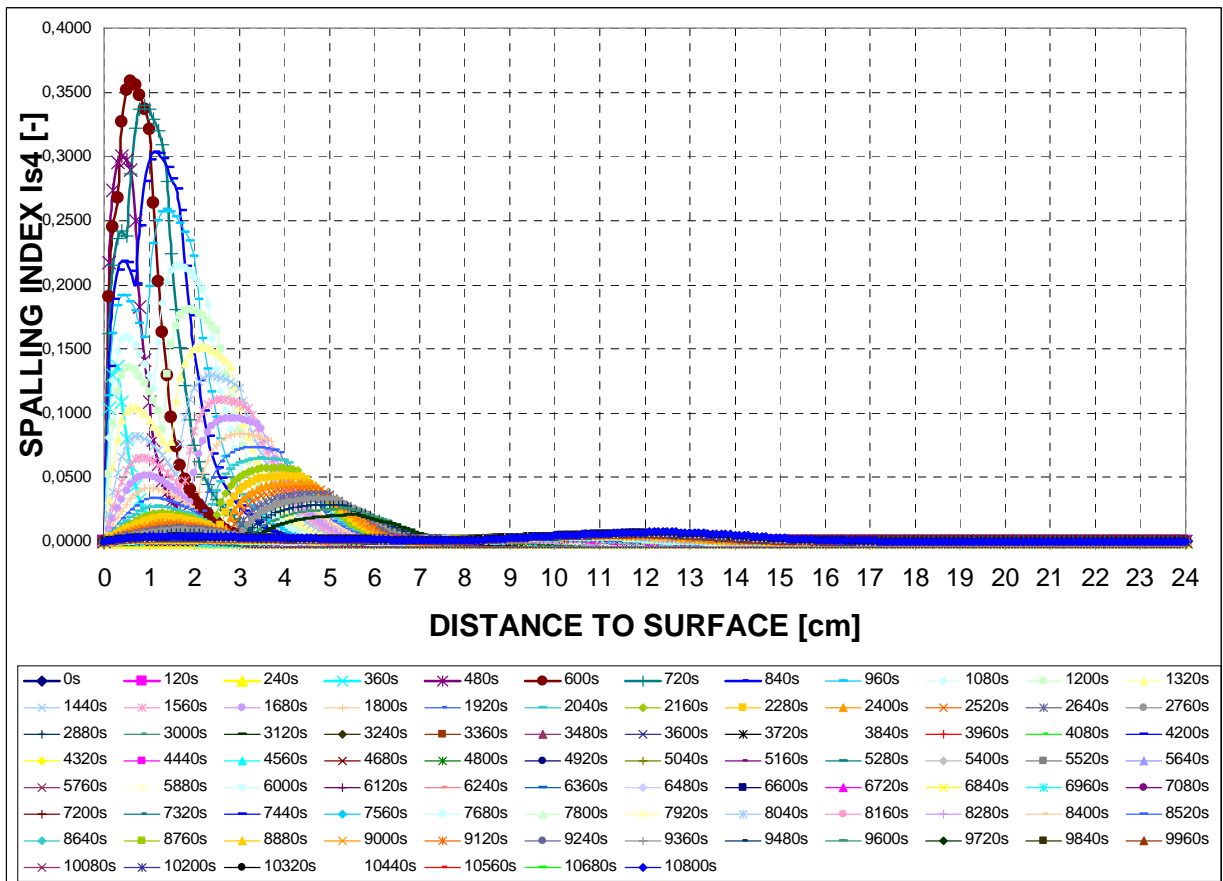


Figure 4A-20. Spalling Index IS_4 evolution for combination 20-TH24K018RH40PAR1C60

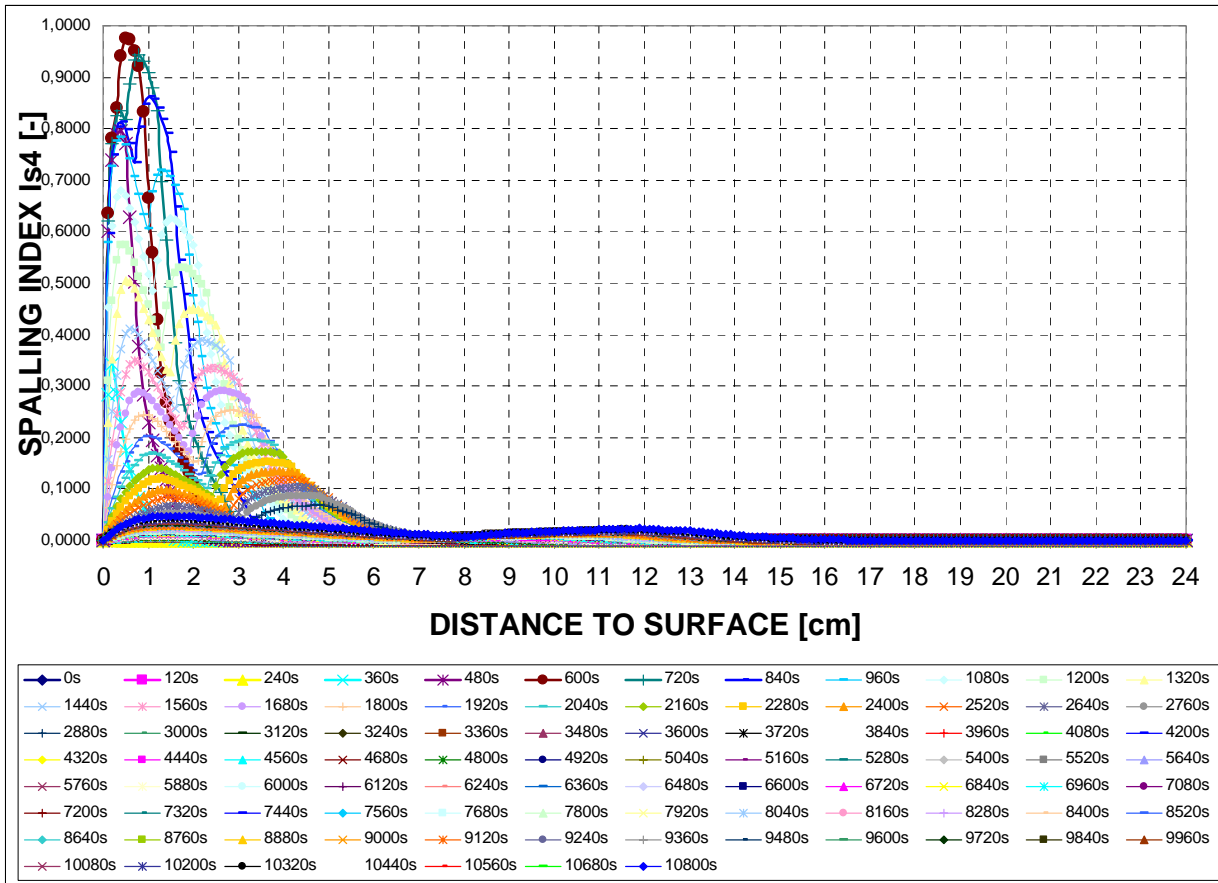


Figure 4A-21. Spalling Index IS_4 evolution for combination 21-TH24K019RH40PAR1C60

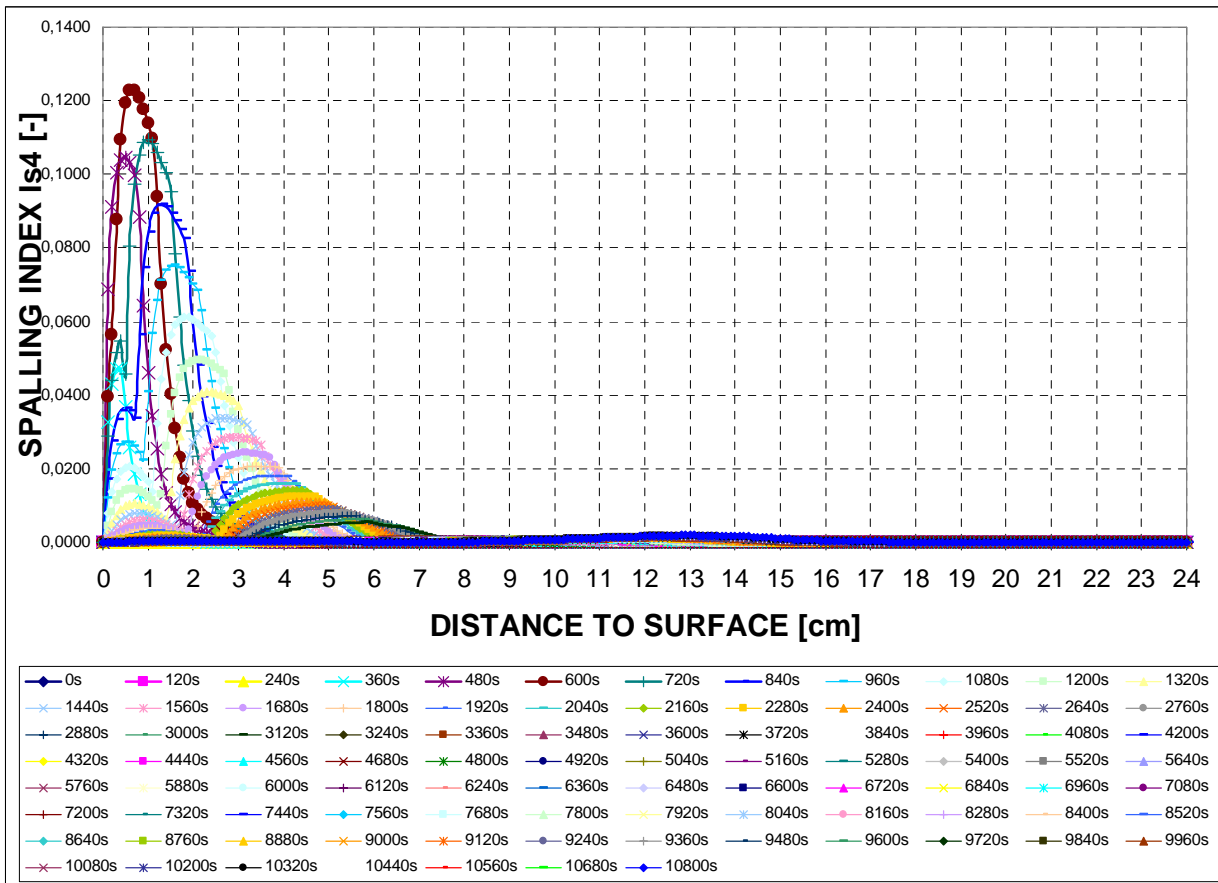


Figure 4A-22. Spalling Index IS_4 evolution for combination 22-TH24K017RH50PAR1C60

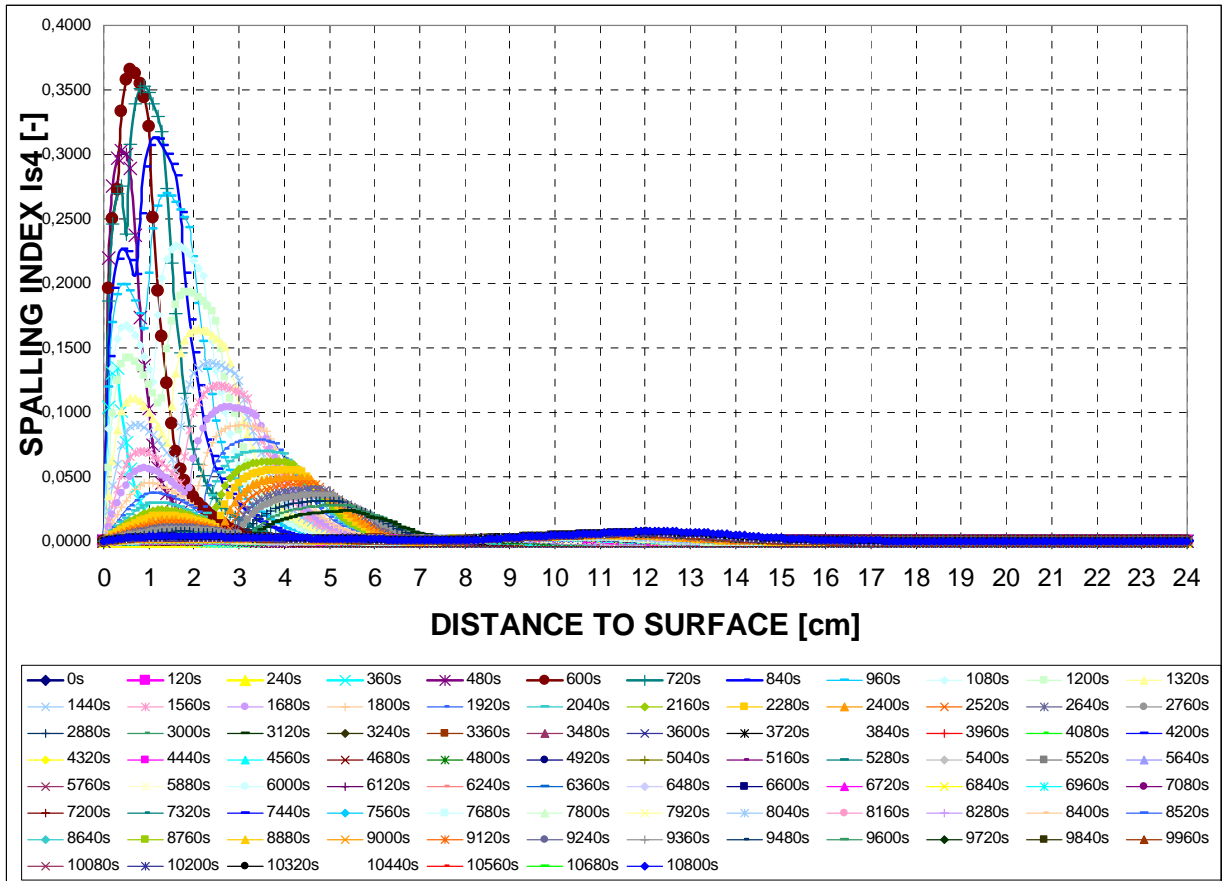


Figure 4A-23. Spalling Index IS_4 evolution for combination 23-TH24K018RH50PAR1C60

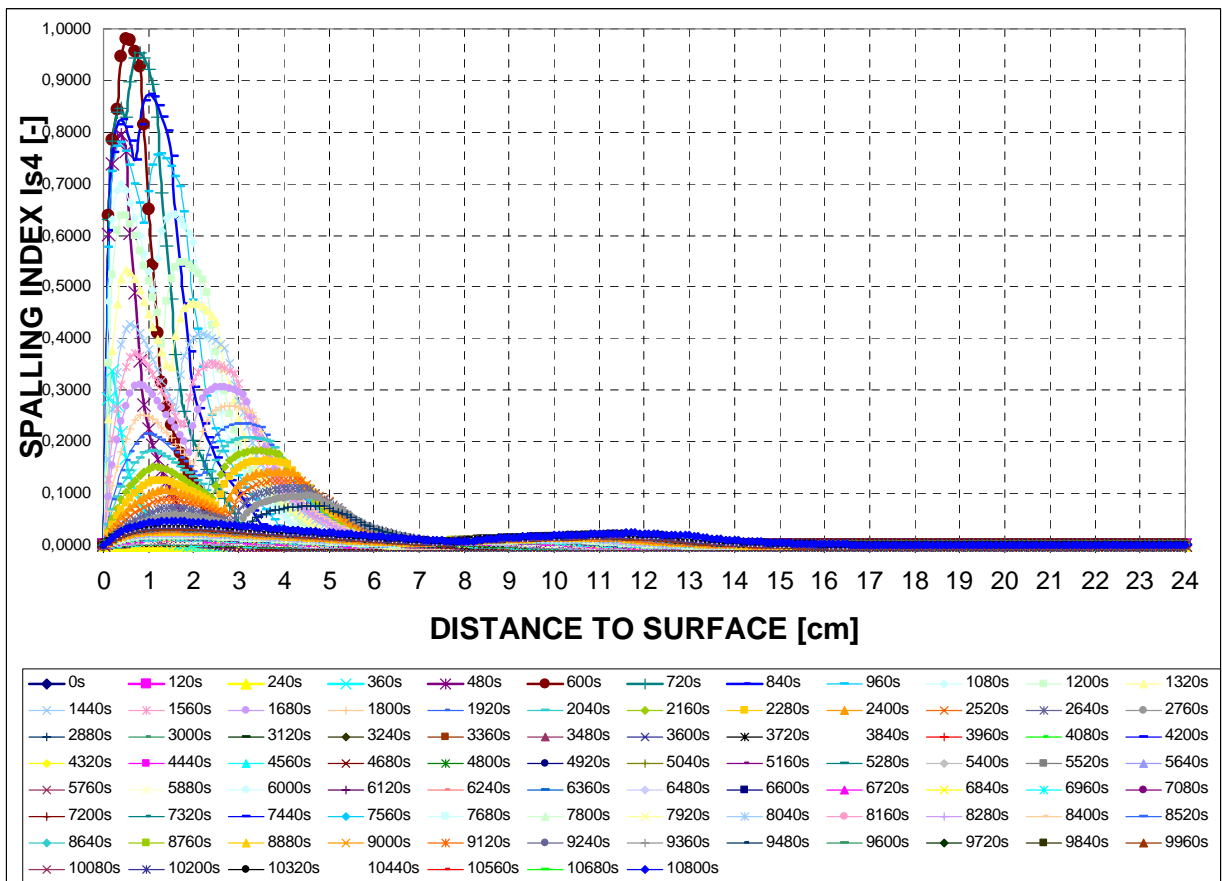


Figure 4A-24. Spalling Index IS_4 evolution for combination 24-TH24K019RH50PAR1C60

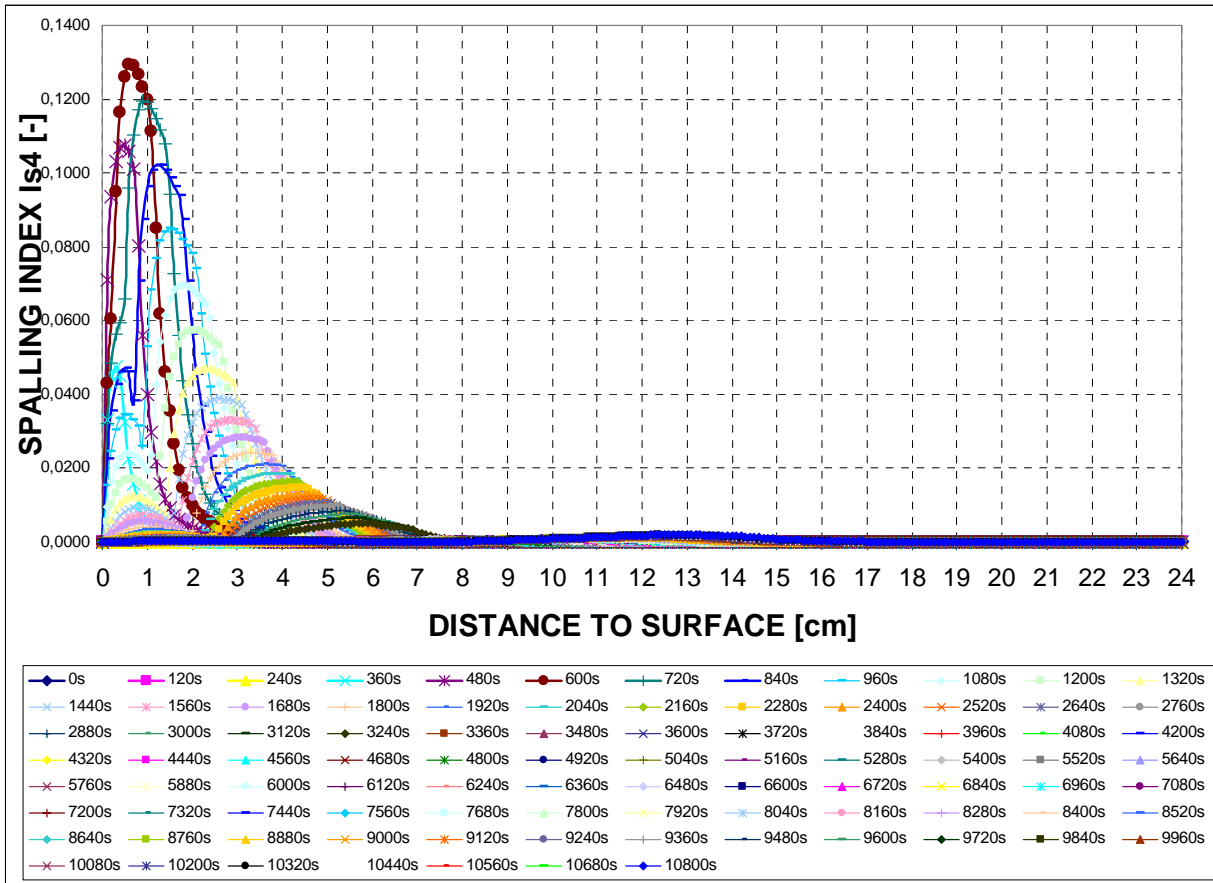


Figure 4A-25. Spalling Index IS4 evolution for combination 25-TH24K017RH60PAR1C60

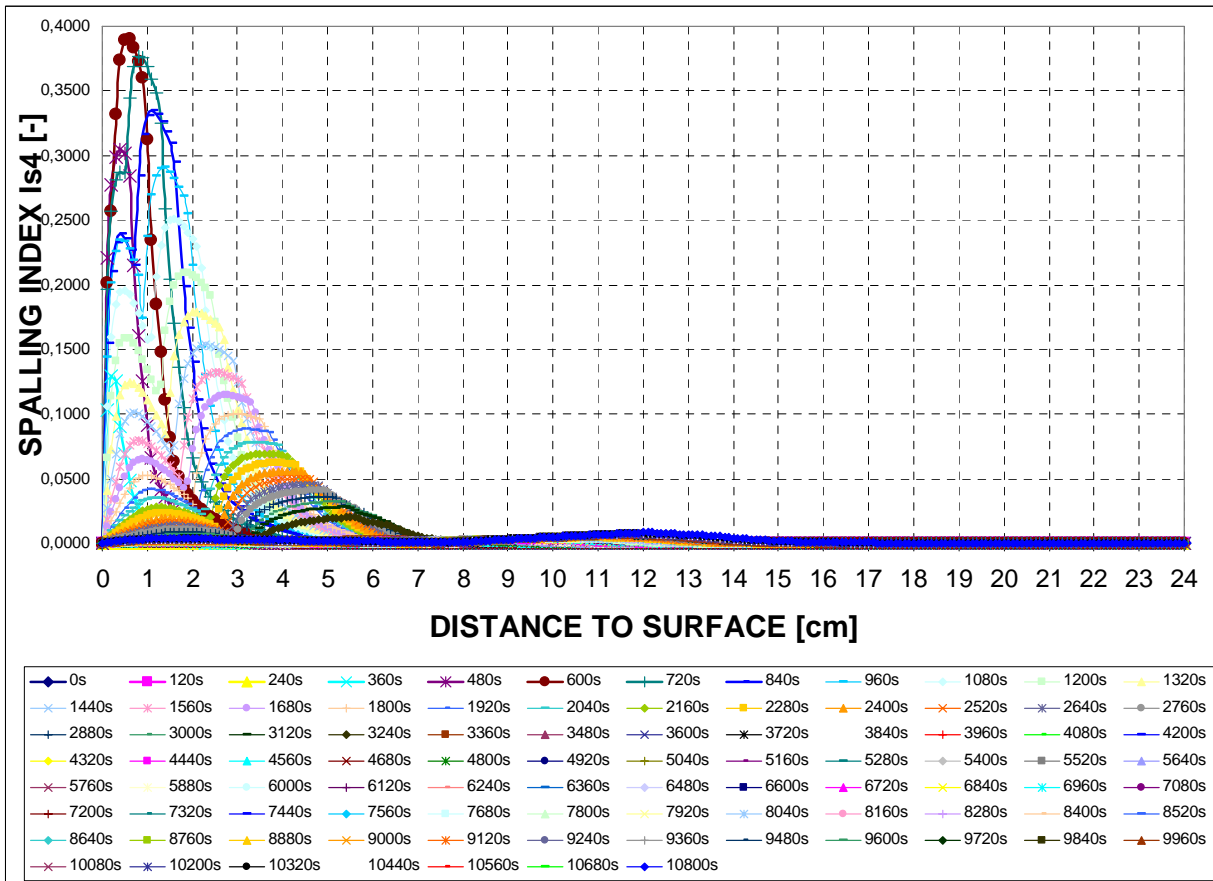


Figure 4A-26. Spalling Index IS4 evolution for combination 26-TH24K018RH60PAR1C60

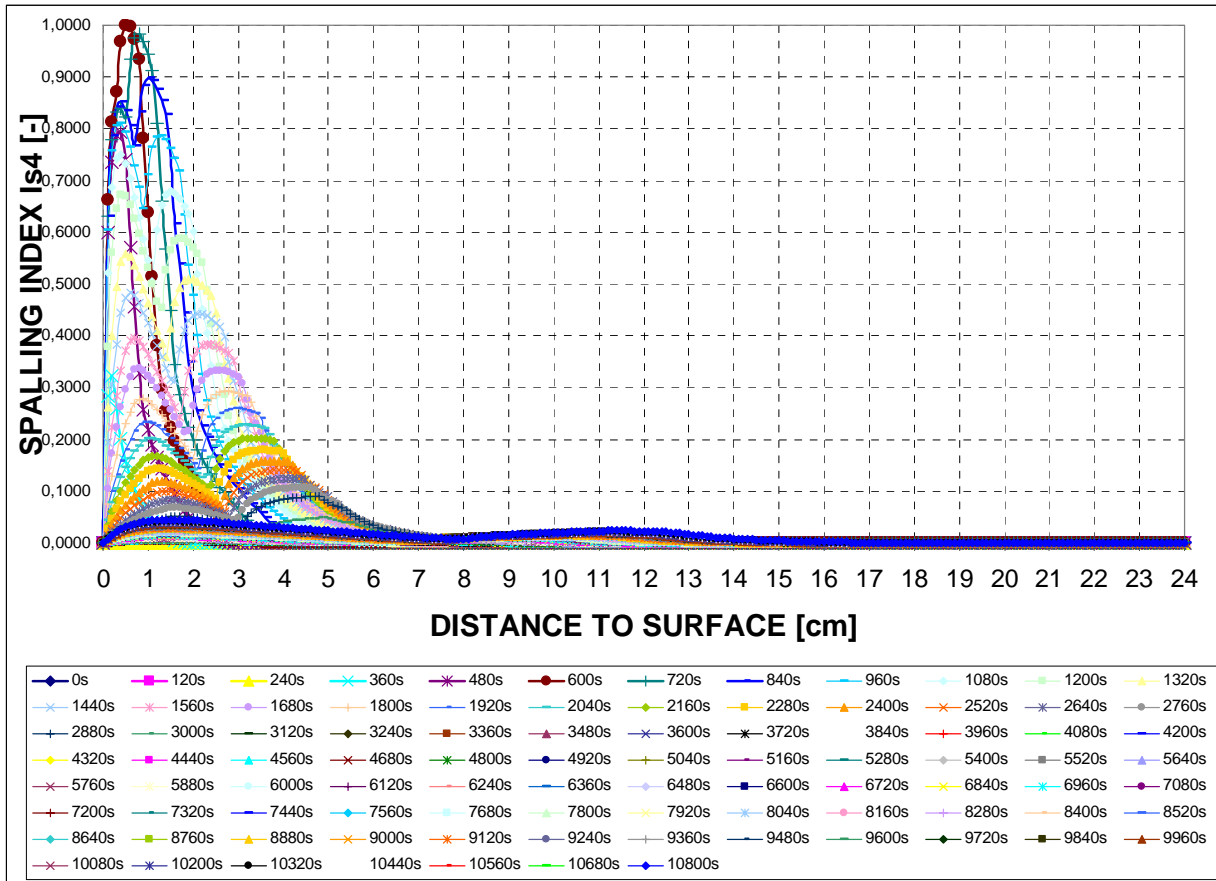


Figure 4A-27. Spalling Index IS4 evolution for combination 27-TH24K019RH60PAR1C60

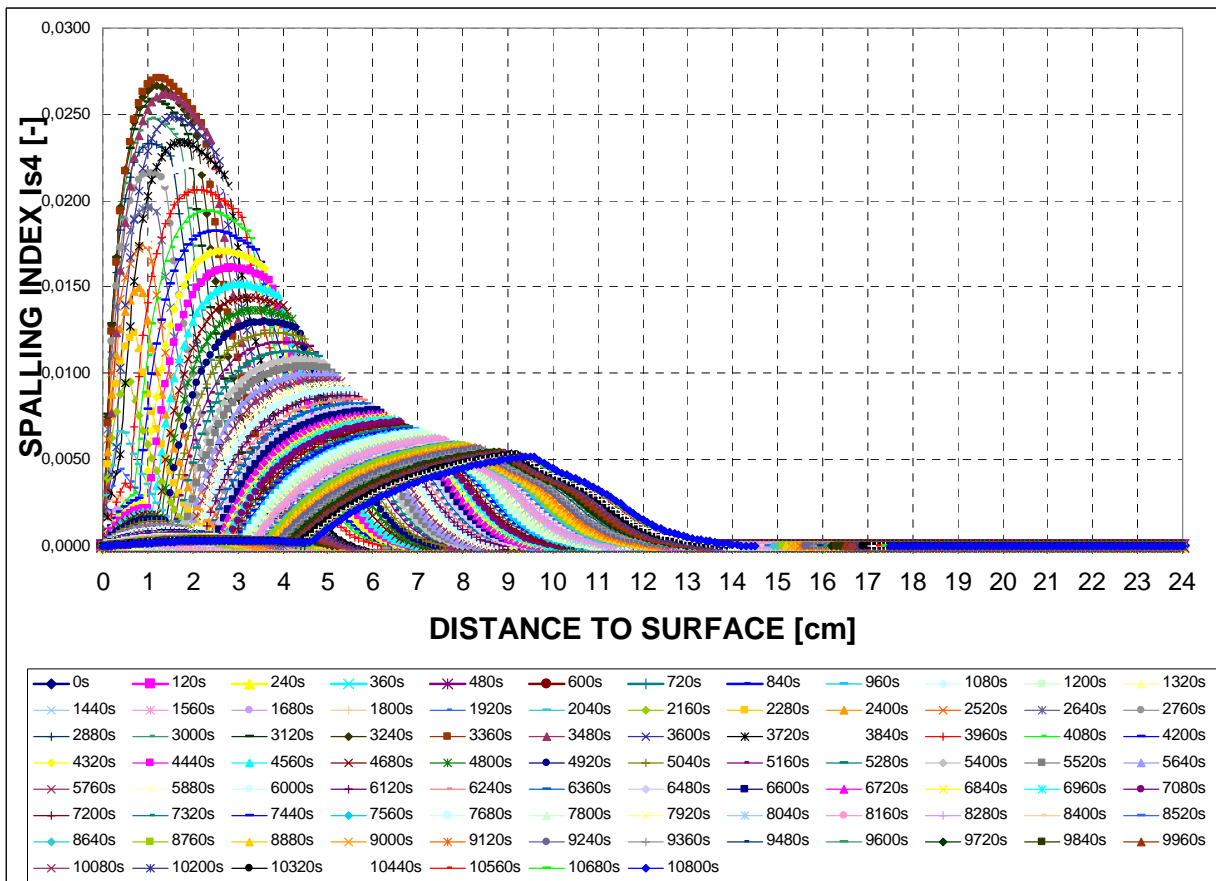


Figure 4A-28. Spalling Index IS4 evolution for combination 28-TH24K017RH40PAR2C60

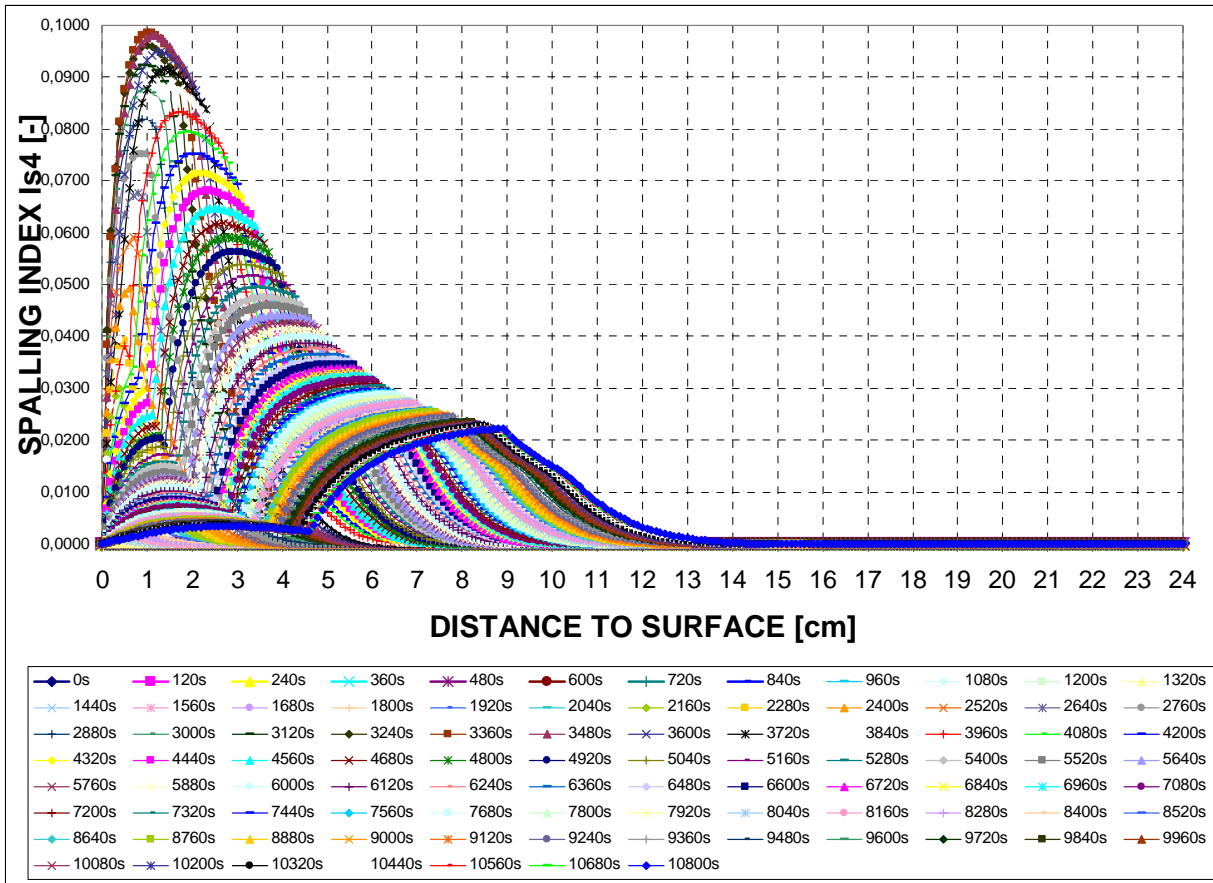


Figure 4A-29. Spalling Index IS4 evolution for combination 29-TH24K018RH40PAR2C60

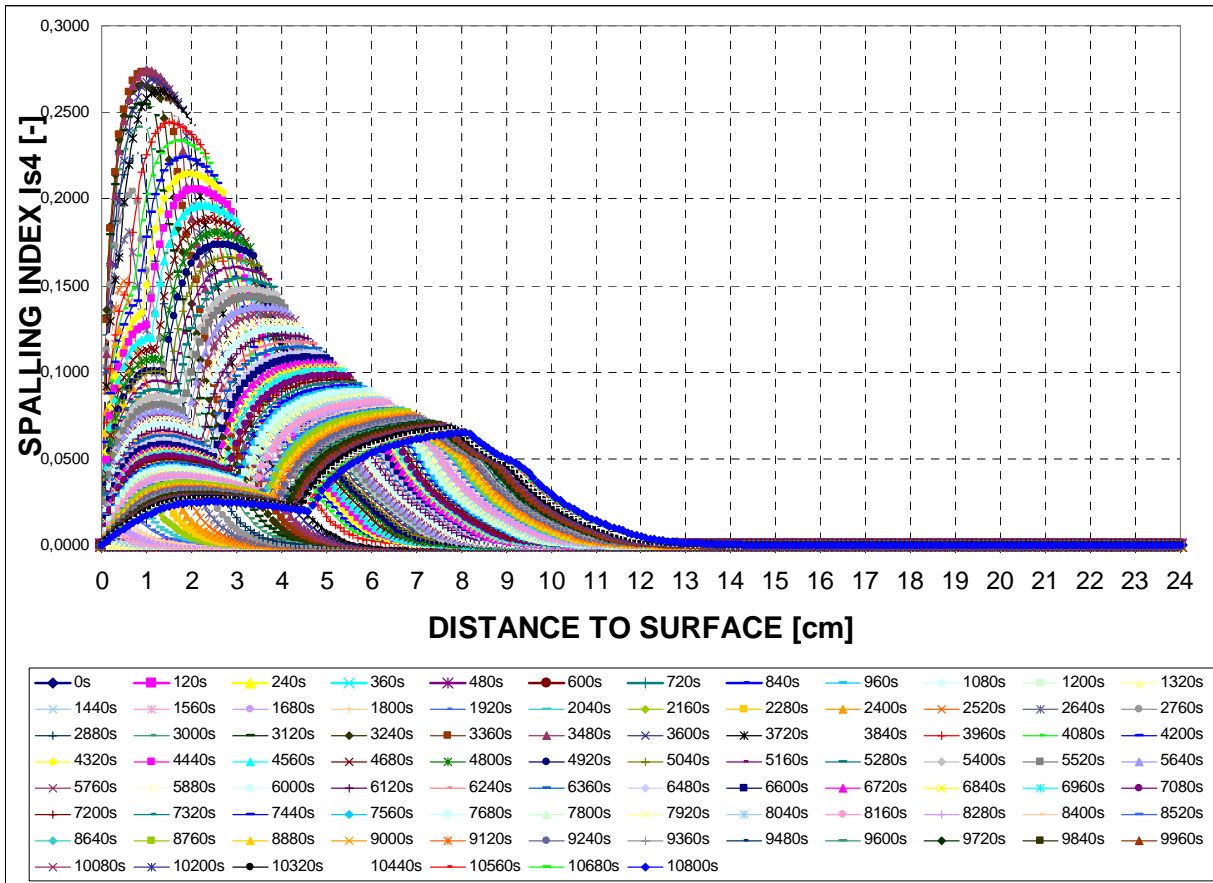


Figure 4A-30. Spalling Index IS4 evolution for combination 30-TH24K019RH40PAR2C60

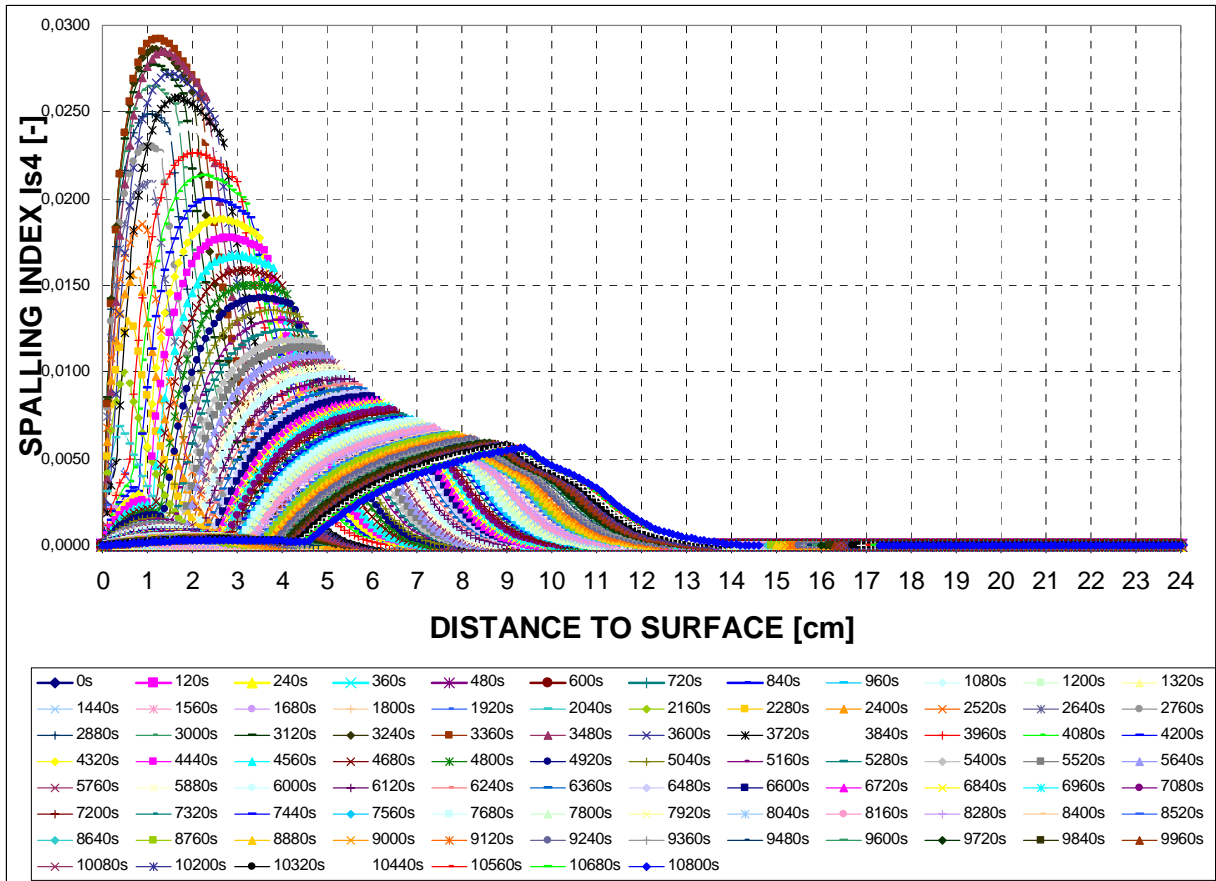


Figure 4A-31. Spalling Index Is_4 evolution for combination 31-TH24K017RH50PAR2C60

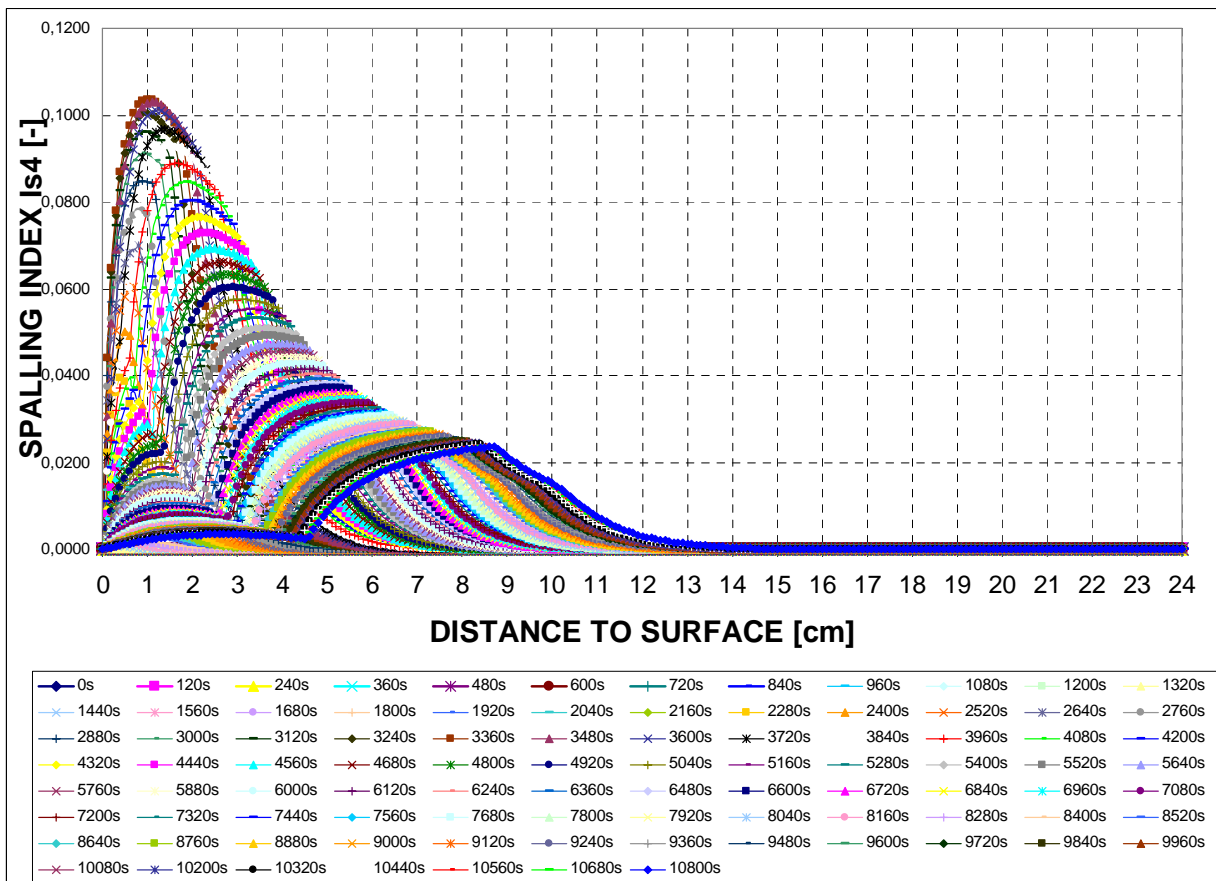


Figure 4A-32. Spalling Index Is_4 evolution for combination 32-TH24K018RH50PAR2C60

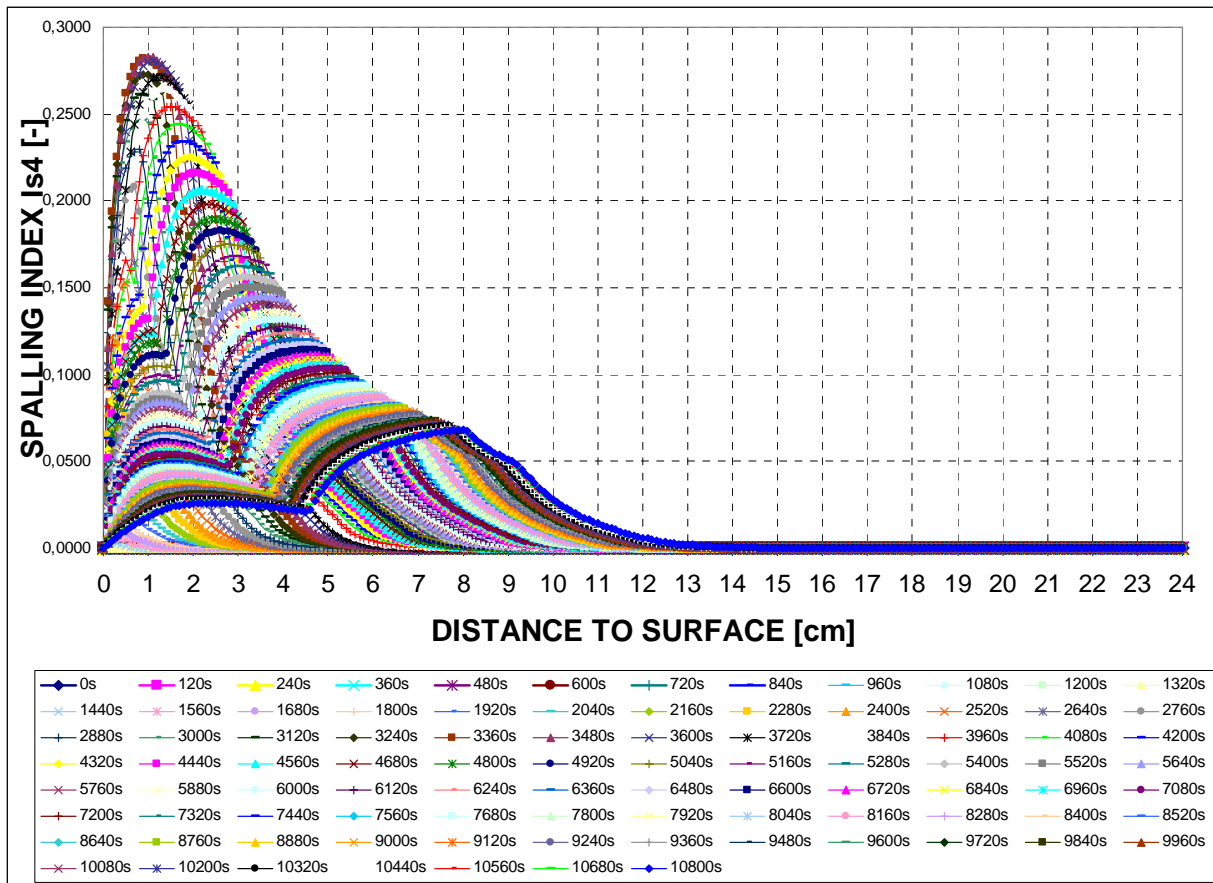


Figure 4A-33. Spalling Index IS_4 evolution for combination 33-TH24K019RH50PAR2C60

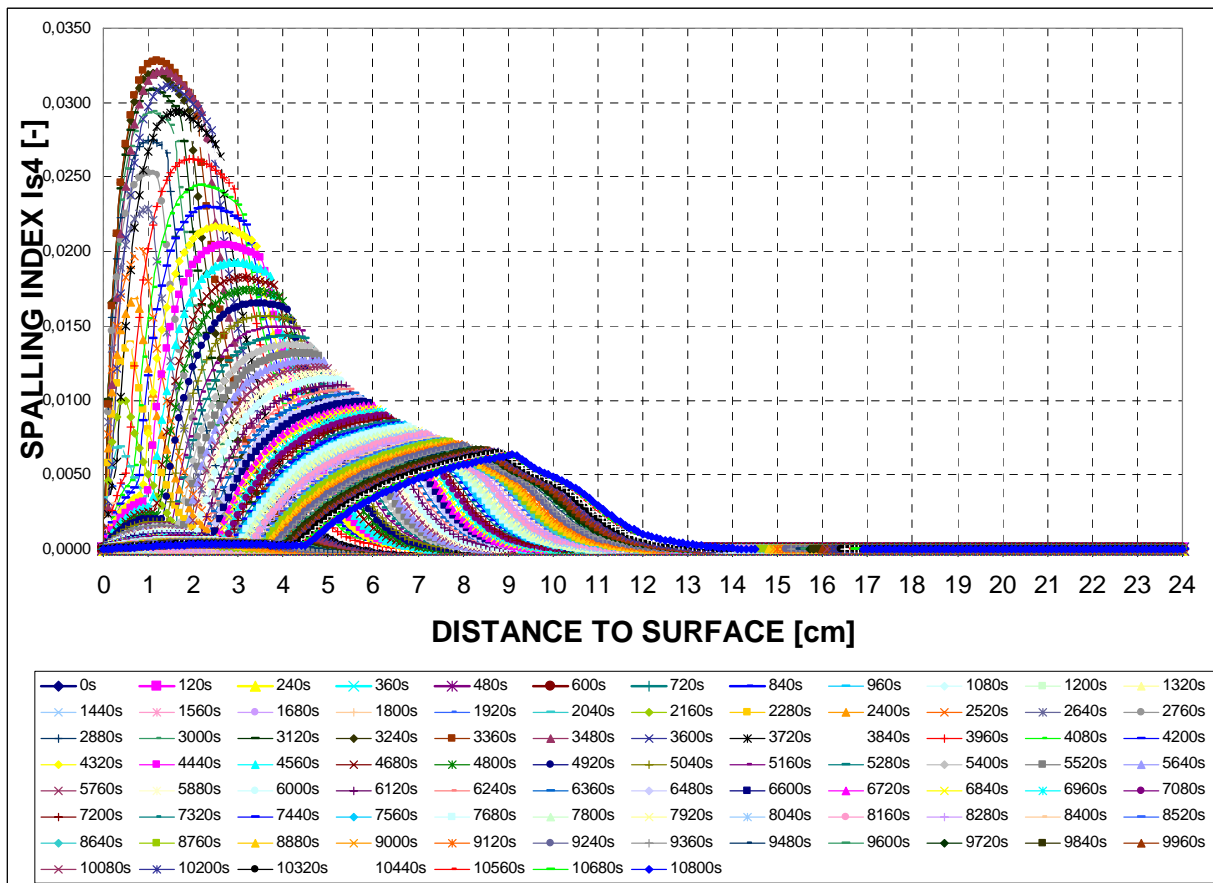


Figure 4A-34. Spalling Index IS_4 evolution for combination 34-TH24K017RH60PAR2C60

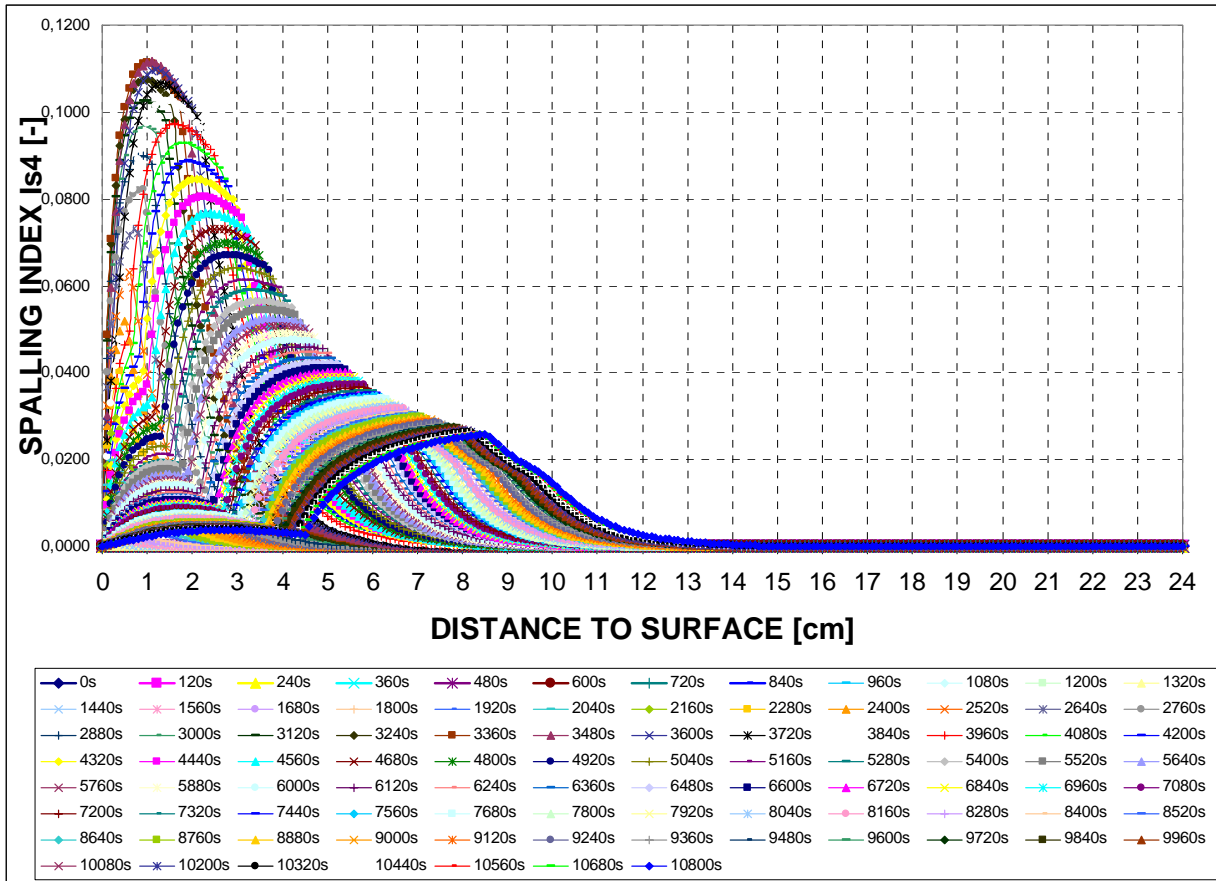


Figure 4A-35. Spalling Index IS_4 evolution for combination 35-TH24K018RH60PAR2C60

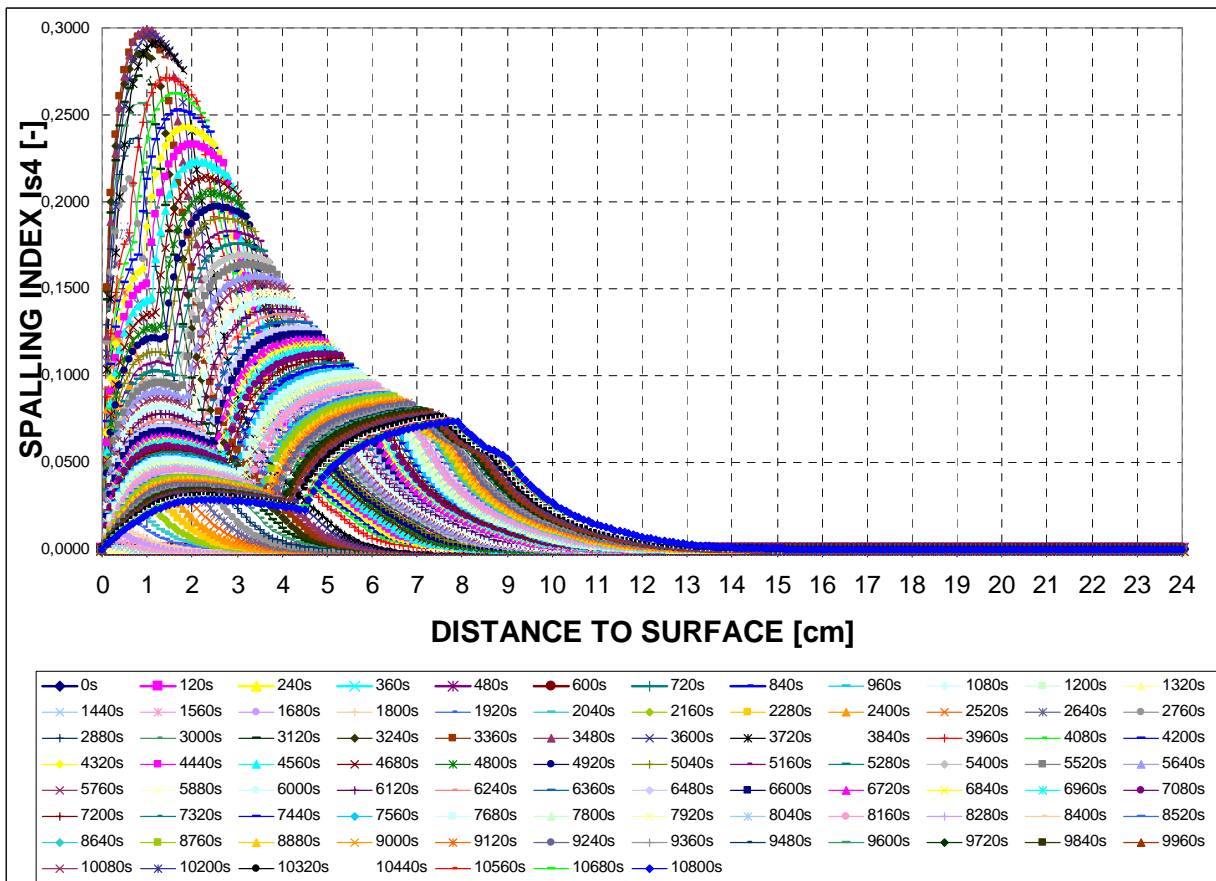


Figure 4A-36. Spalling Index IS_4 evolution for combination 36-TH24K019RH60PAR2C60

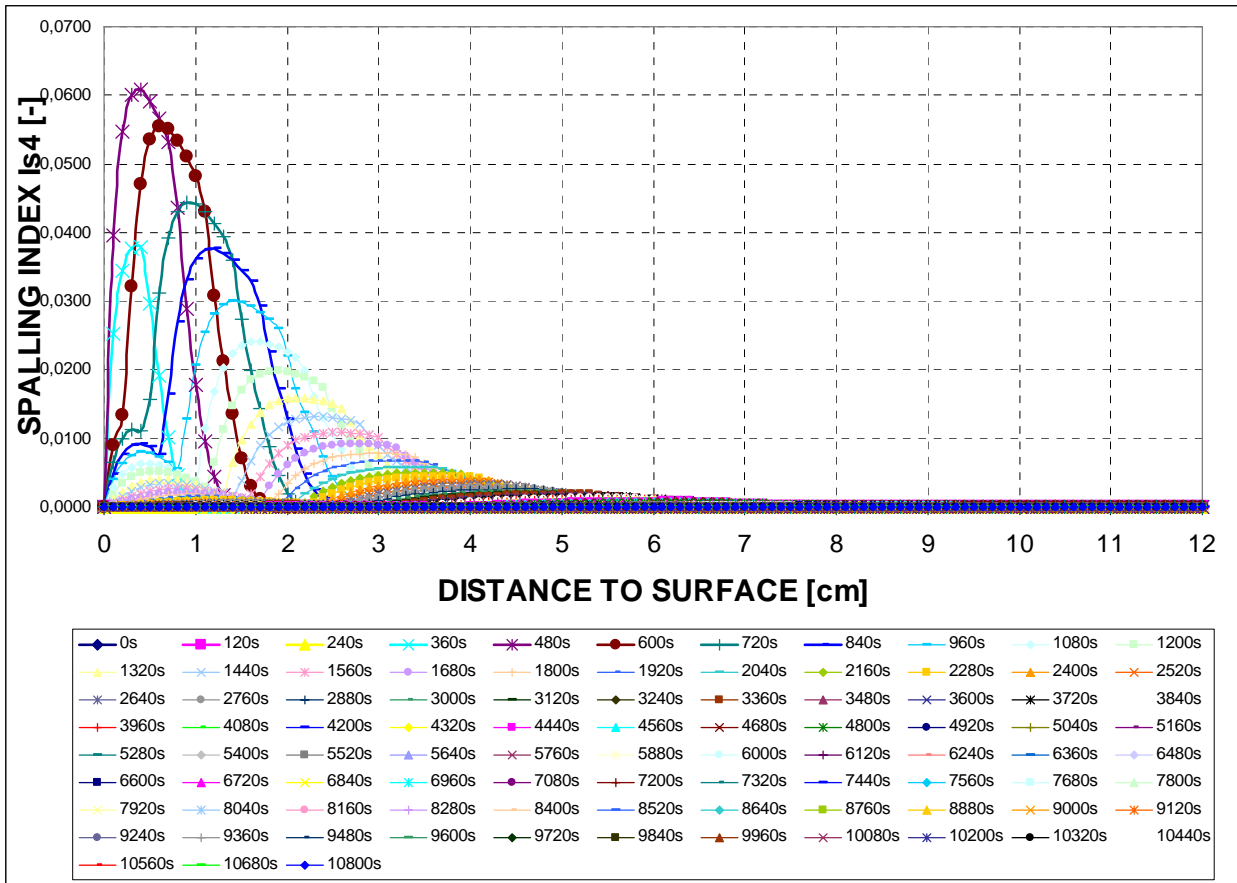


Figure 4A-37. Spalling Index IS4 evolution for combination 37-TH12K017RH40PAR1C90

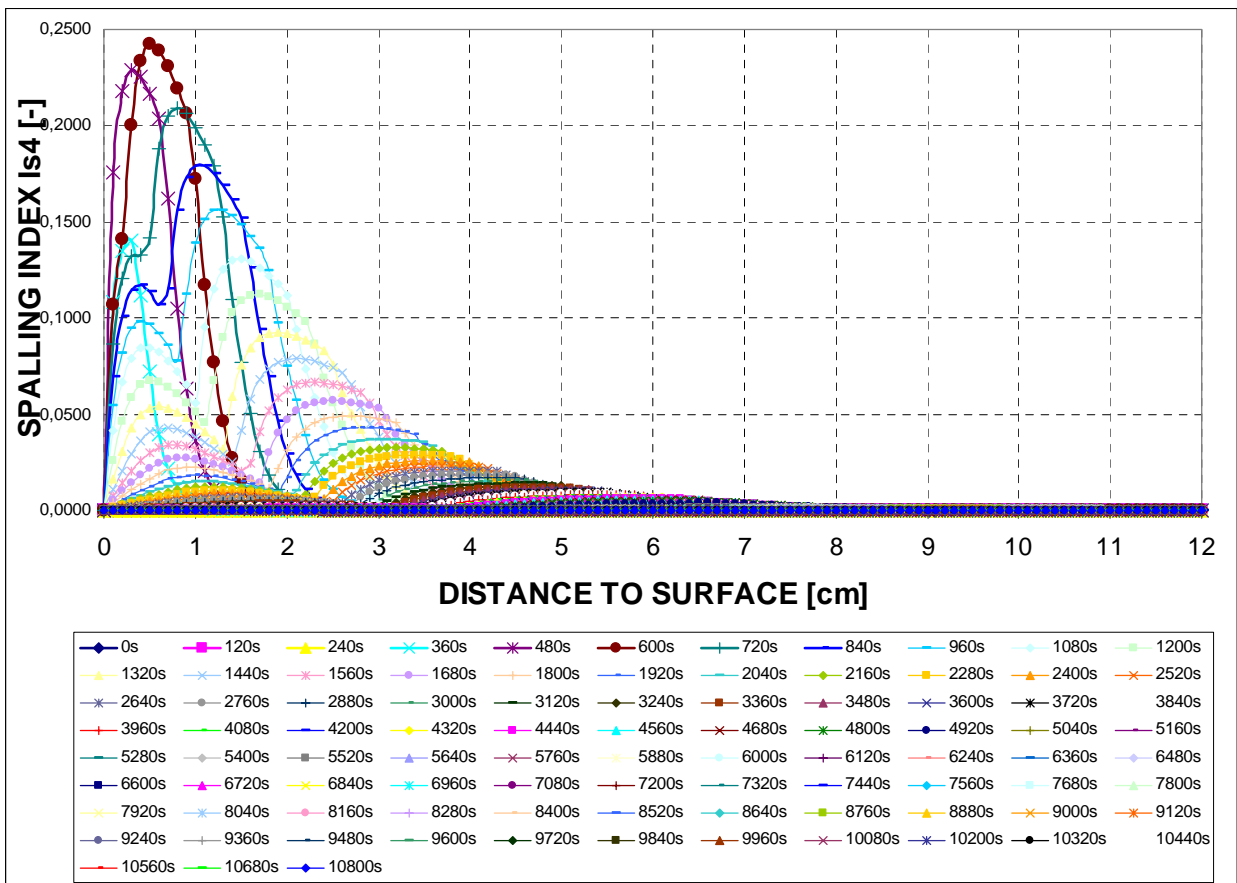


Figure 4A-38. Spalling Index IS4 evolution for combination 38-TH12K018RH40PAR1C90

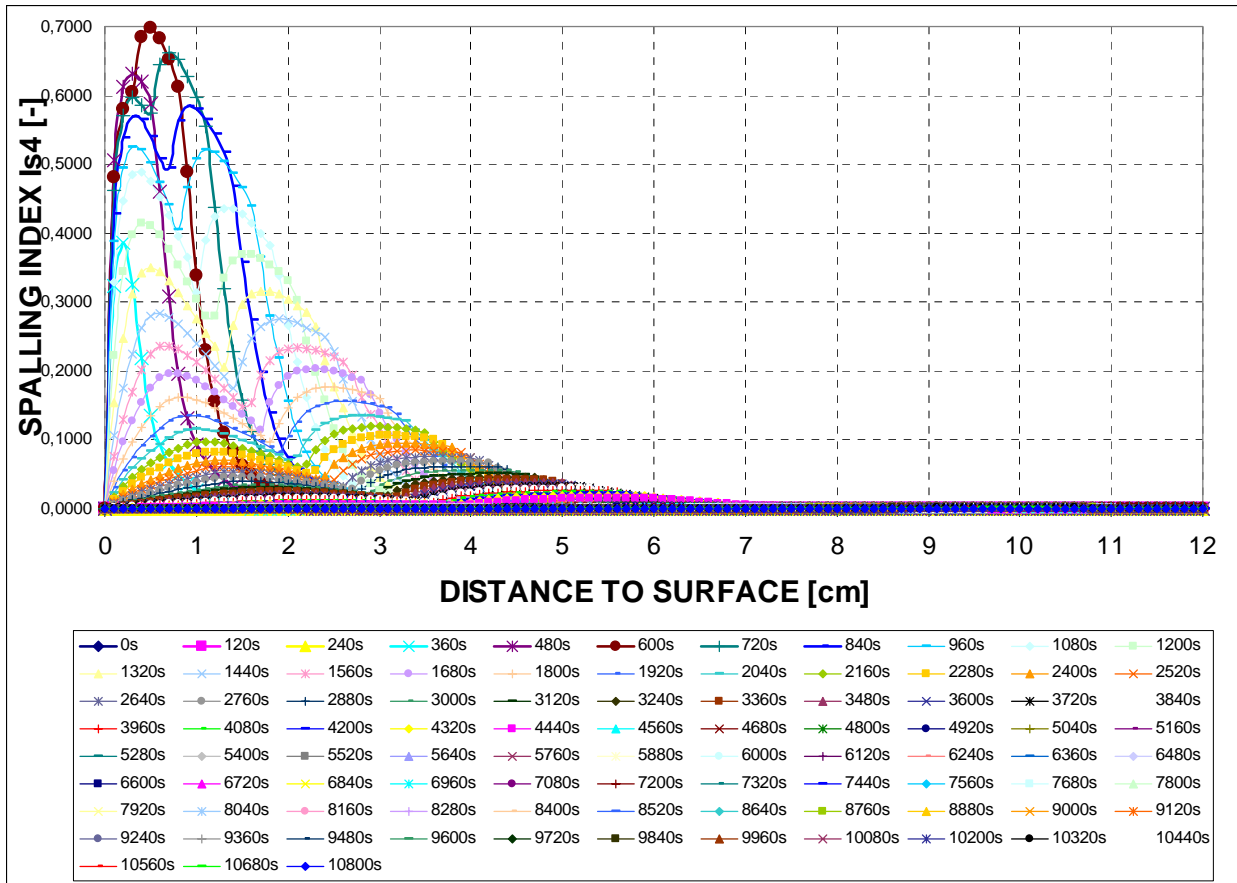


Figure 4A-39. Spalling Index IS_4 evolution for combination 39-TH12K019RH40PAR1C90

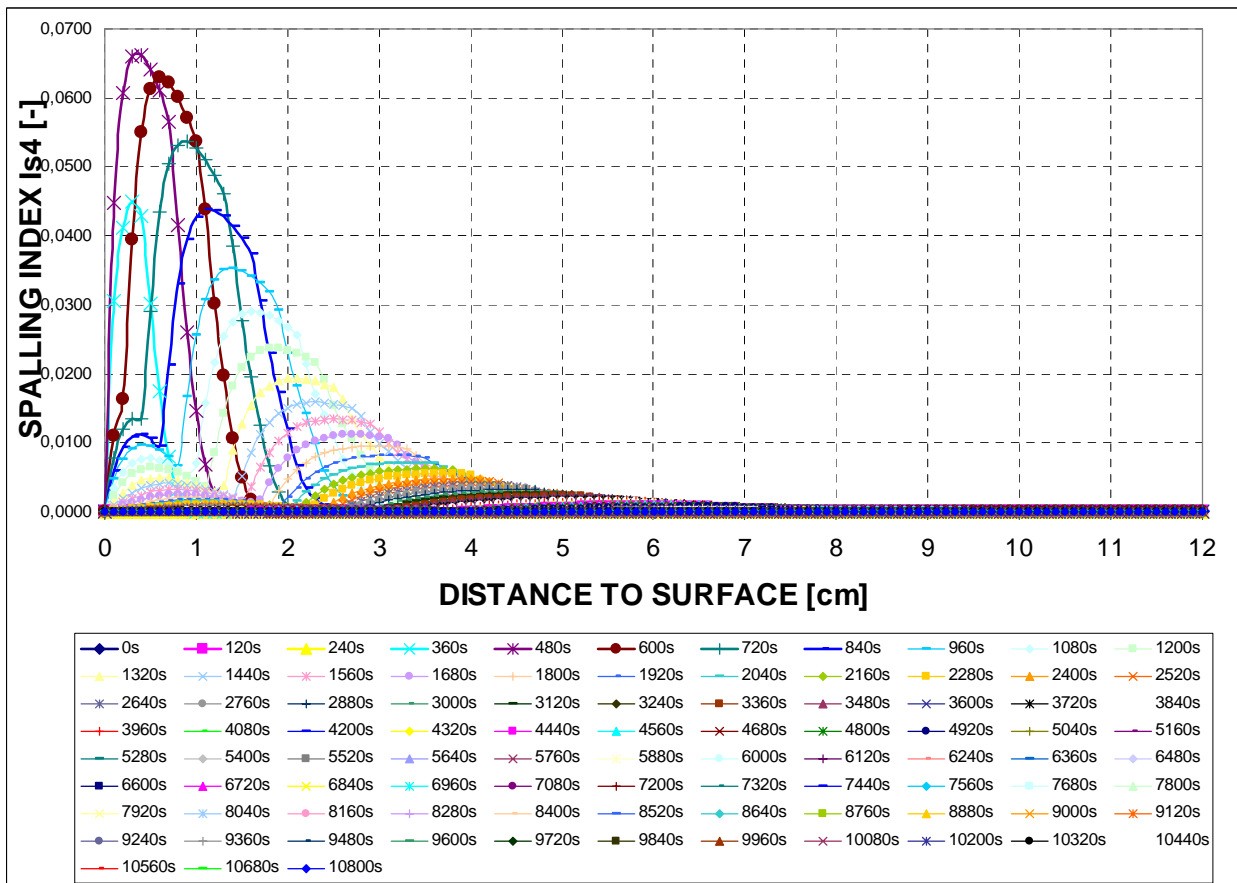


Figure 4A-40. Spalling Index IS_4 evolution for combination 40-TH12K017RH50PAR1C90

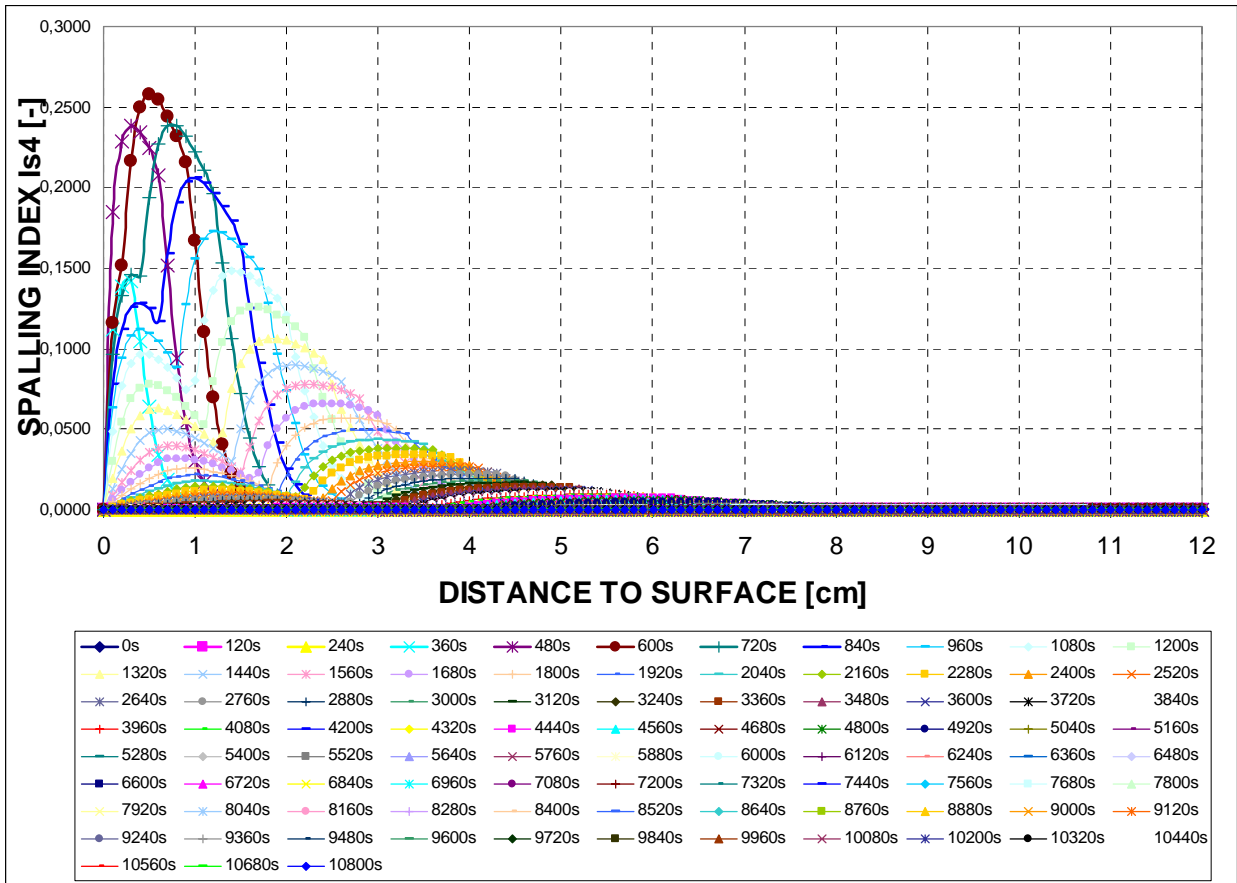


Figure 4A-41. Spalling Index IS4 evolution for combination 41-TH12K018RH50PAR1C90

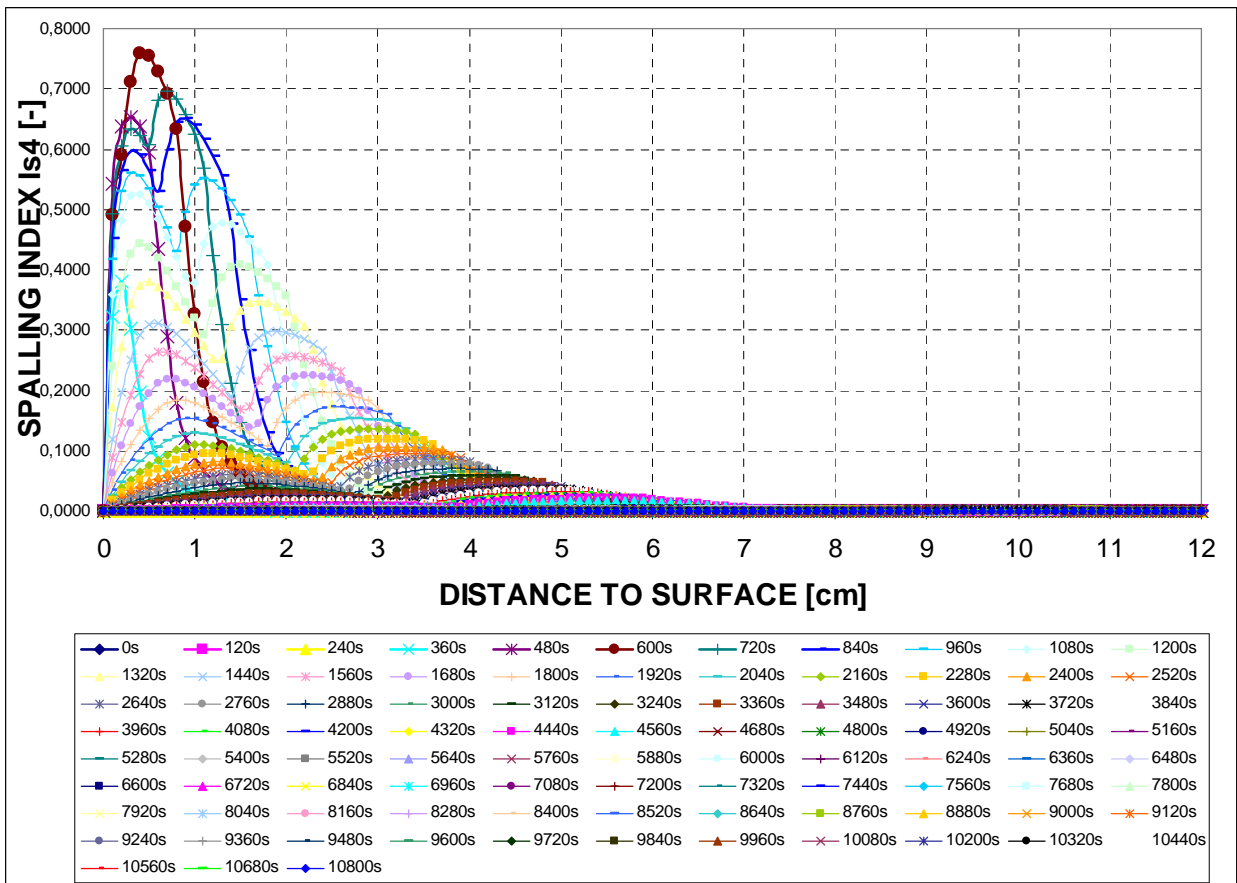


Figure 4A-42. Spalling Index IS4 evolution for combination 42-TH12K019RH50PAR1C90

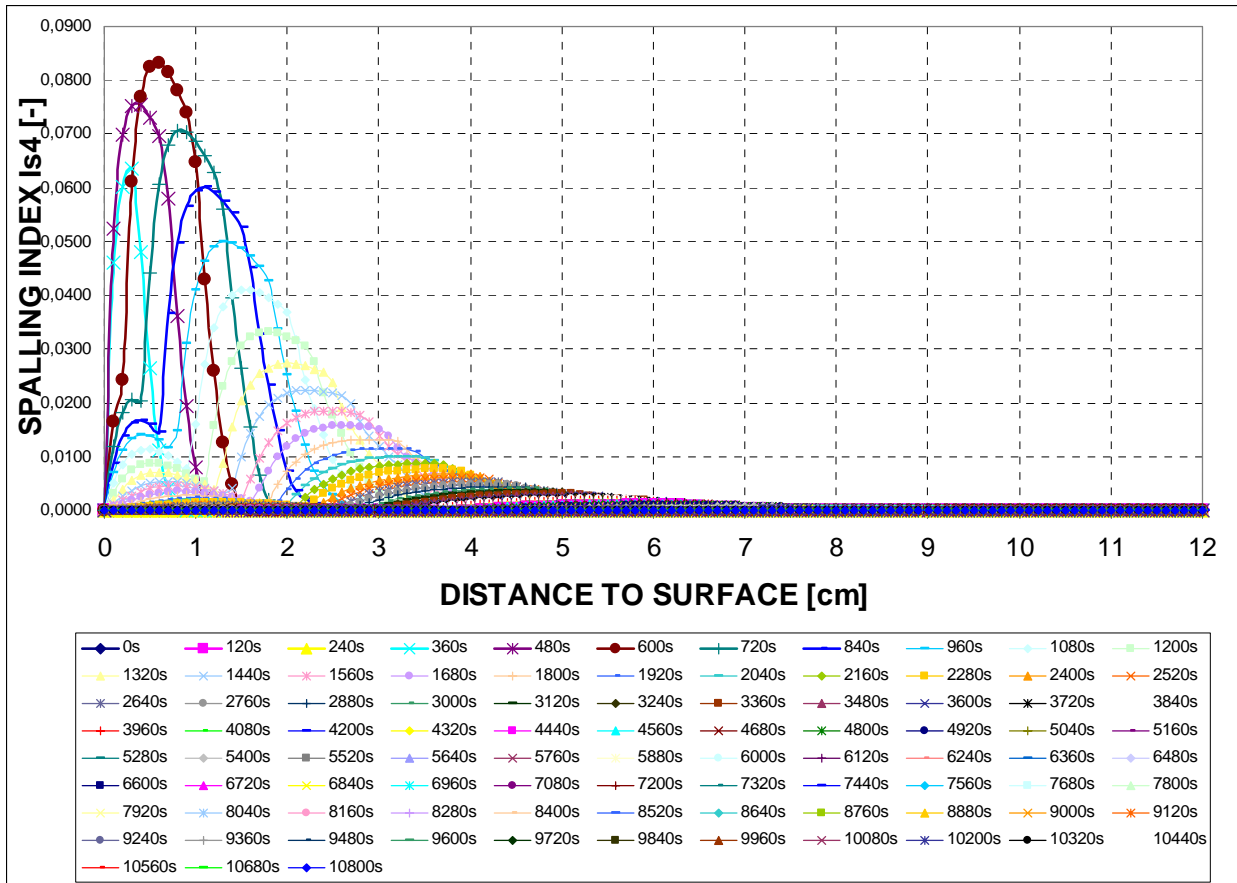


Figure 4A-43. Spalling Index IS_4 evolution for combination 43-TH12K017RH60PAR1C90

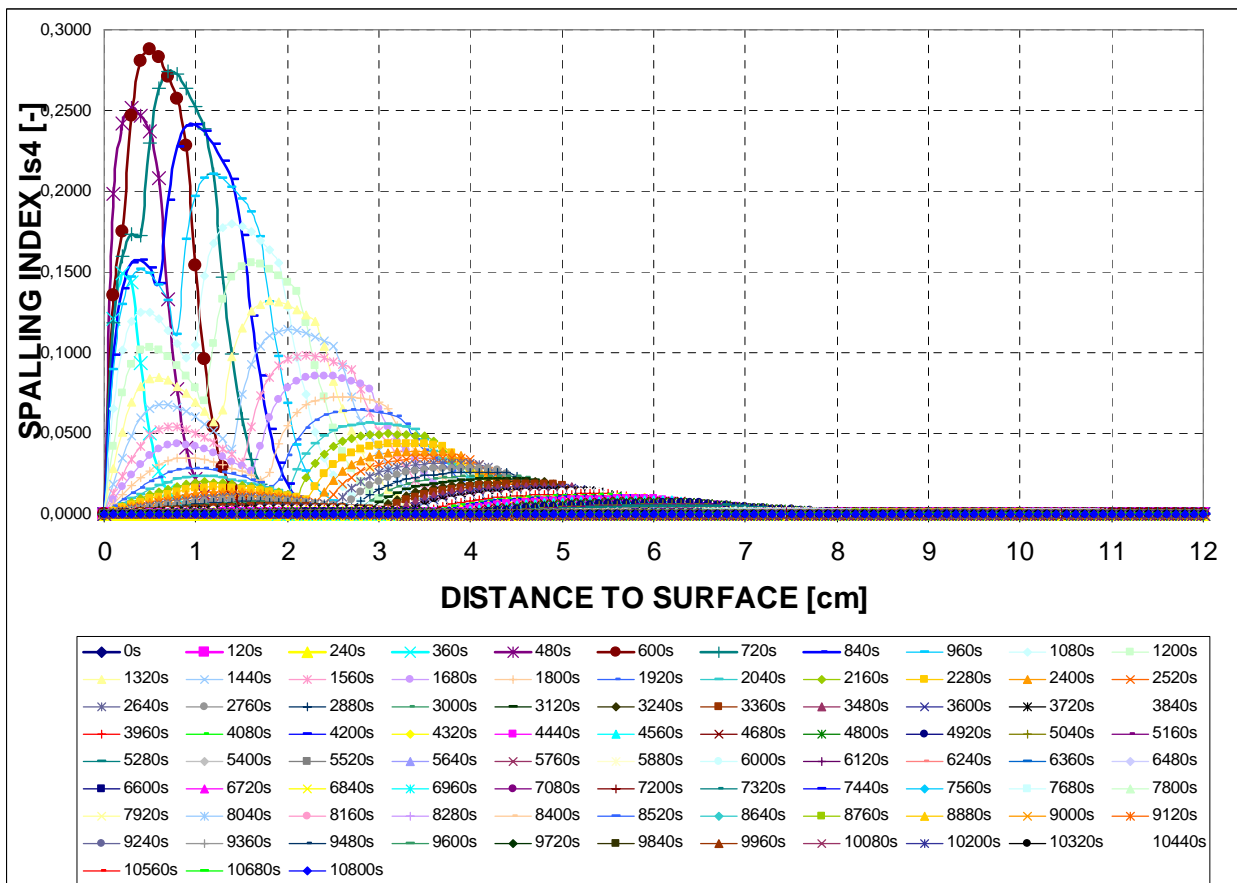


Figure 4A-44. Spalling Index IS_4 evolution for combination 44-TH12K018RH60PAR1C90

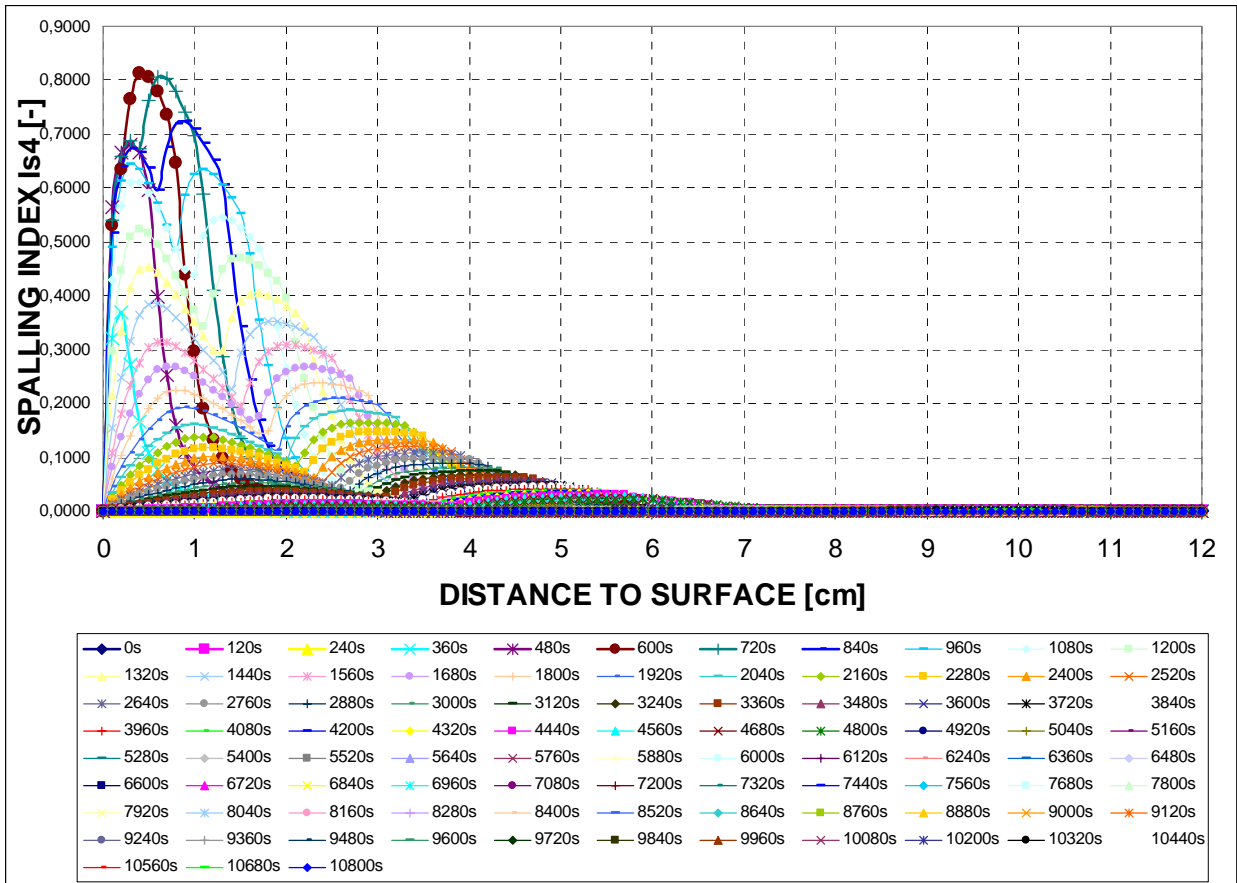


Figure 4A-45. Spalling Index IS_4 evolution for combination 45-TH12K019RH60PAR1C90

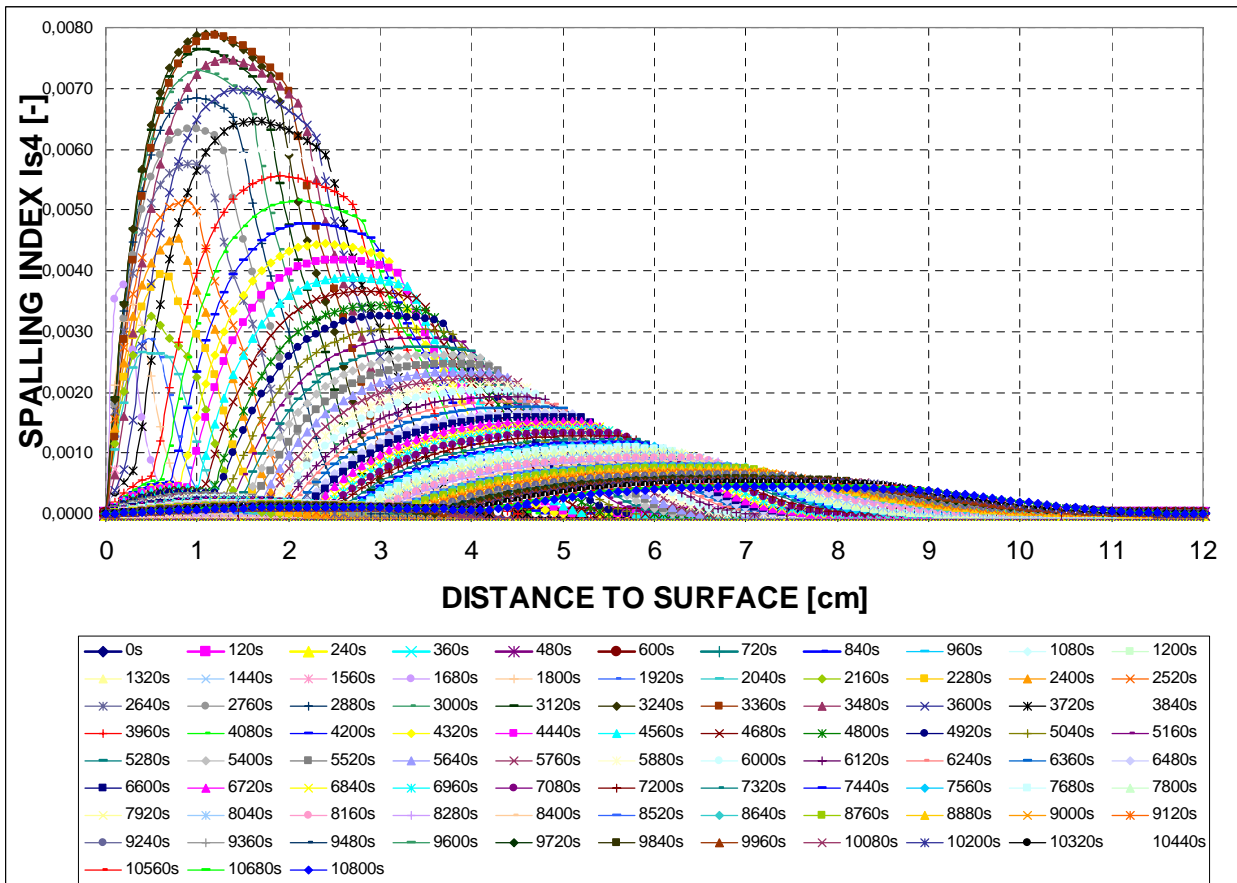


Figure 4A-46. Spalling Index IS_4 evolution for combination 46-TH12K017RH40PAR2C90

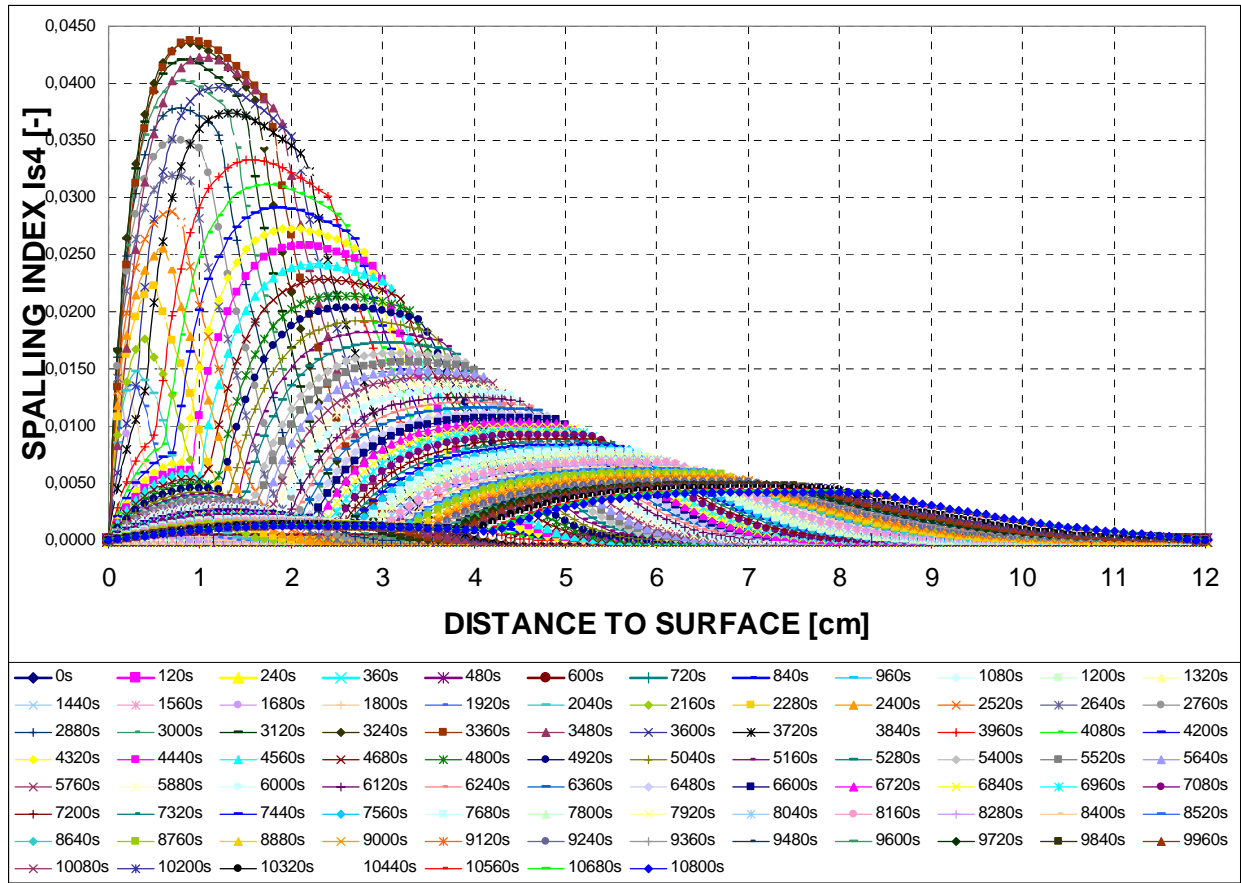


Figure 4A-47. Spalling Index IS_4 evolution for combination 47-TH12K018RH40PAR2C90

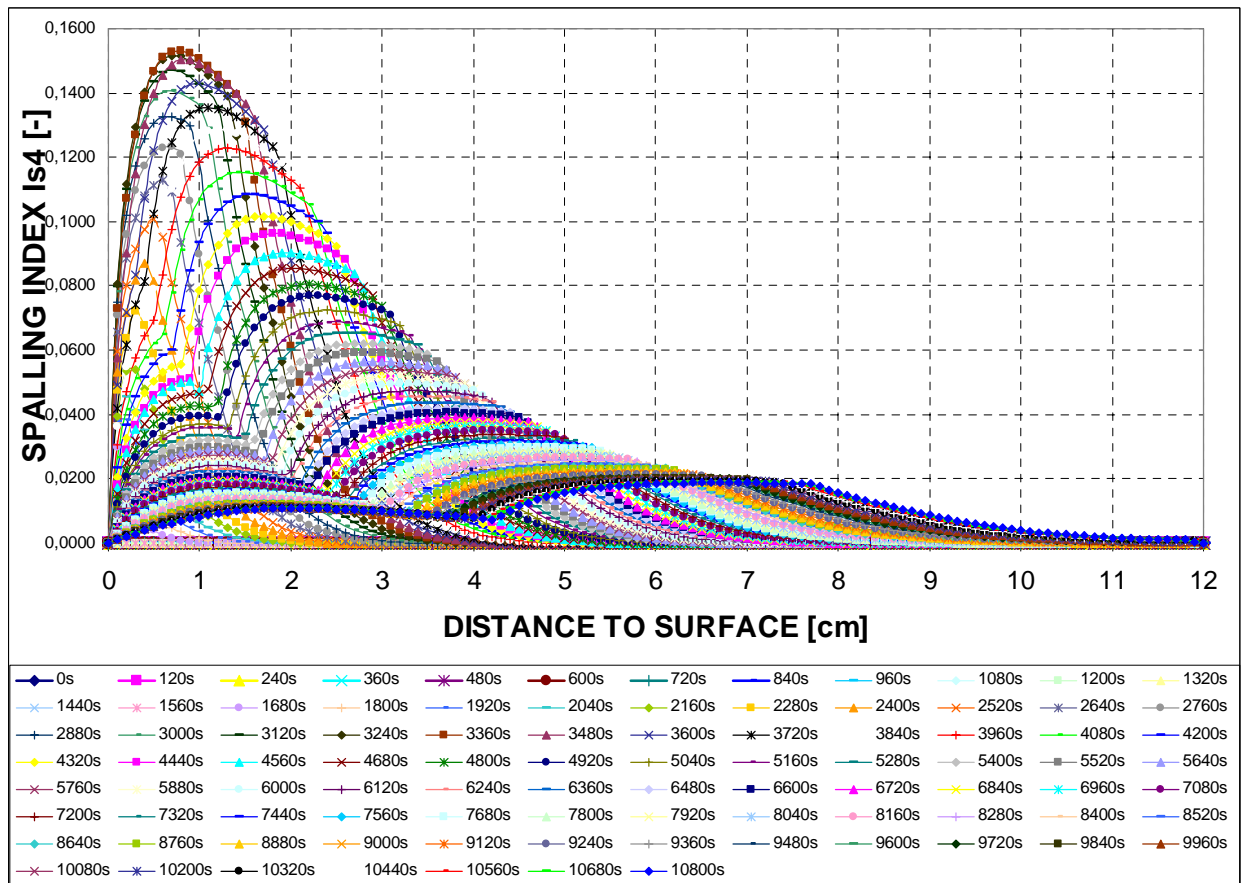


Figure 4A-48. Spalling Index IS_4 evolution for combination 48-TH12K019RH40PAR2C90

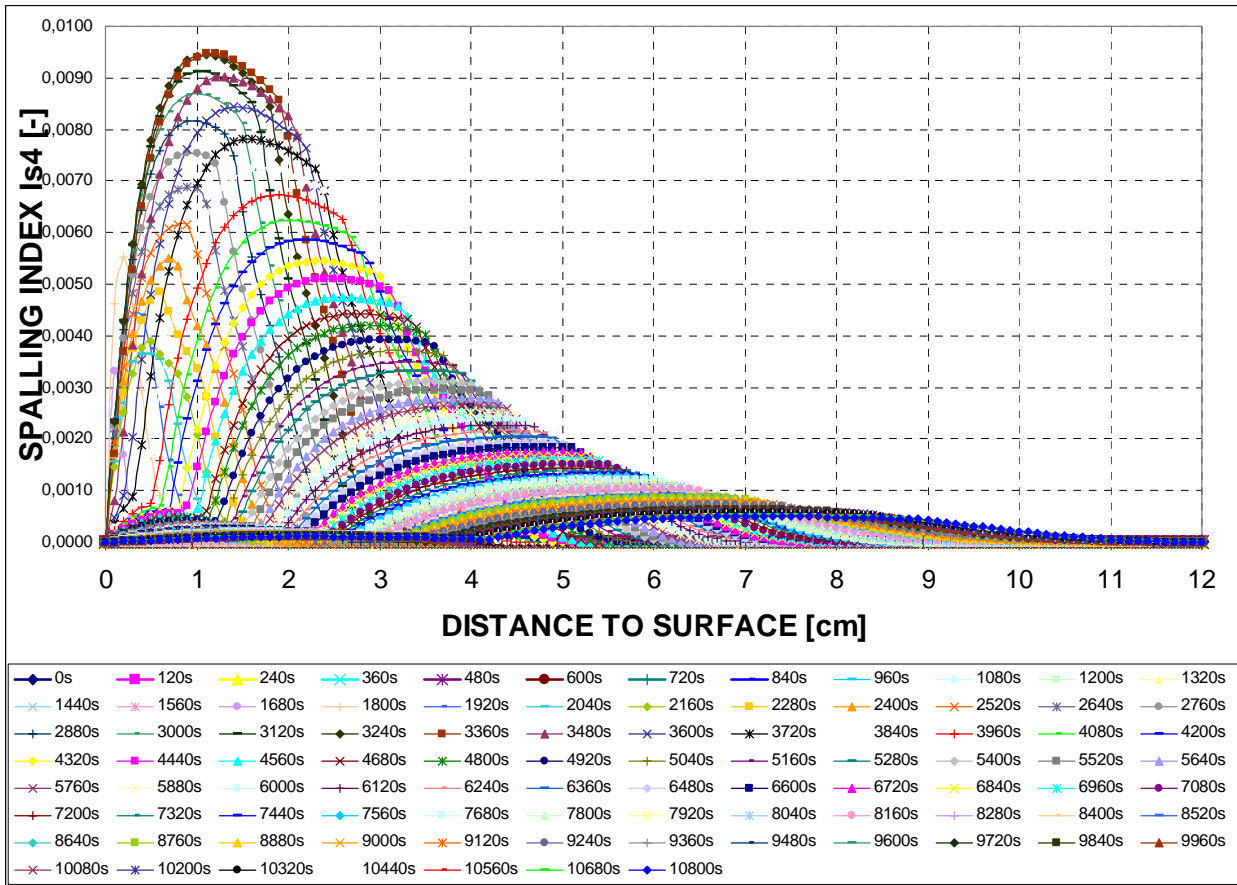


Figure 4A-49. Spalling Index IS_4 evolution for combination 49-TH12K017RH50PAR2C90

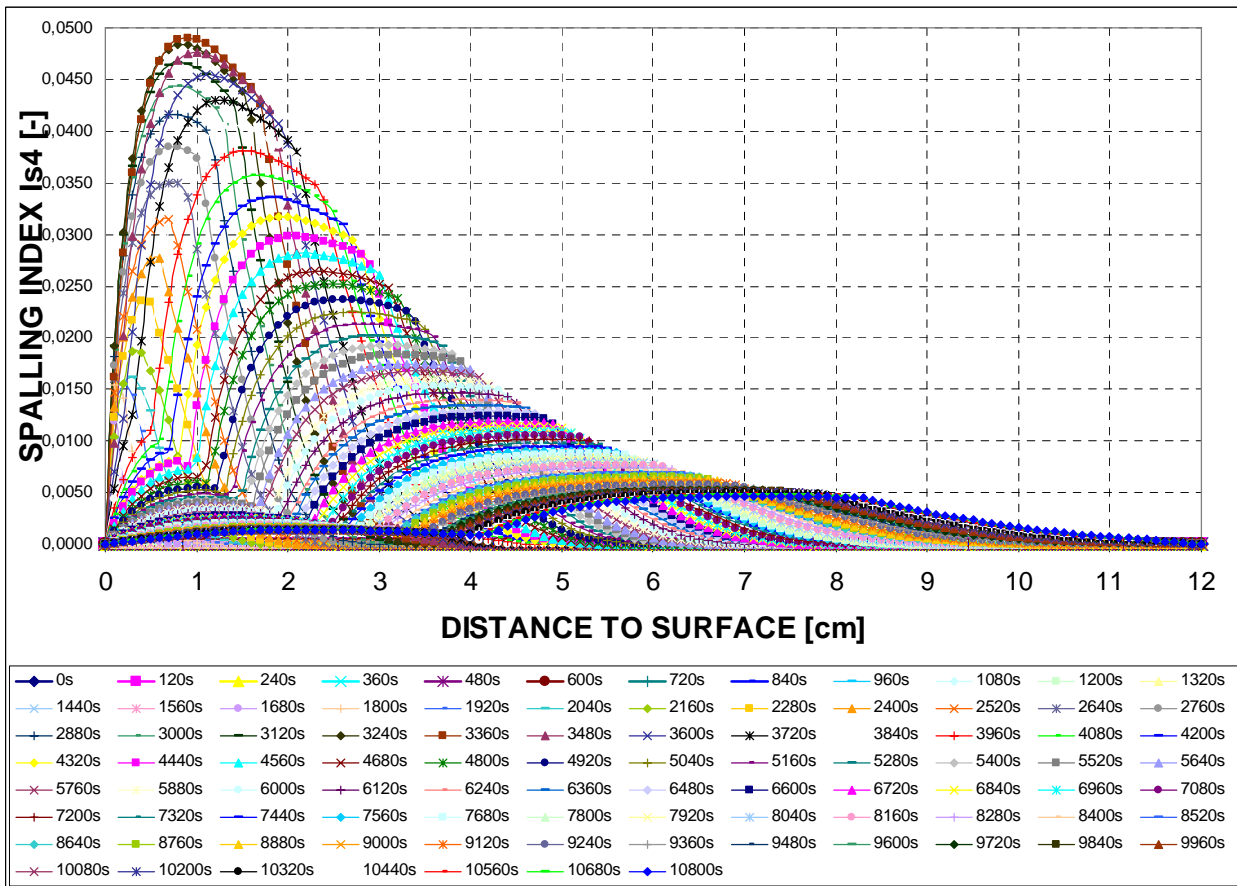


Figure 4A-50. Spalling Index IS_4 evolution for combination 50-TH12K018RH50PAR2C90

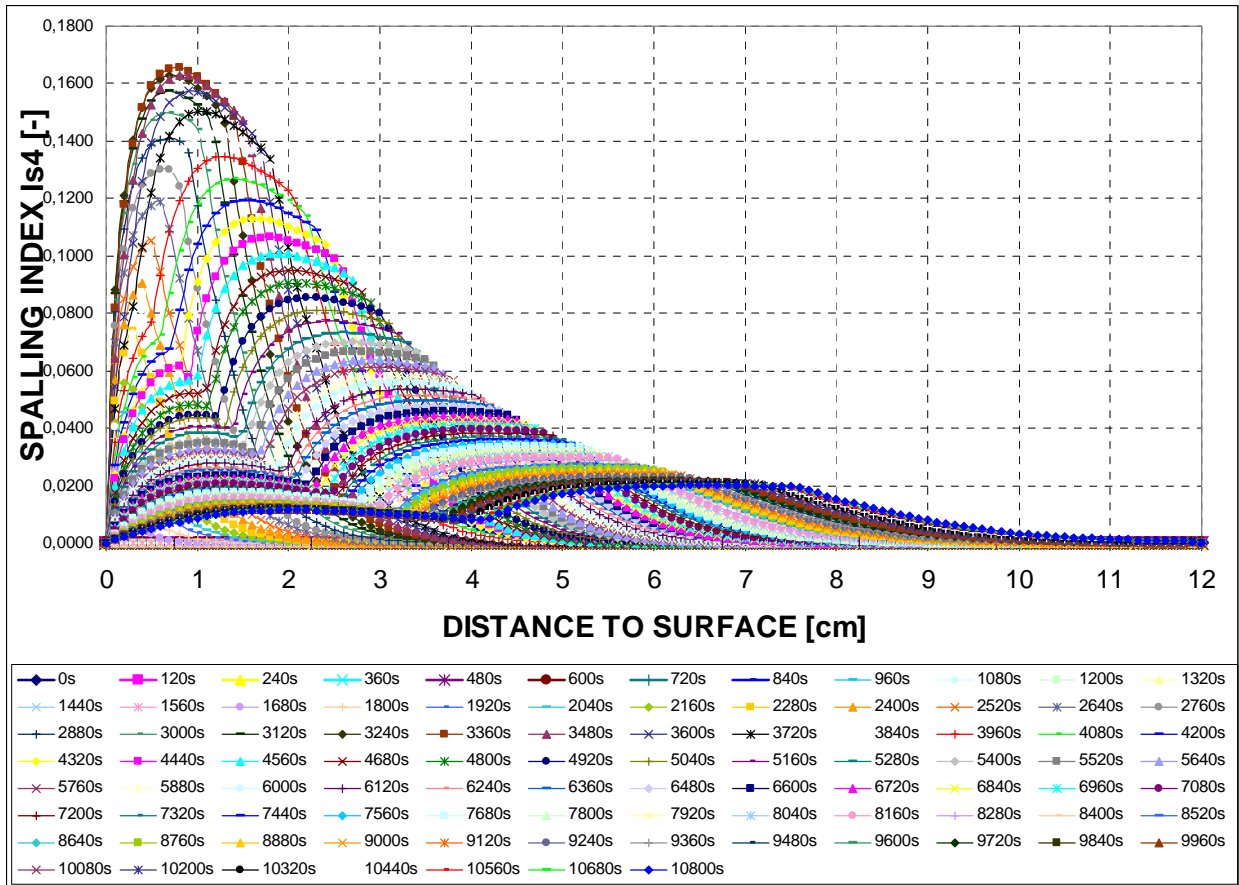


Figure 4A-51. Spalling Index IS_4 evolution for combination 51-TH12K019RH50PAR2C90

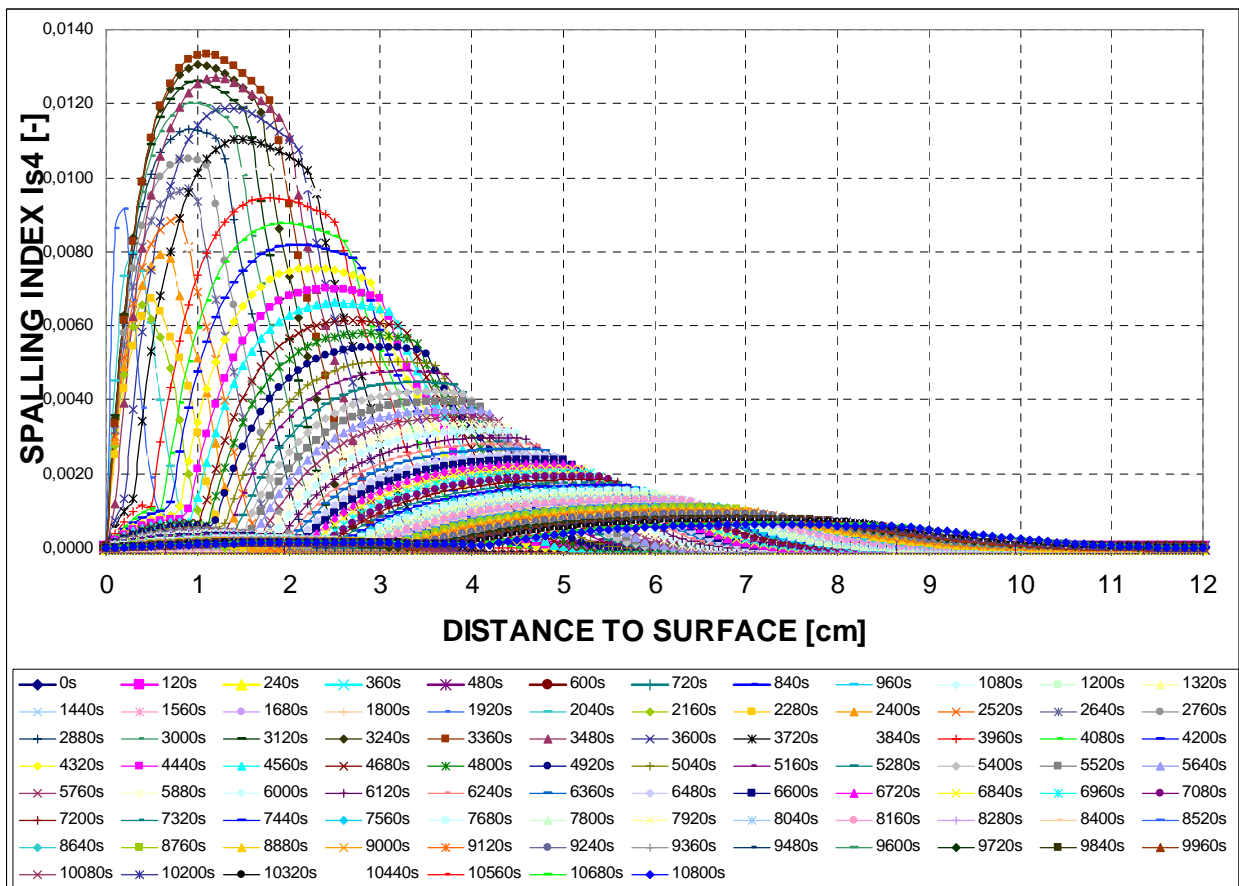


Figure 4A-52. Spalling Index IS_4 evolution for combination 52-TH12K017RH60PAR2C90

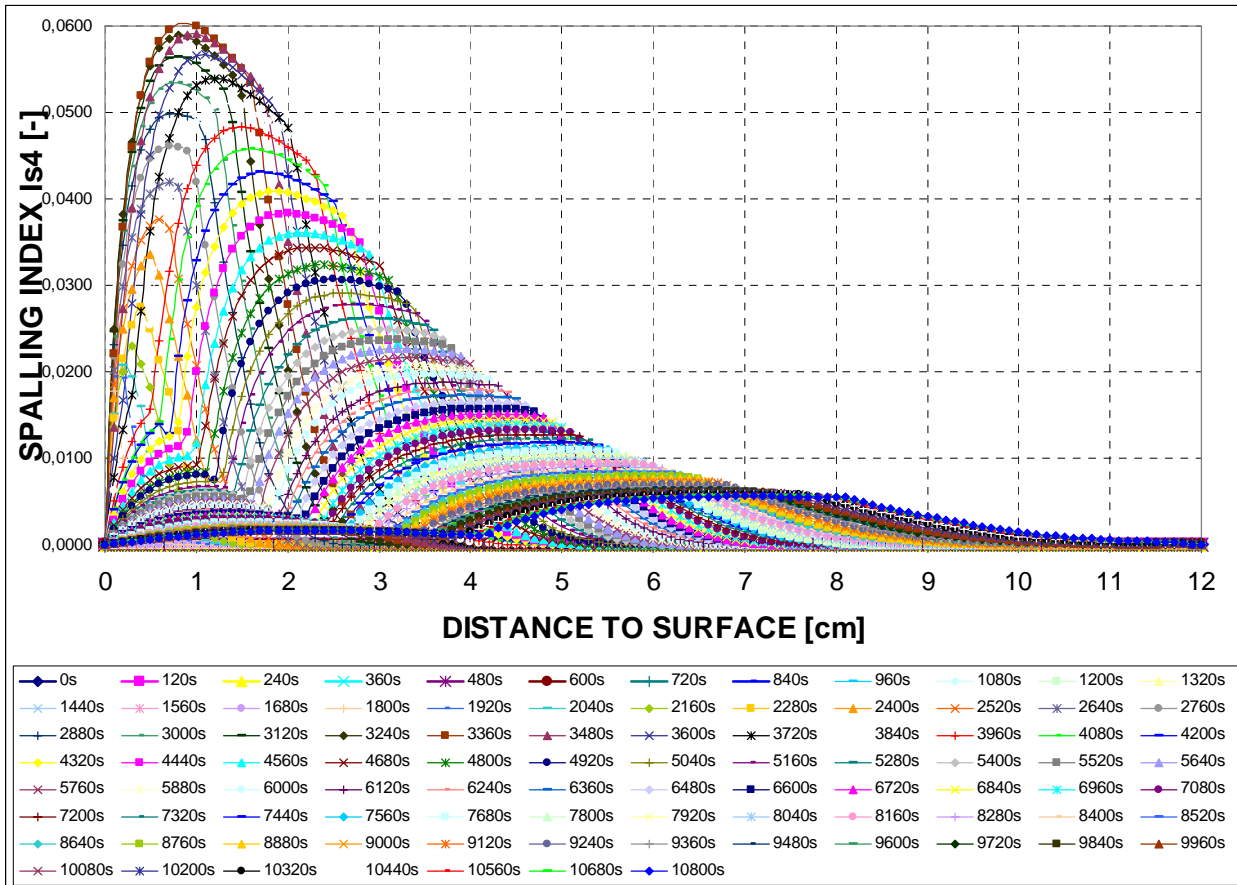


Figure 4A-53. Spalling Index IS4 evolution for combination 53-TH12K018RH60PAR2C90

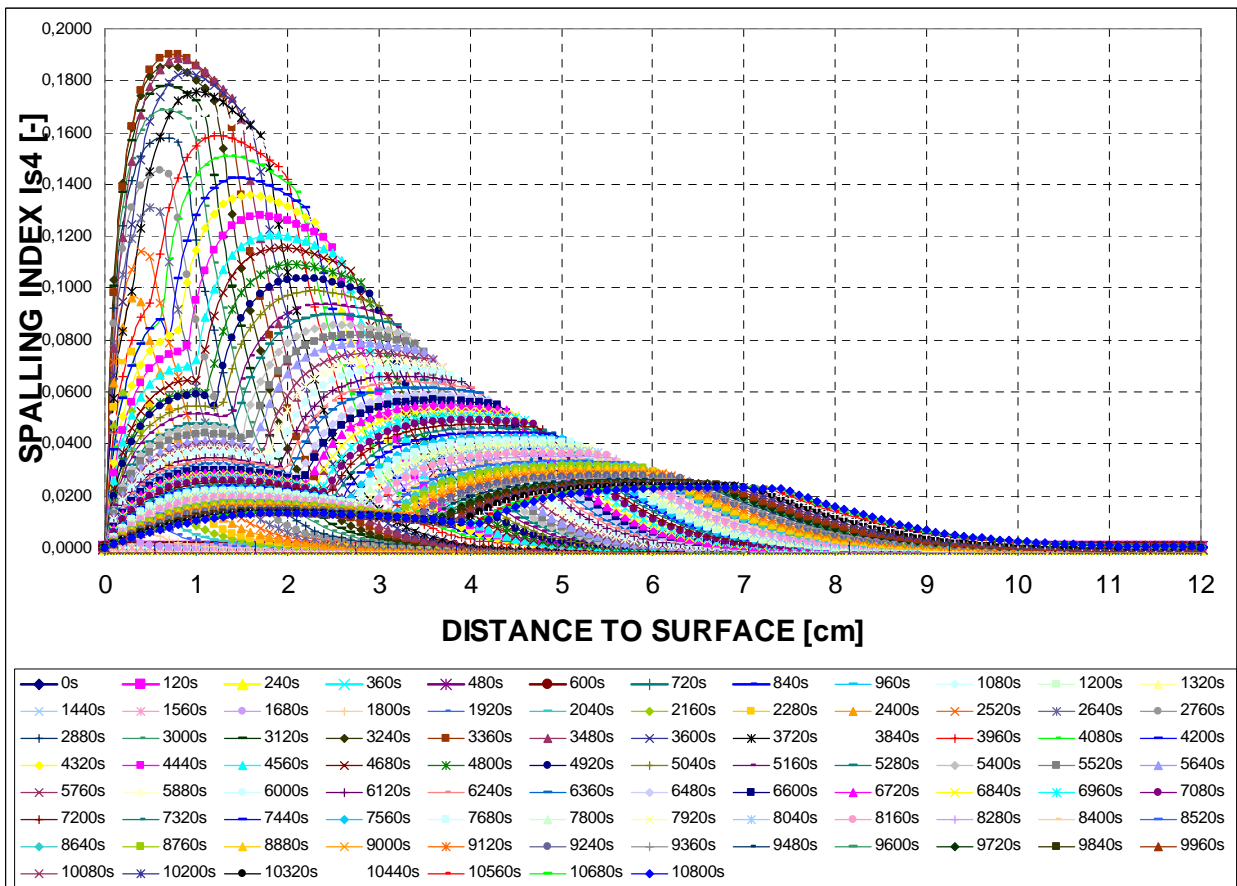


Figure 4A-54. Spalling Index IS4 evolution for combination 54-TH12K019RH60PAR2C90

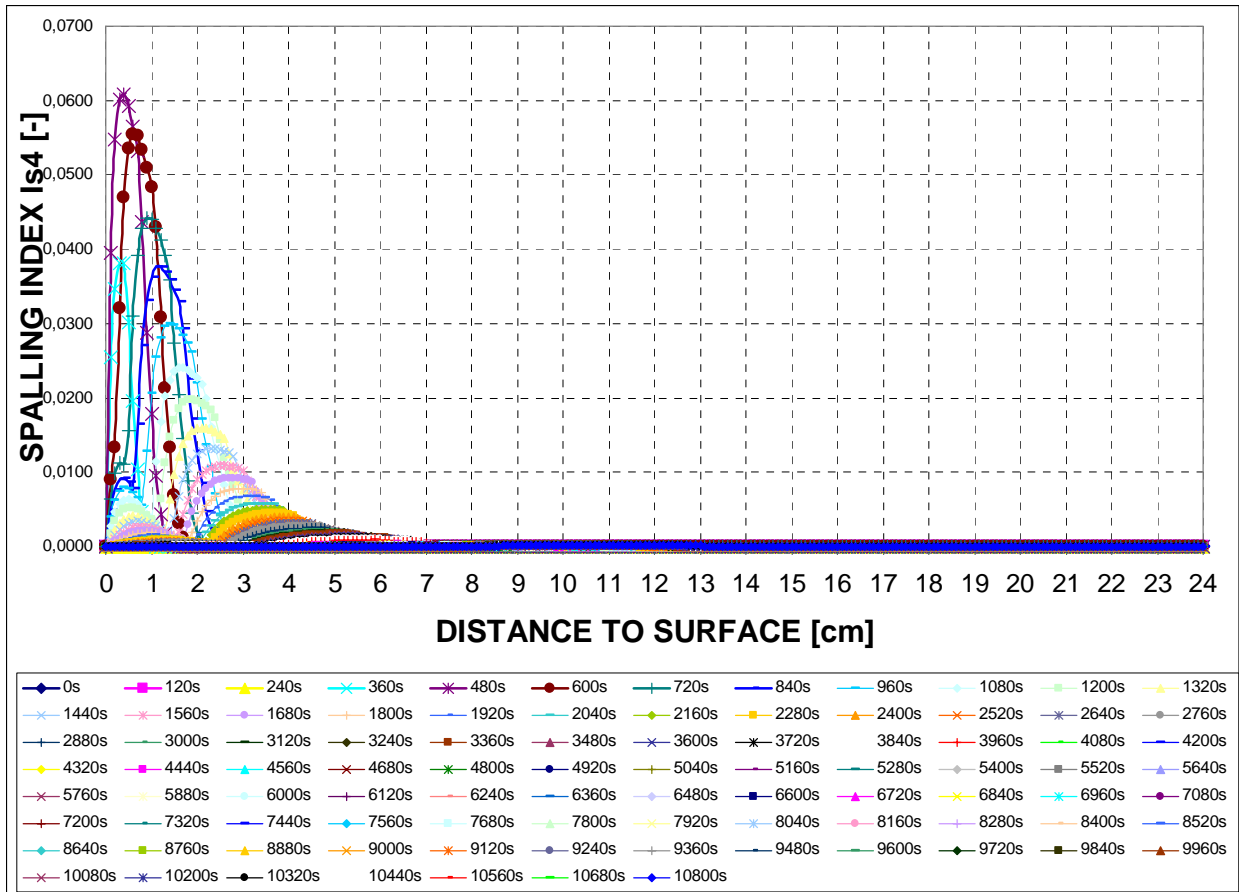


Figure 4A-55. Spalling Index IS_4 evolution for combination 55-TH24K017RH40PAR1C90

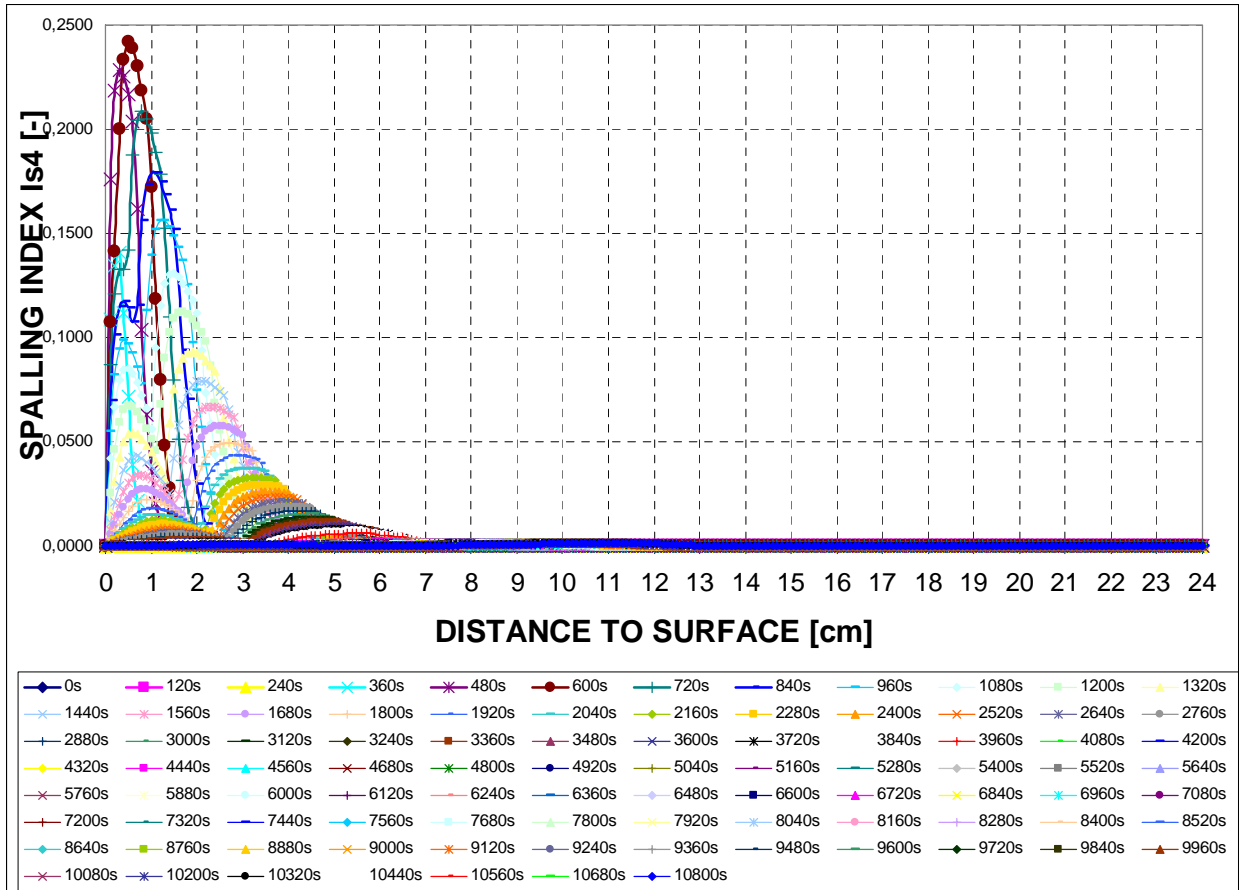


Figure 4A-56. Spalling Index IS_4 evolution for combination 56-TH24K018RH40PAR1C90

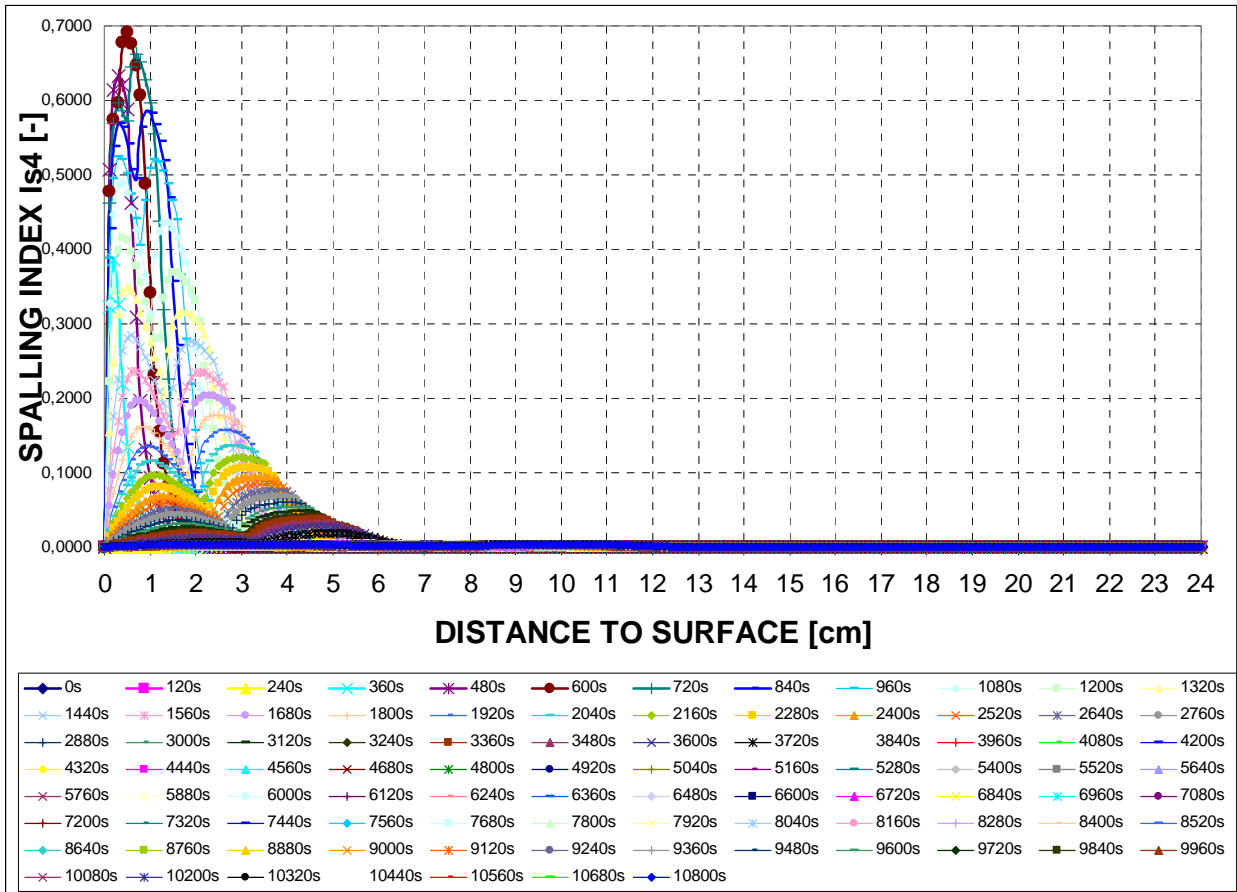


Figure 4A-57. Spalling Index IS4 evolution for combination 57-TH24K019RH40PAR1C90

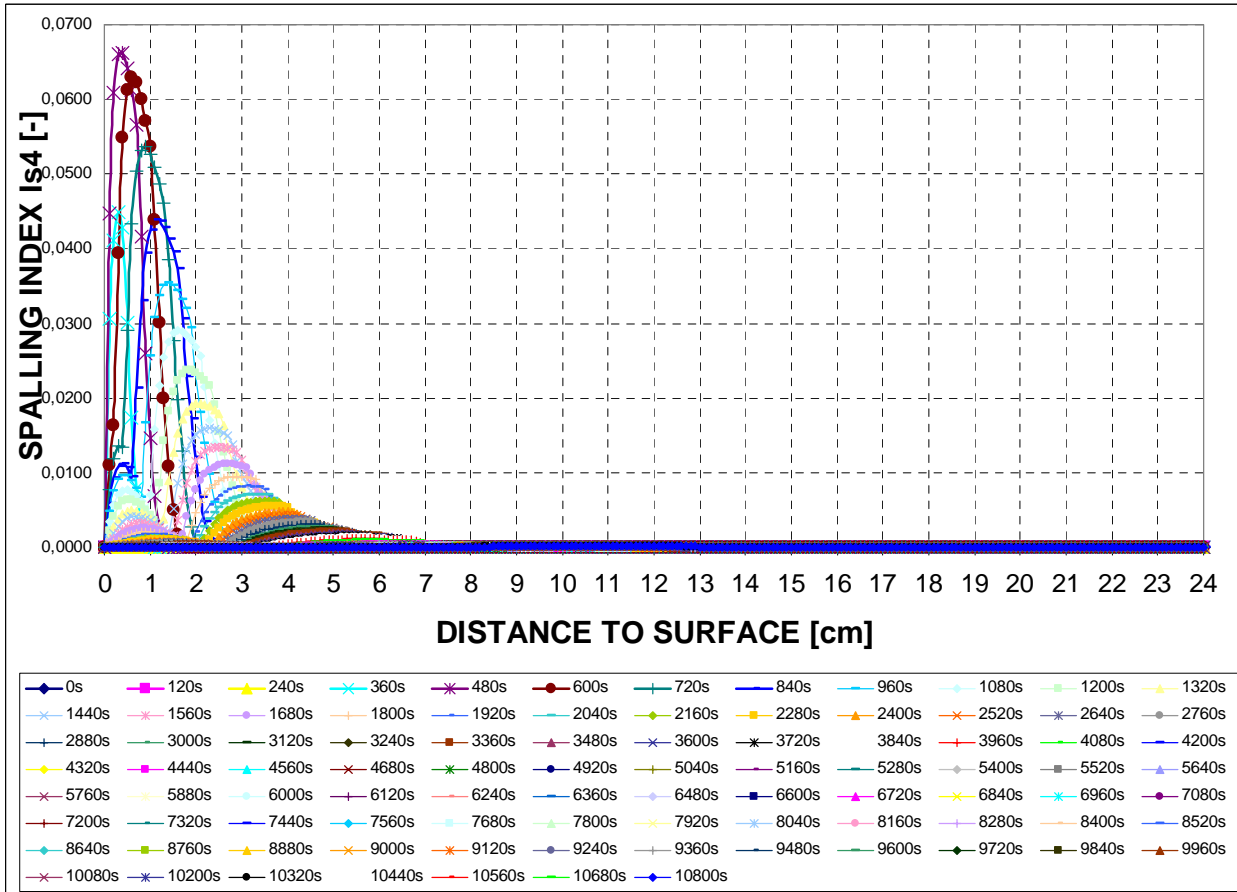


Figure 4A-58. Spalling Index IS4 evolution for combination 58-TH24K017RH50PAR1C90

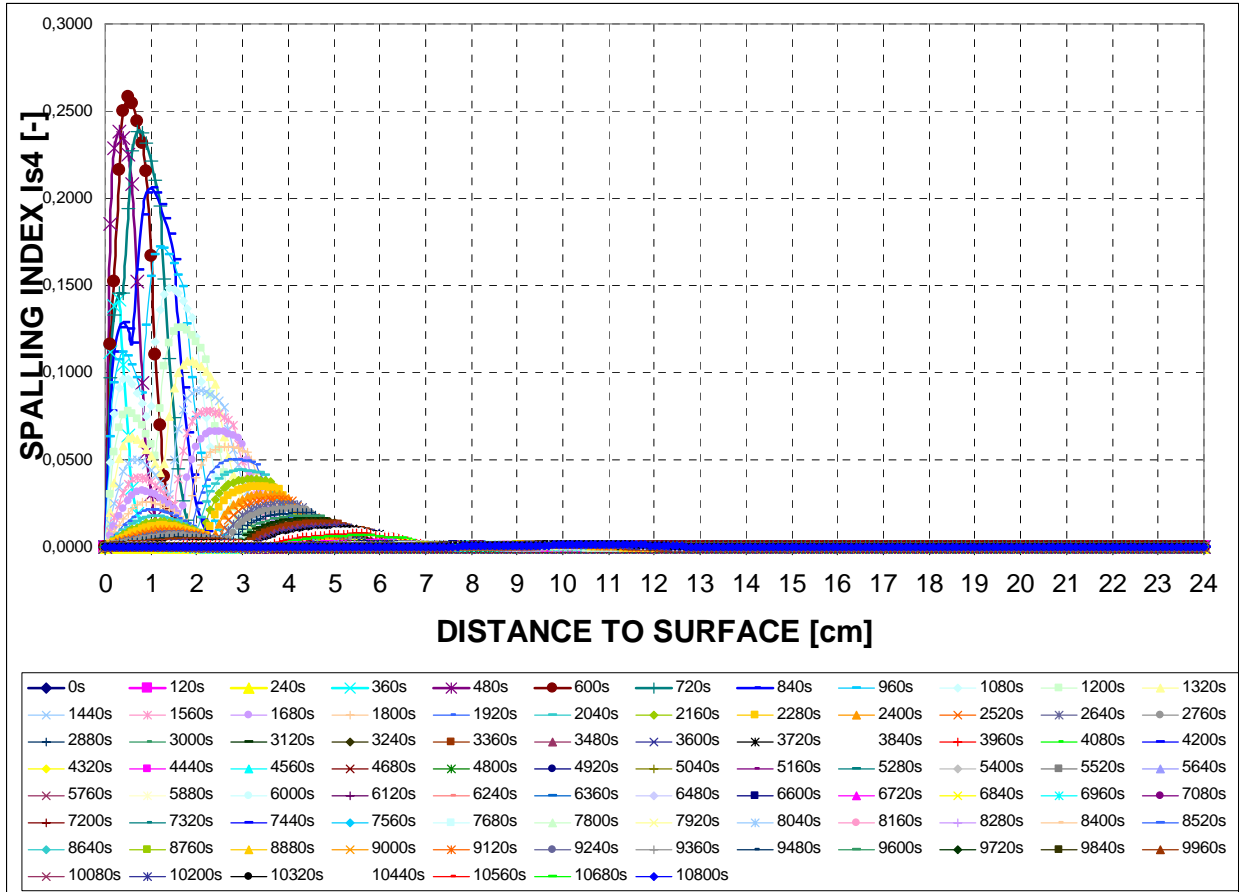


Figure 4A-59. Spalling Index IS_4 evolution for combination 59-TH24K018RH50PAR1C90

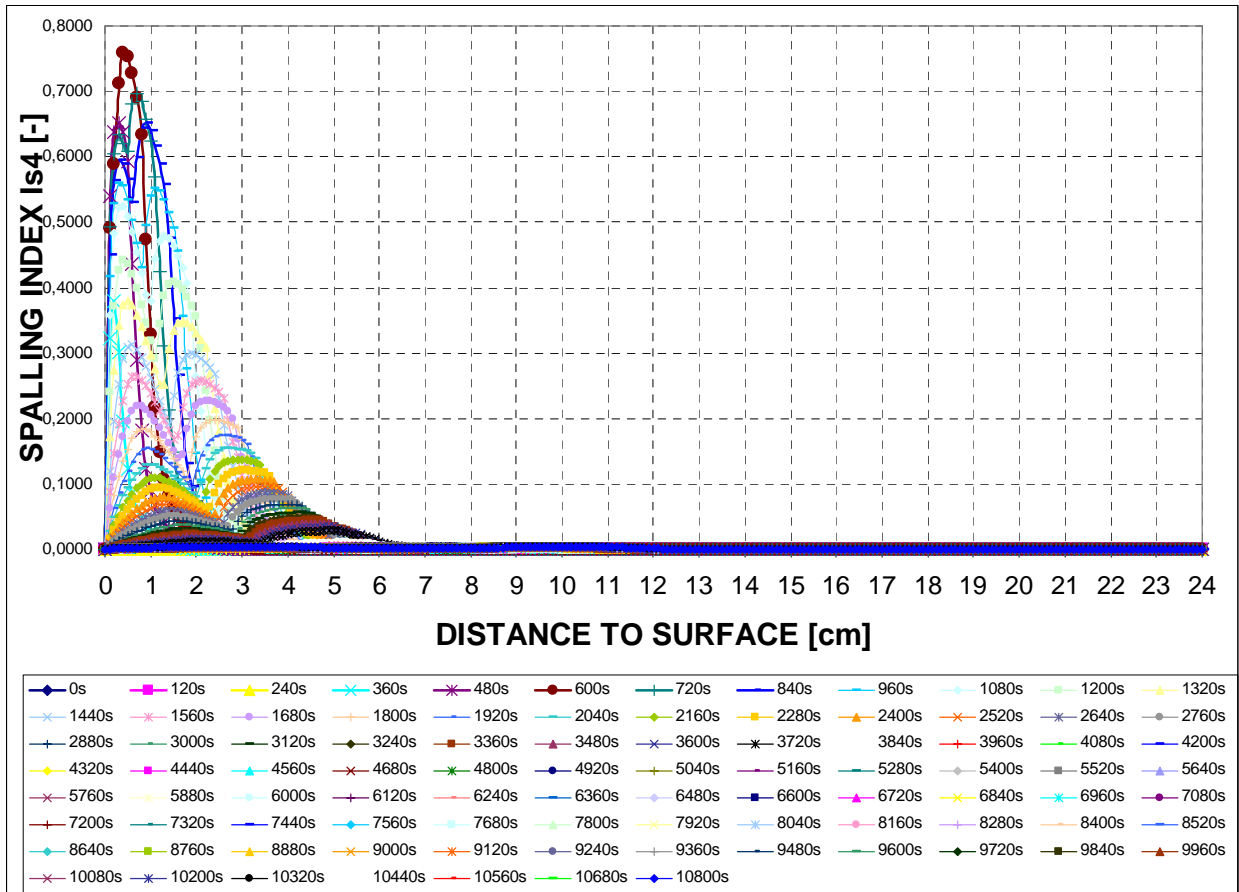


Figure 4A-60. Spalling Index IS_4 evolution for combination 60-TH24K019RH50PAR1C90

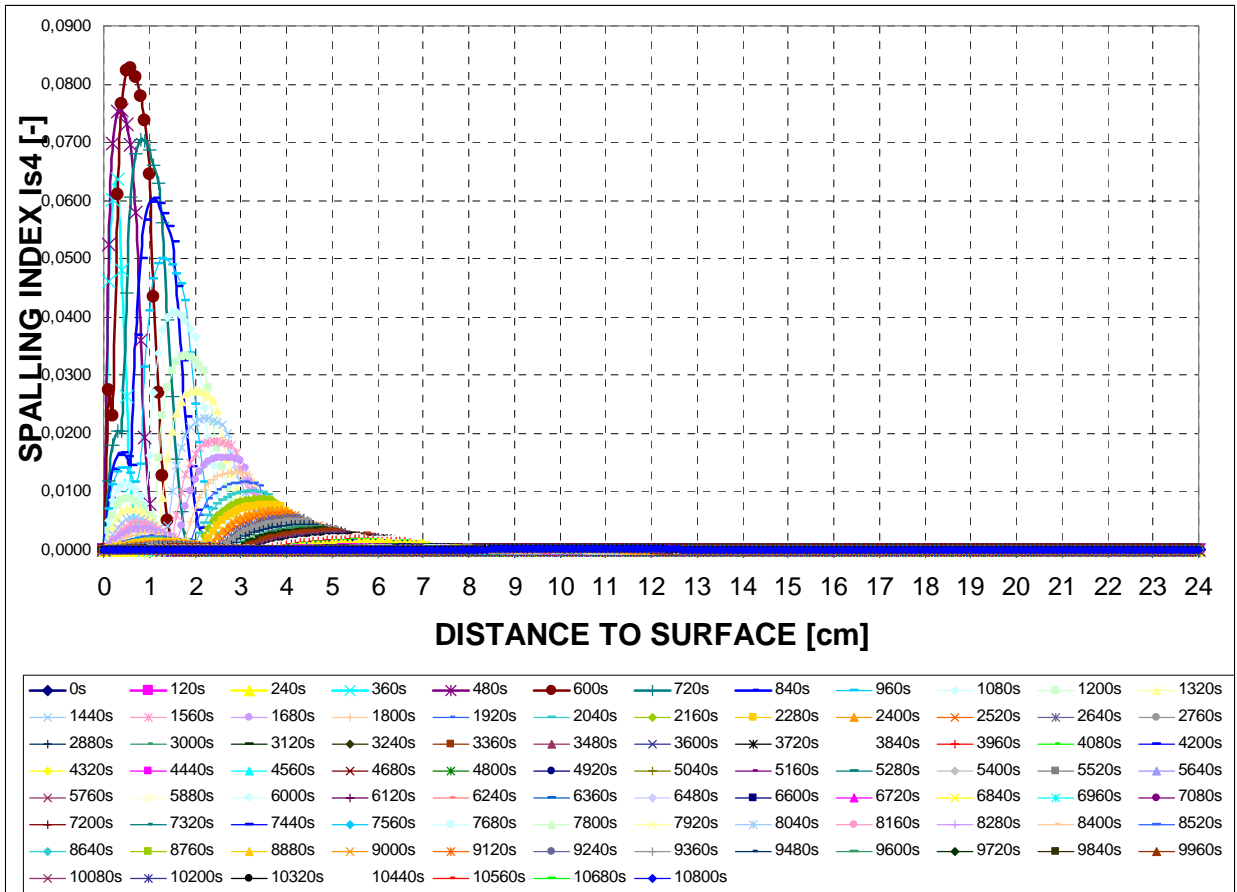


Figure 4A-61. Spalling Index IS_4 evolution for combination 61-TH24K017RH60PAR1C90

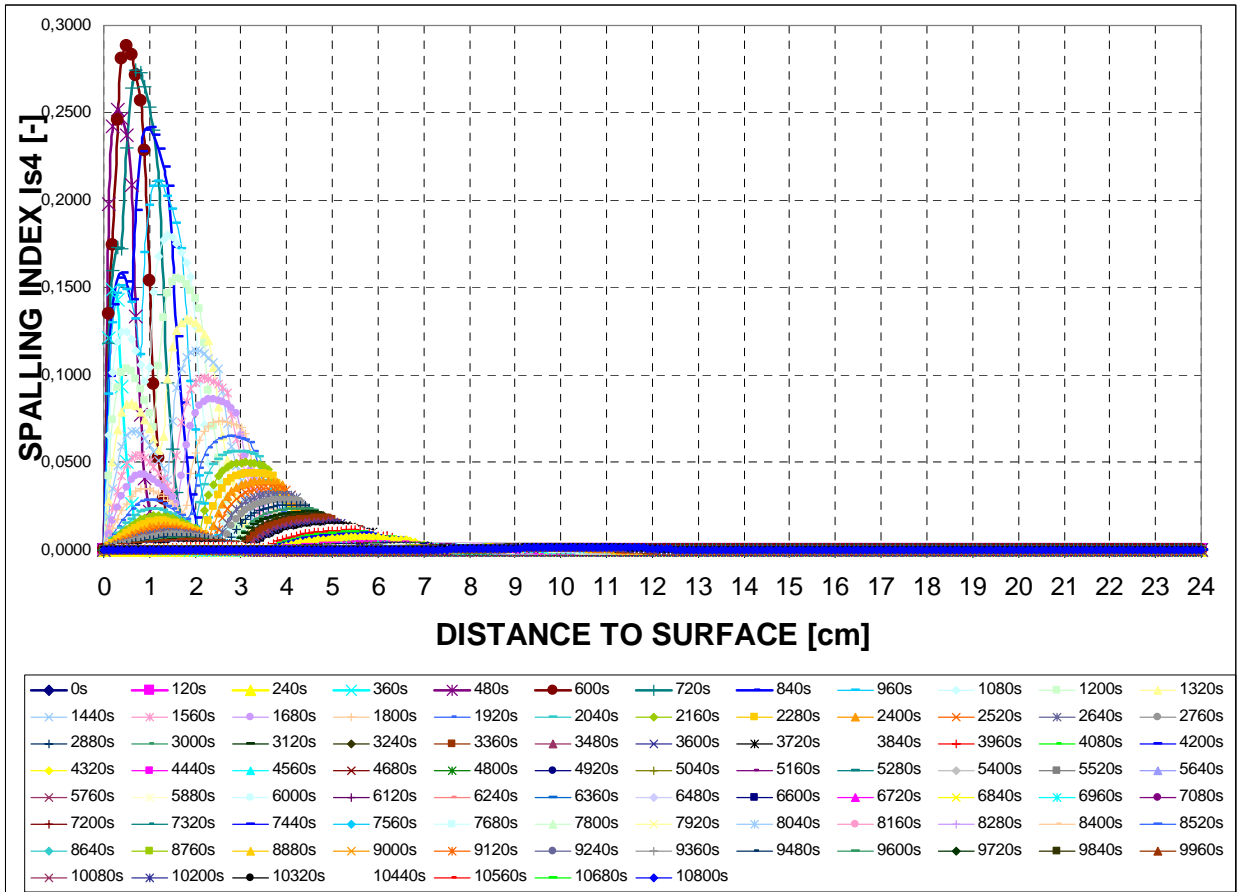


Figure 4A-62. Spalling Index IS_4 evolution for combination 62-TH24K018RH60PAR1C90

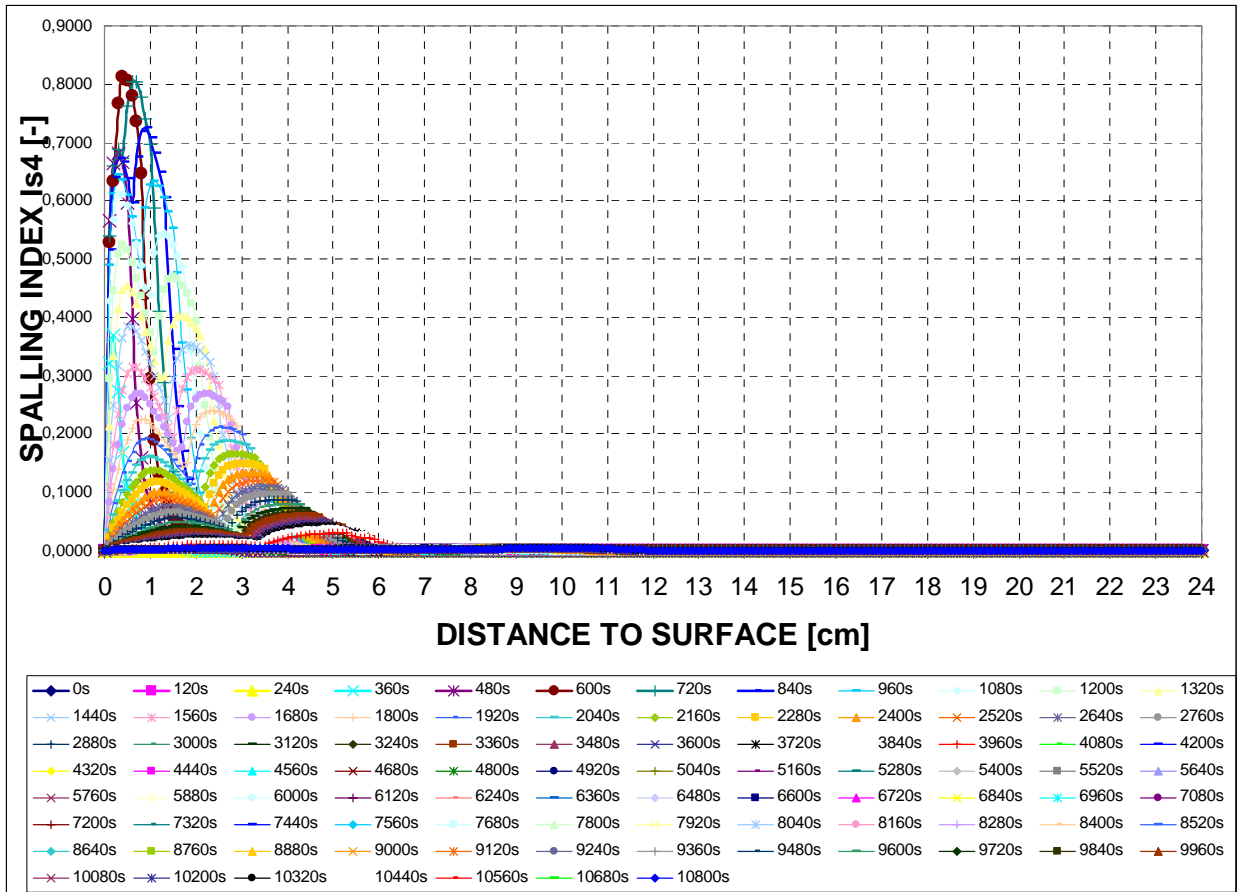


Figure 4A-63. Spalling Index IS_4 evolution for combination 63-TH24K019RH60PAR1C90

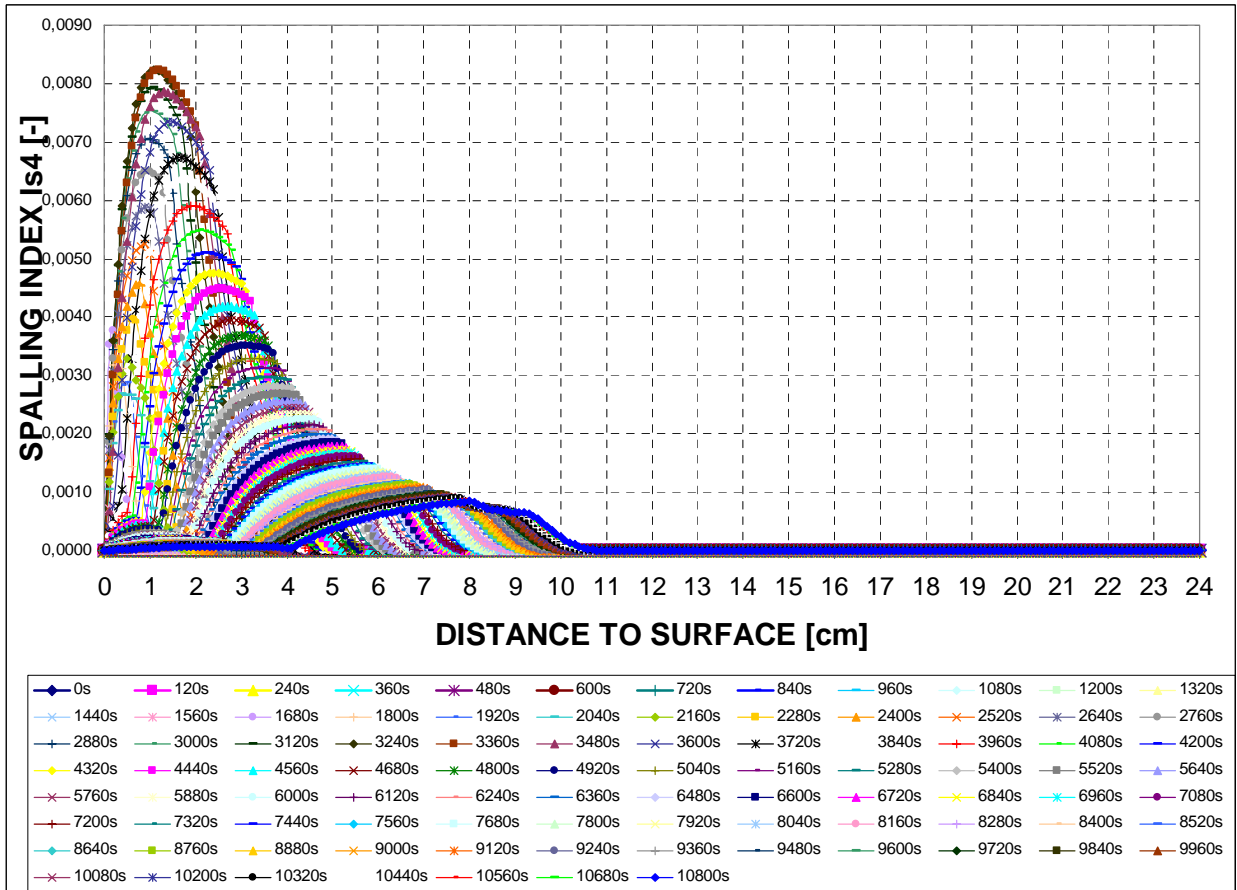


Figure 4A-64. Spalling Index IS_4 evolution for combination 64-TH24K017RH40PAR2C90

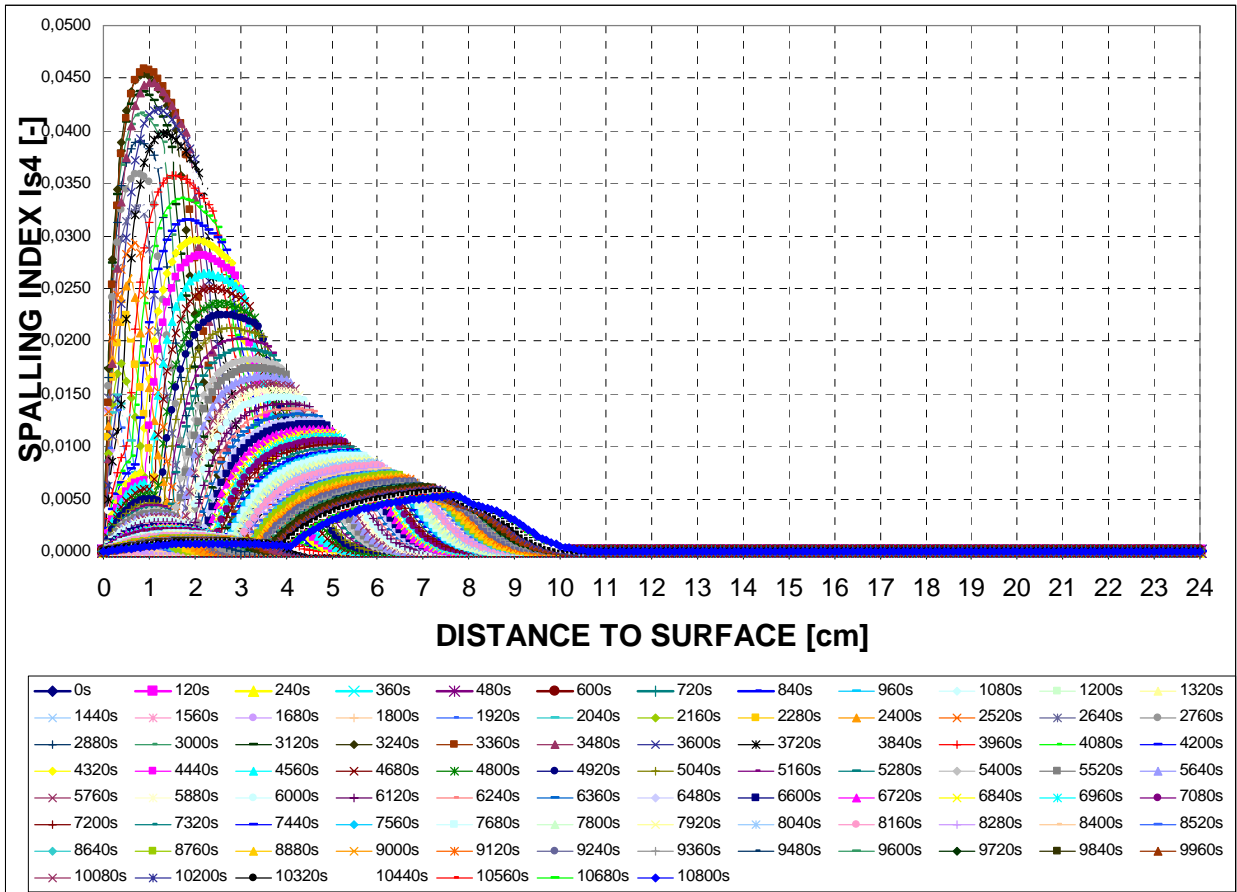


Figure 4A-65. Spalling Index IS4 evolution for combination 65-TH24K018RH40PAR2C90

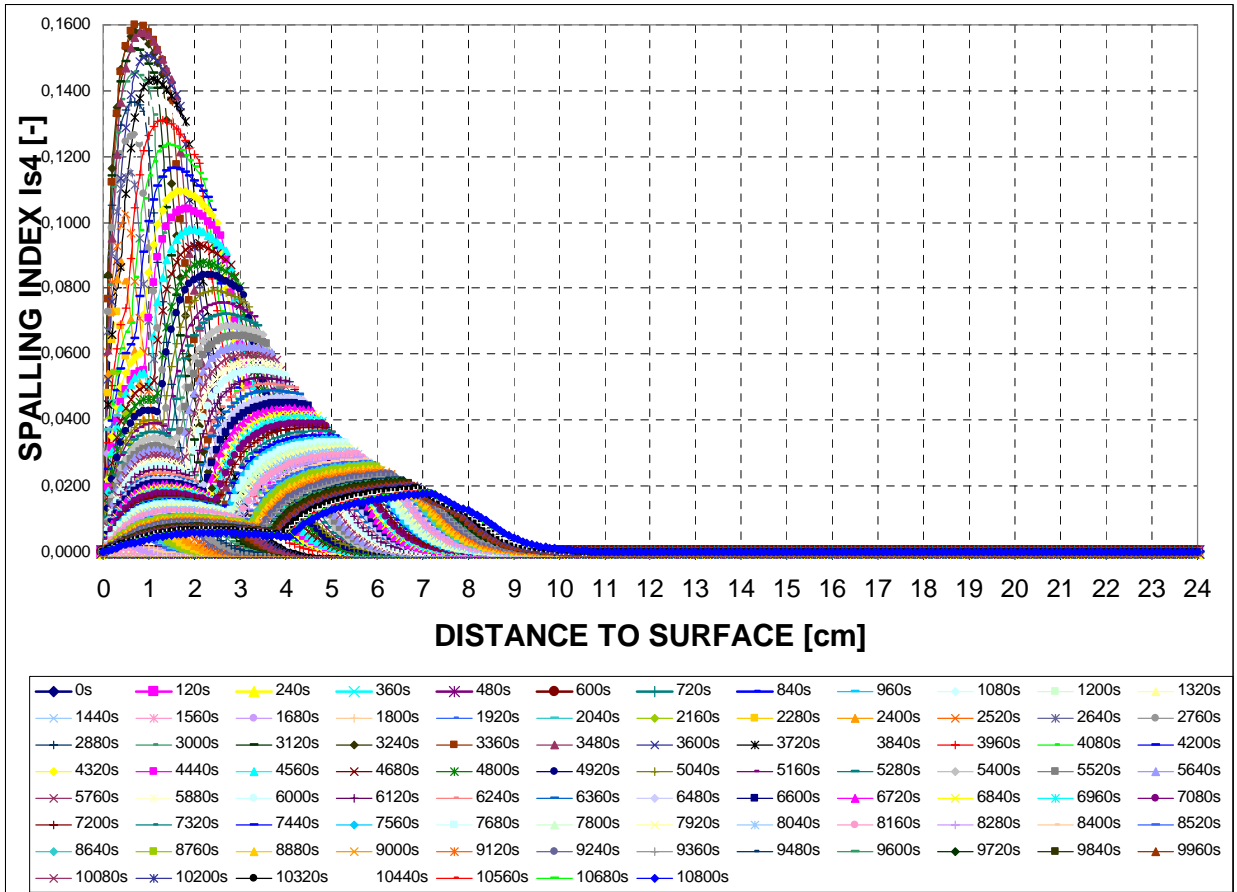


Figure 4A-66. Spalling Index IS4 evolution for combination 66-TH24K019RH40PAR2C90

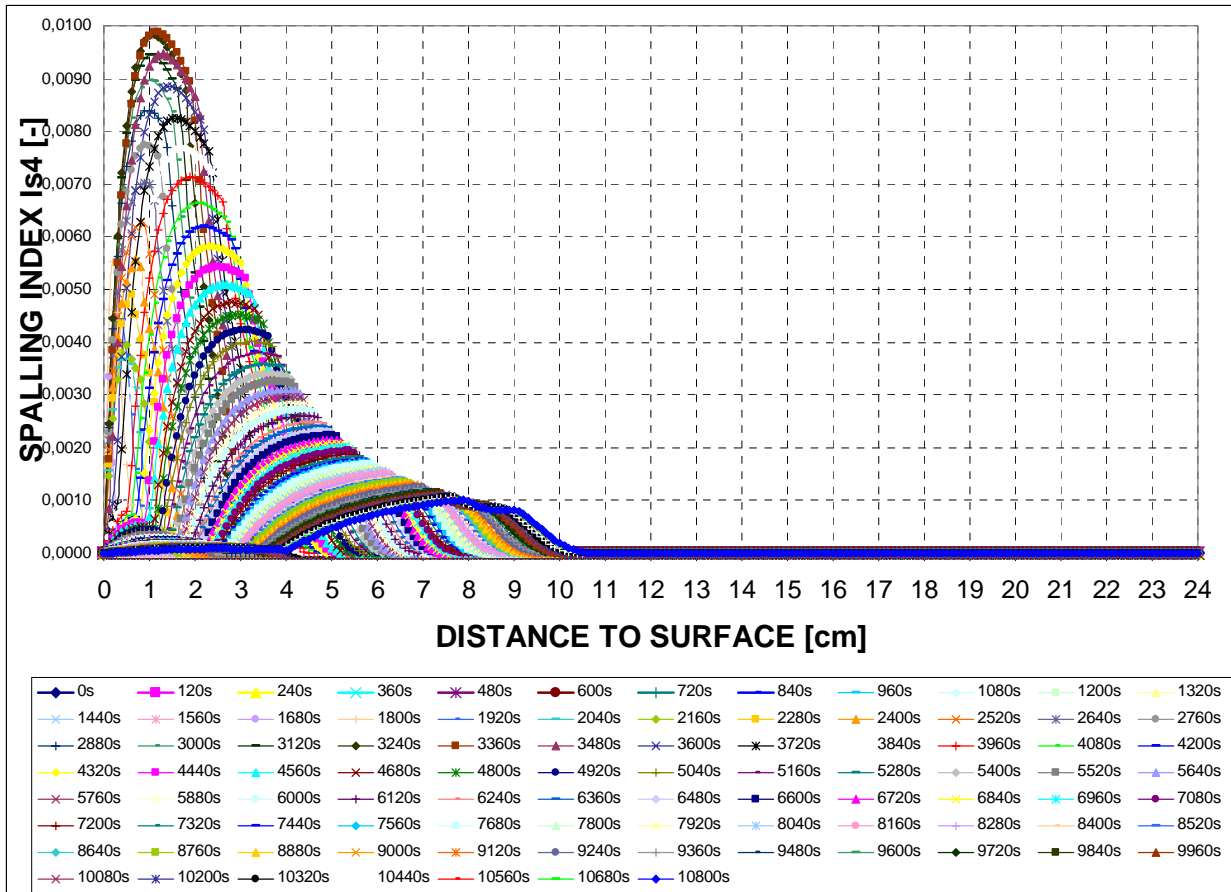


Figure 4A-67. Spalling Index IS_4 evolution for combination 67-TH24K017RH50PAR2C90

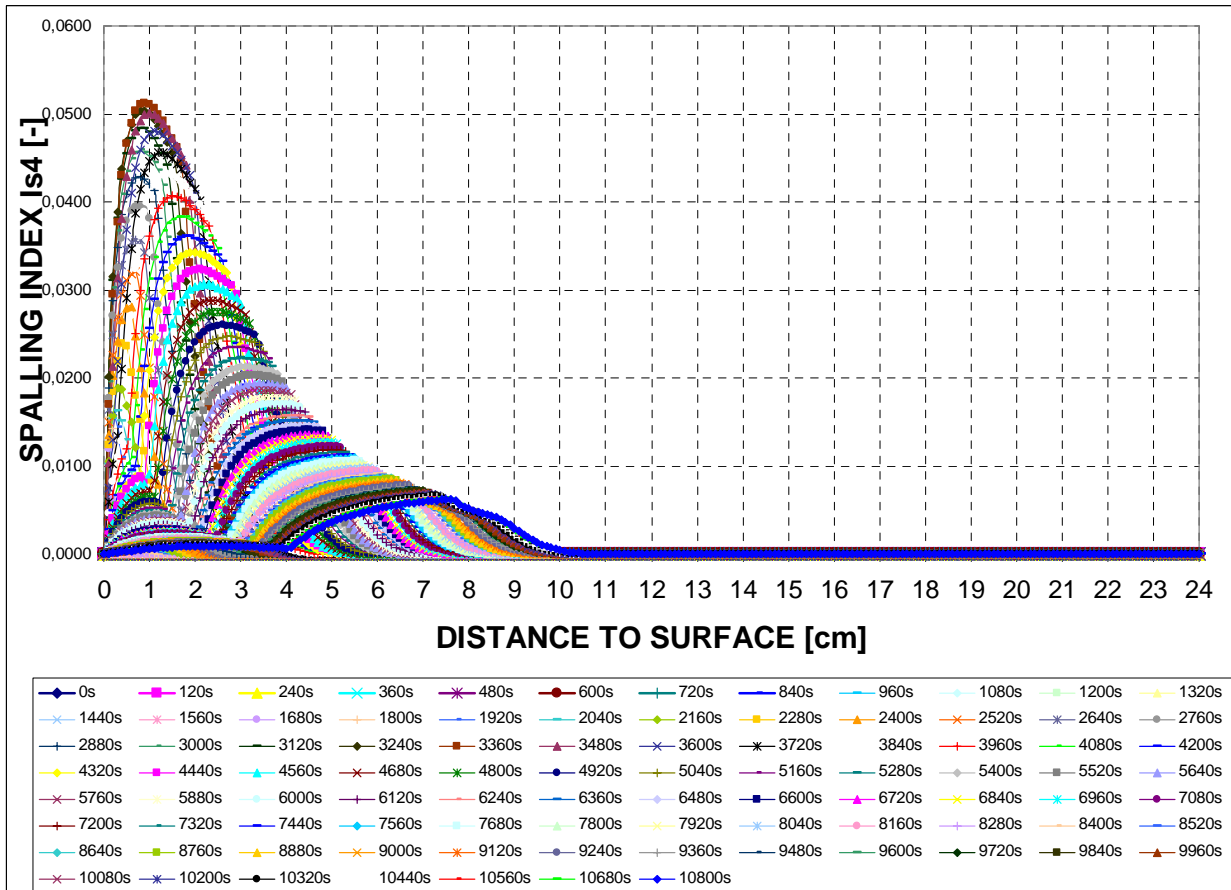


Figure 4A-68. Spalling Index IS_4 evolution for combination 68-TH24K018RH50PAR2C90

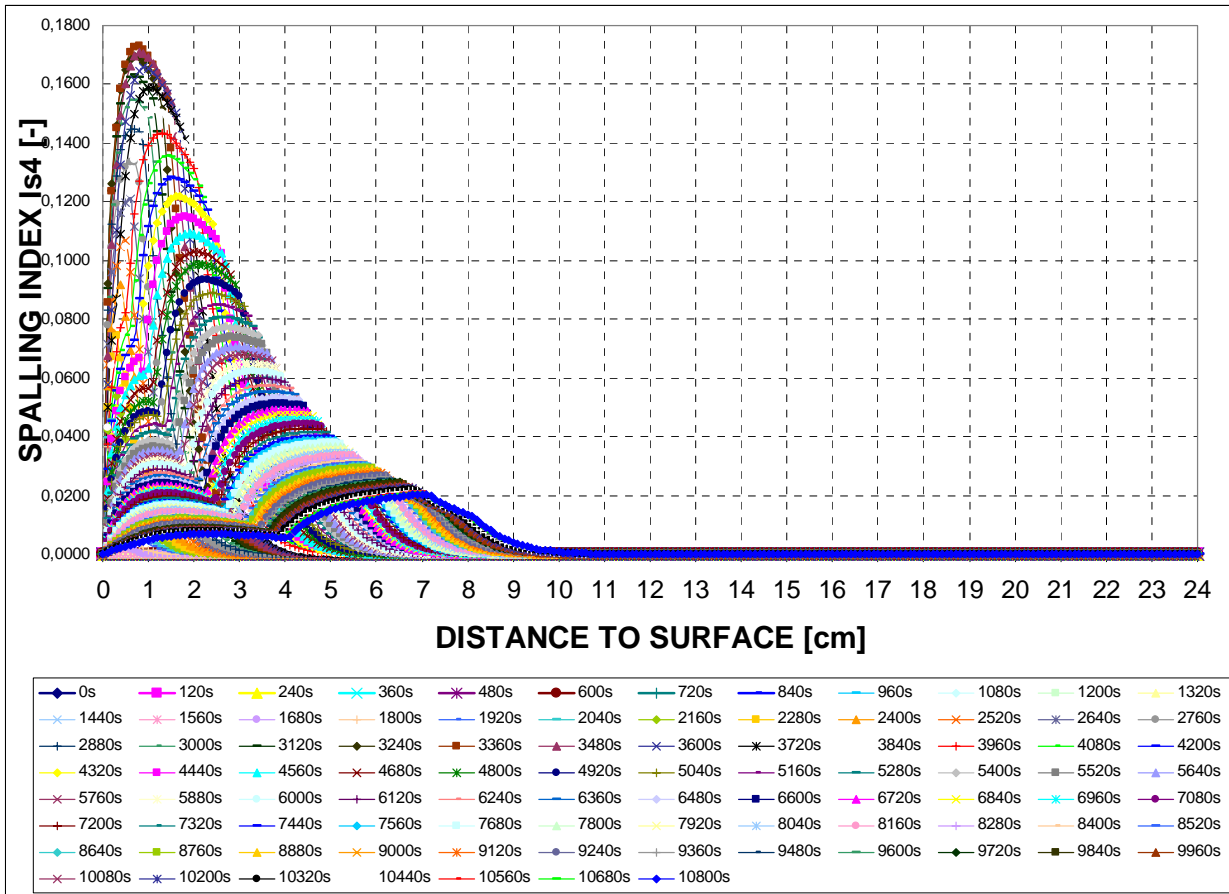


Figure 4A-69. Spalling Index IS4 evolution for combination 69-TH24K019RH50PAR2C90

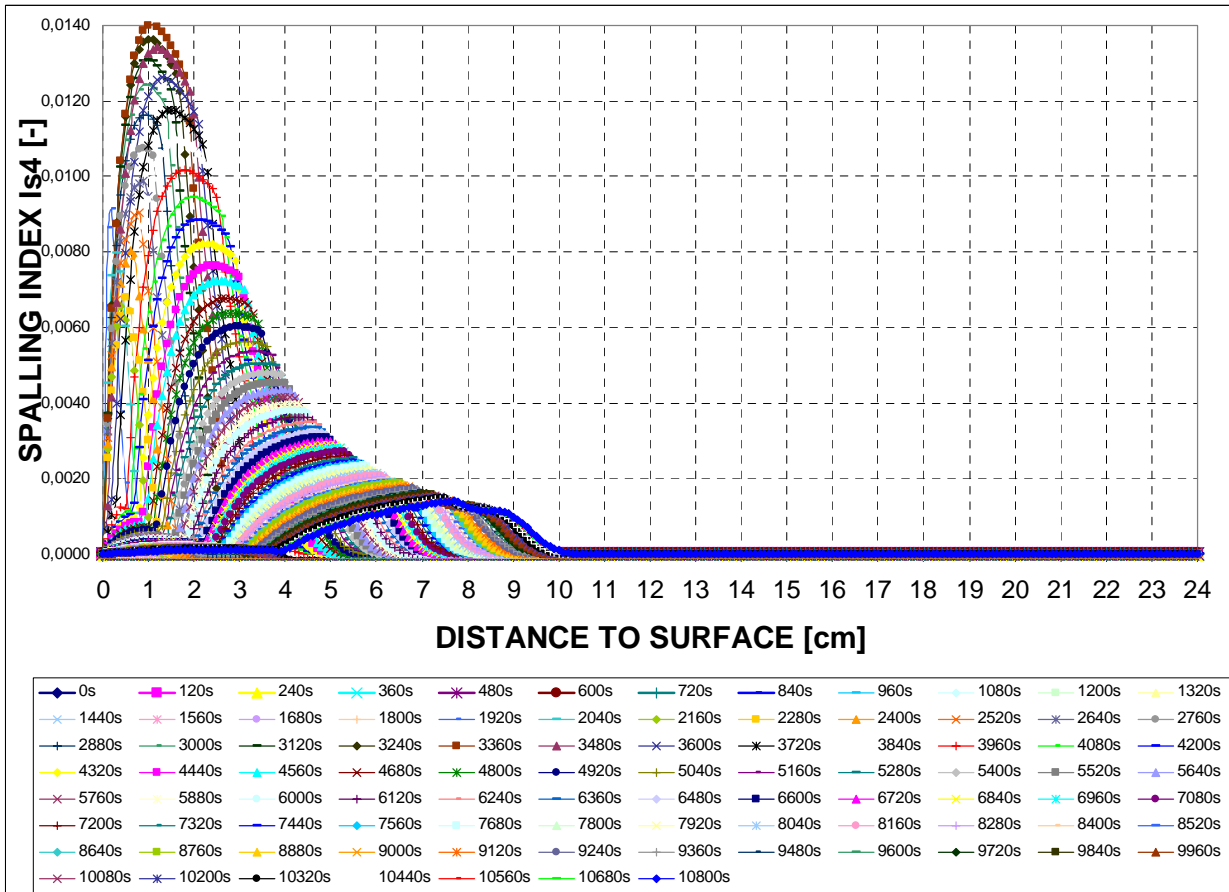


Figure 4A-70. Spalling Index IS4 evolution for combination 70-TH24K017RH60PAR2C90

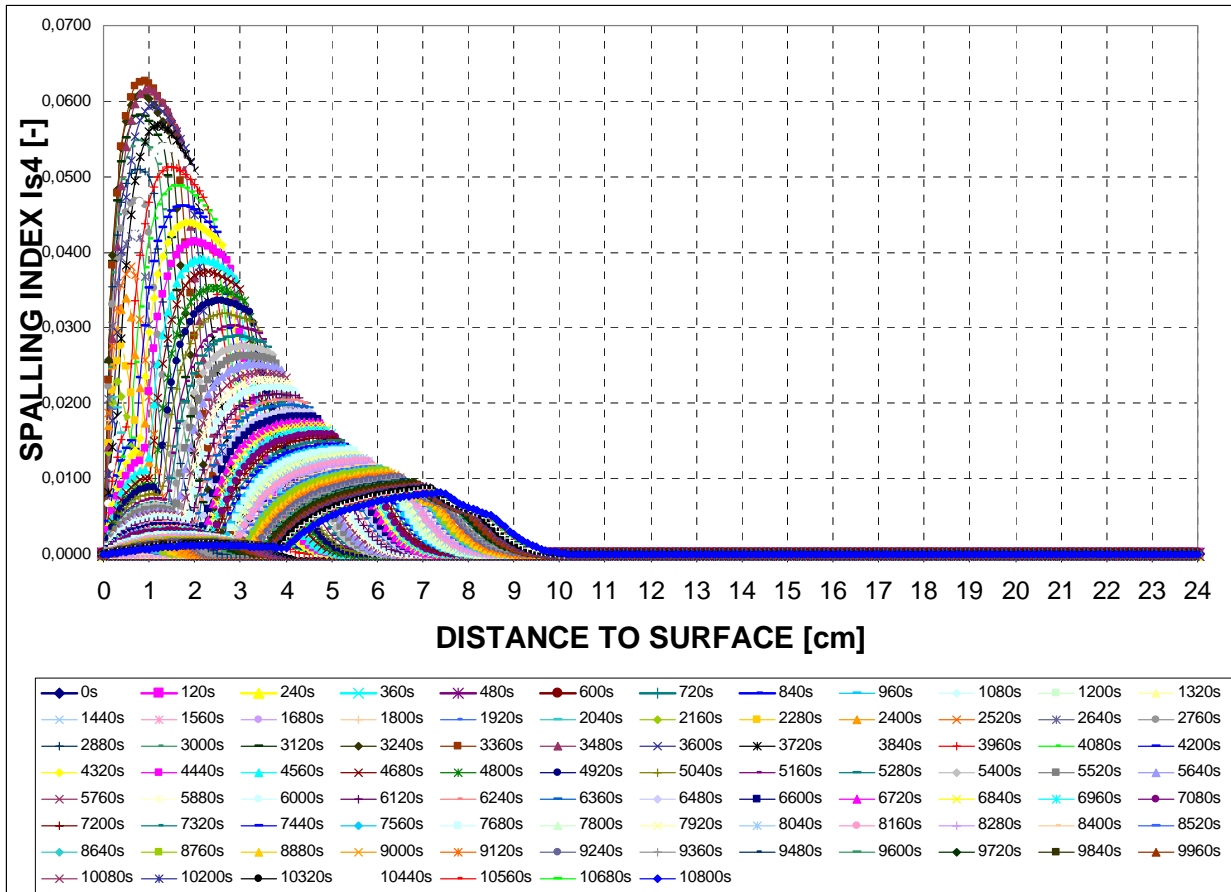


Figure 4A-71. Spalling Index IS4 evolution for combination 71-TH24K018RH60PAR2C90

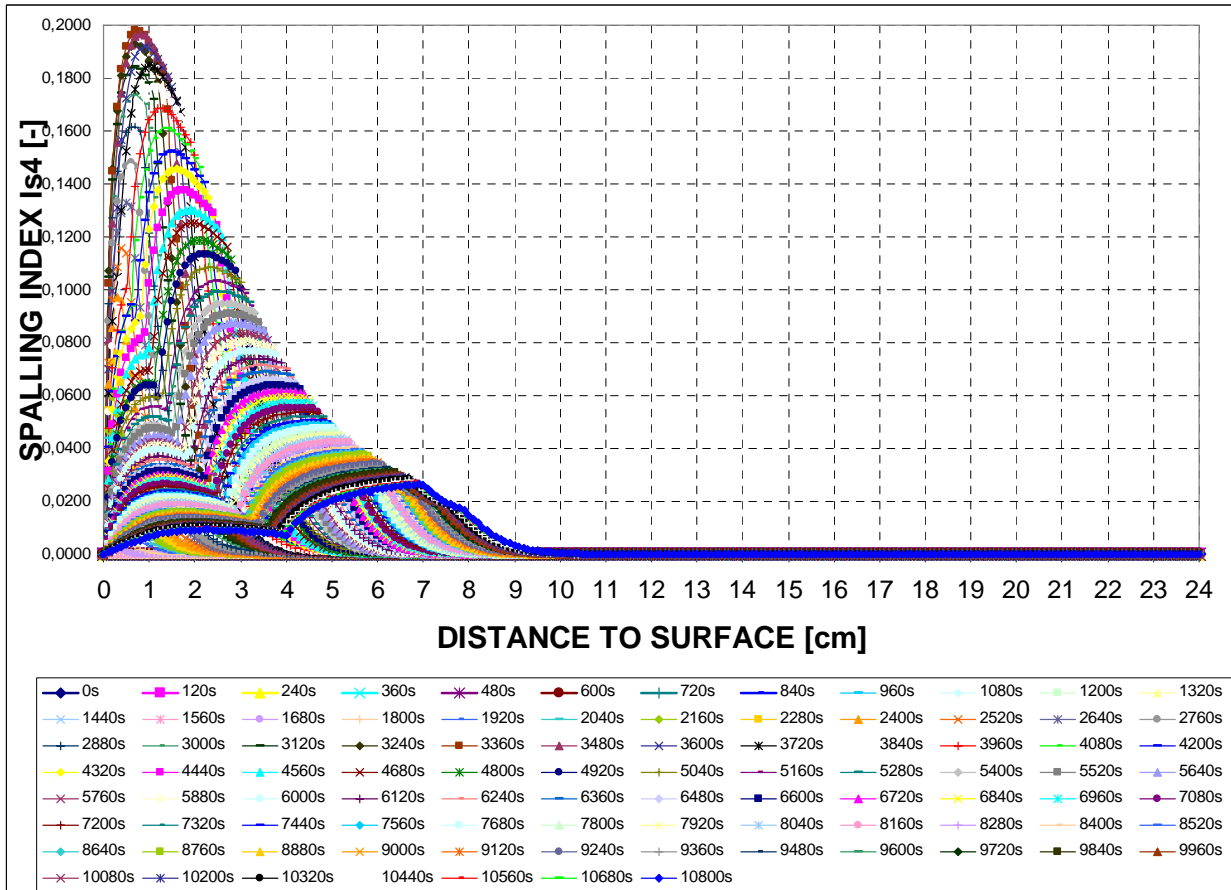


Figure 4A-72. Spalling Index IS4 evolution for combination 72-TH24K019RH60PAR2C90

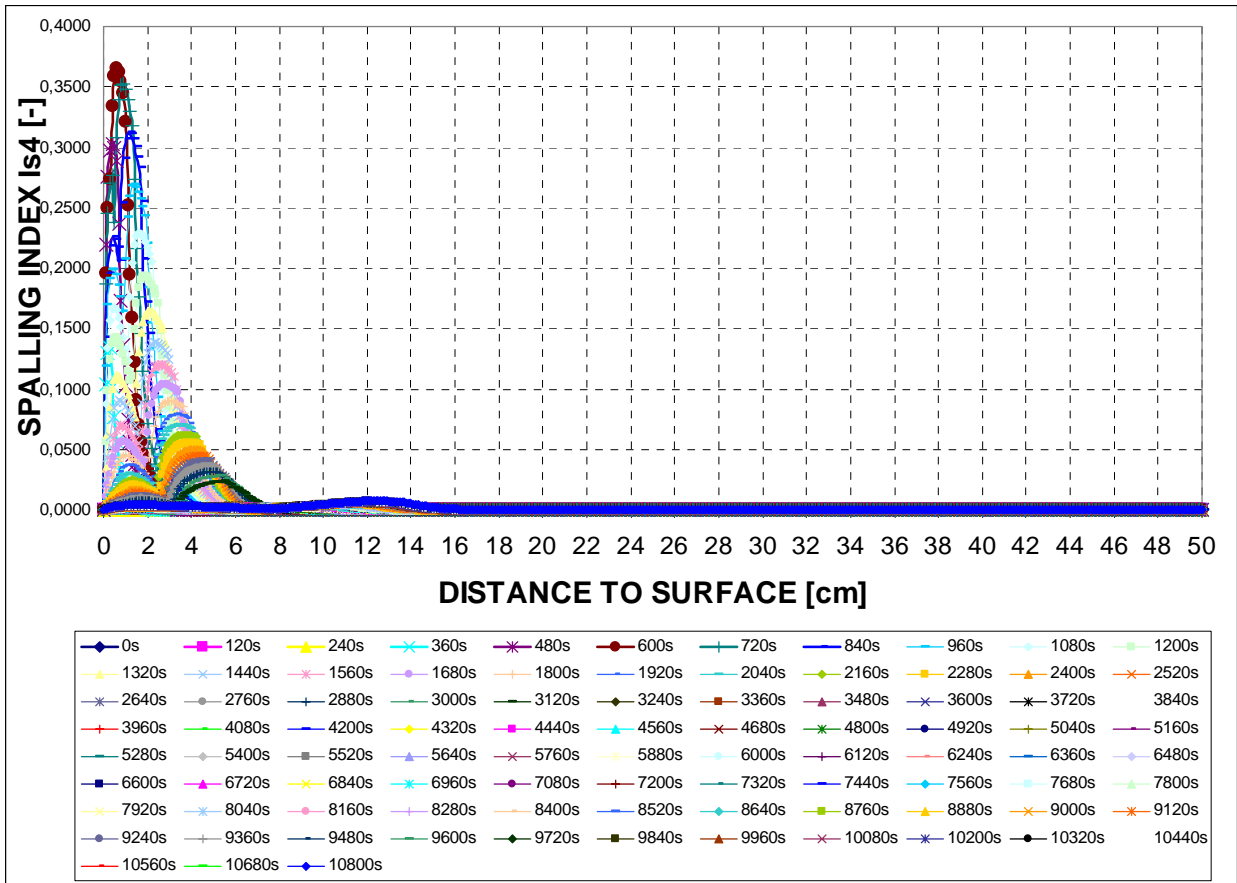


Figure 4A-73. Spalling Index IS4 evolution for combination 73-TH50K018RH50PAR1C60

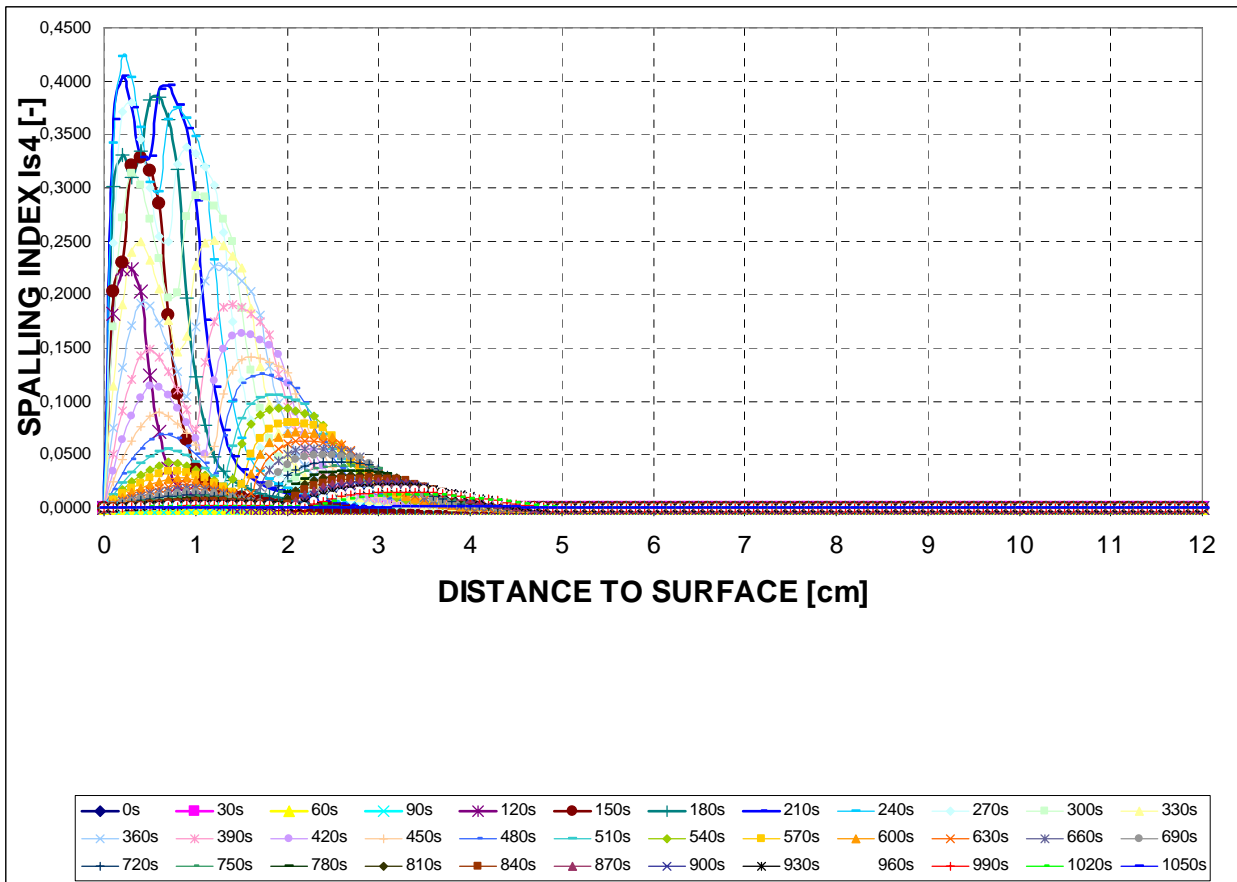


Figure 4A-74. Spalling Index IS4 evolution for combination 74-TH12K017RH40PAR3C60

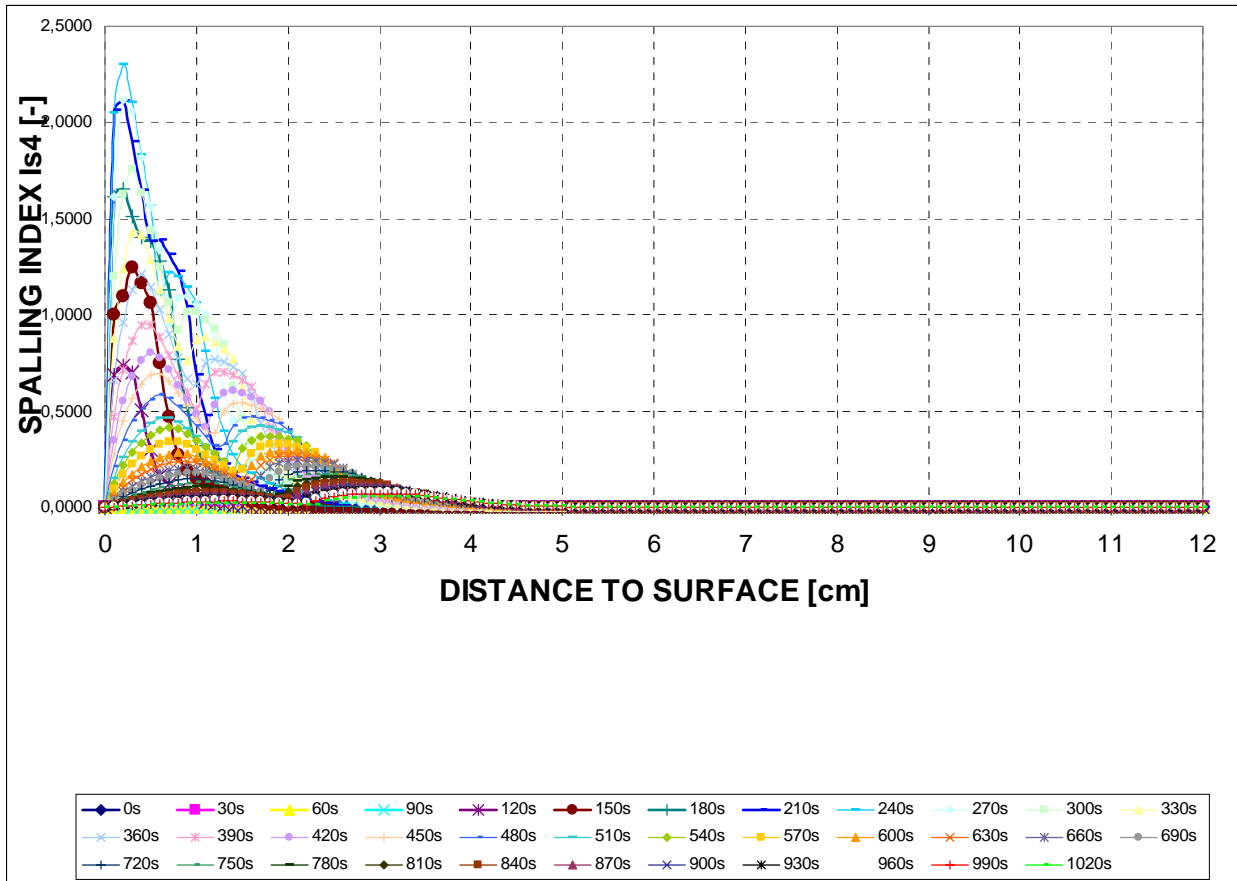


Figure 4A-75. Spalling Index IS4 evolution for combination 75-TH12K018RH40PAR3C60

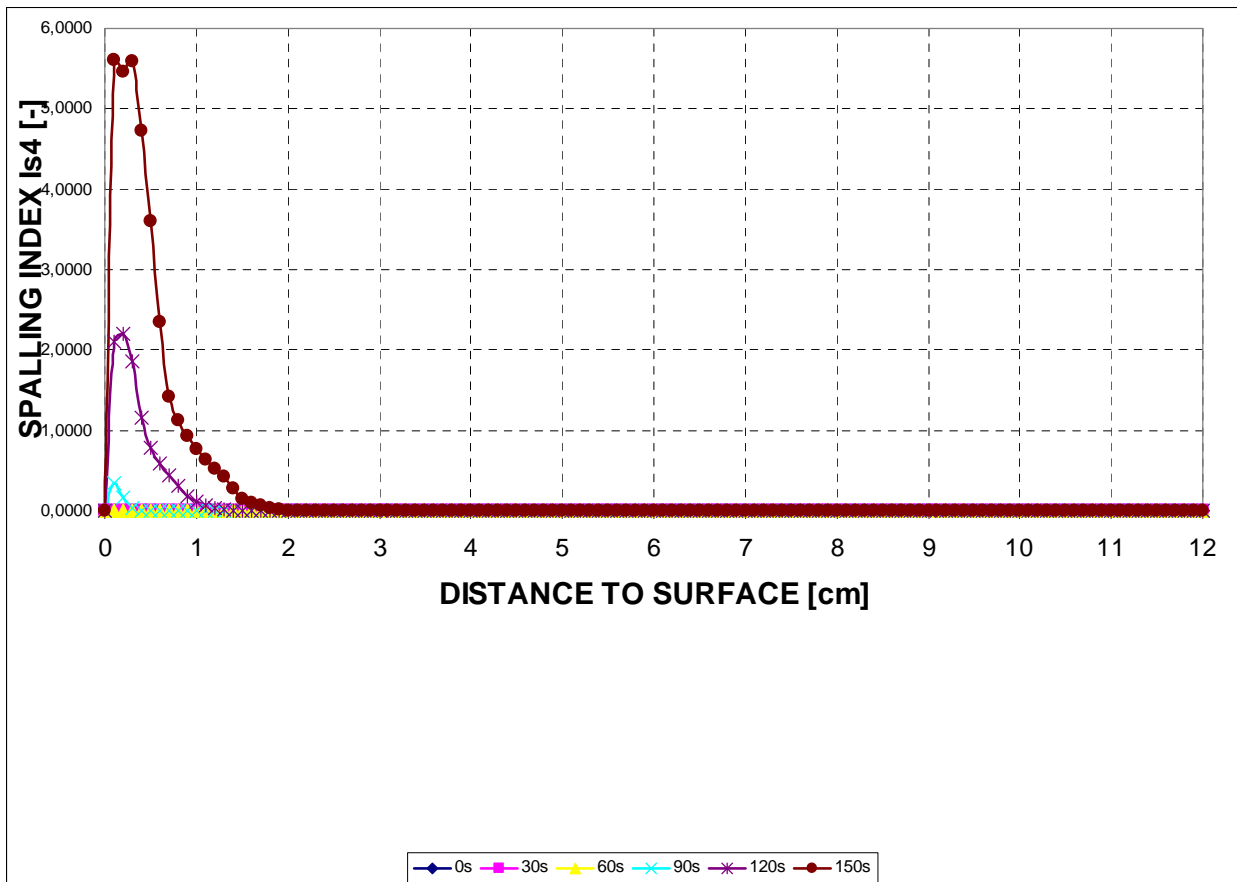


Figure 4A-76. Spalling Index IS4 evolution for combination 76-TH12K019RH40PAR3C60

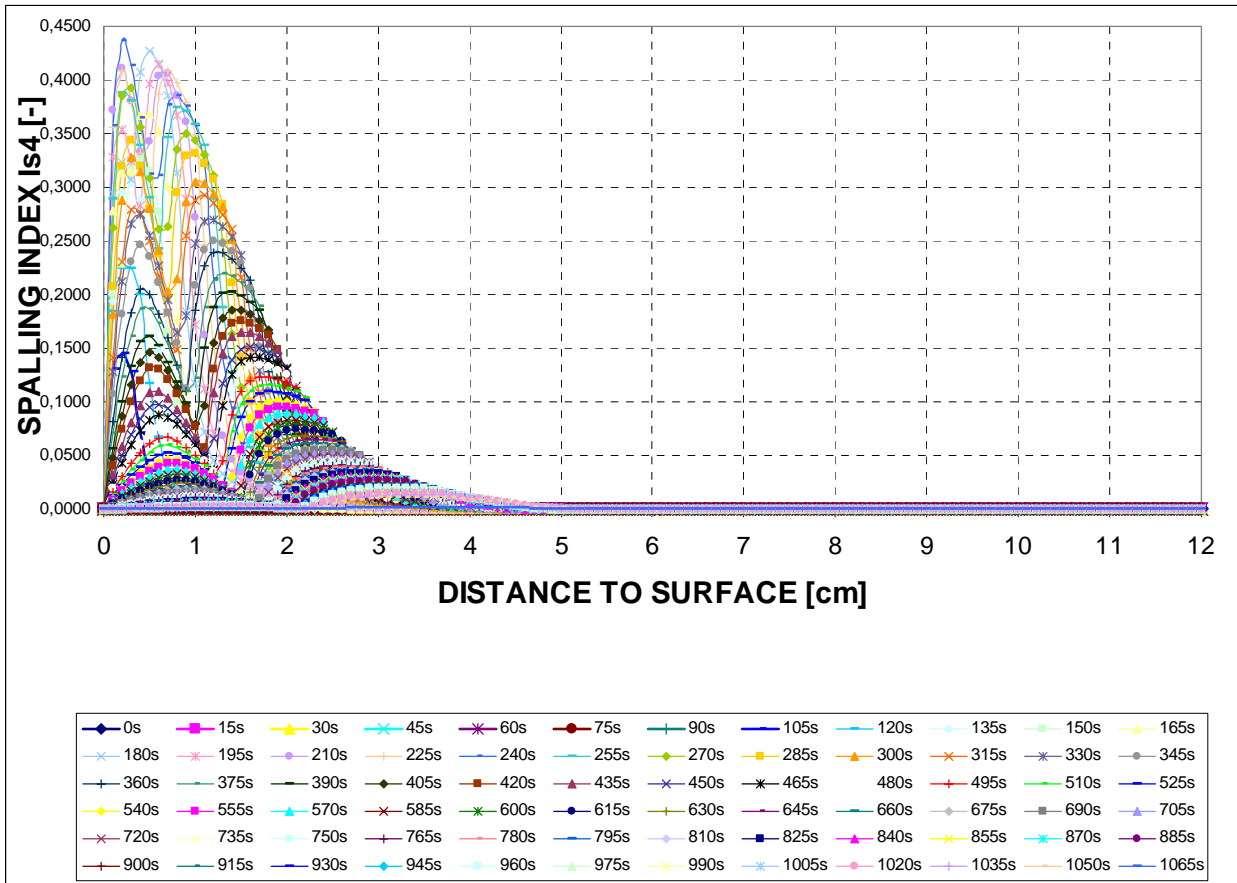


Figure 4A-77. Spalling Index IS4 evolution for combination 77-TH12K017RH50PAR3C60

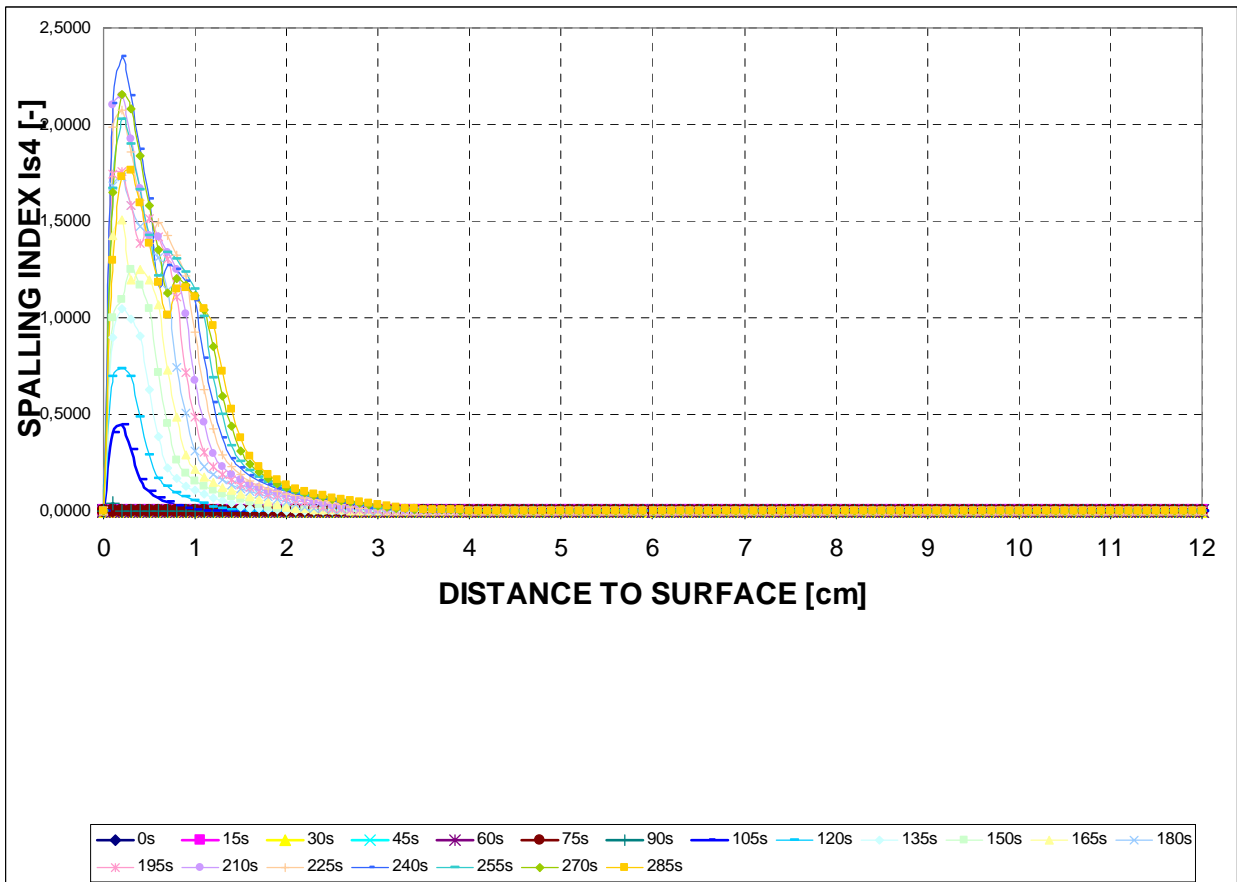


Figure 4A-78. Spalling Index IS4 evolution for combination 78-TH12K018RH50PAR3C60

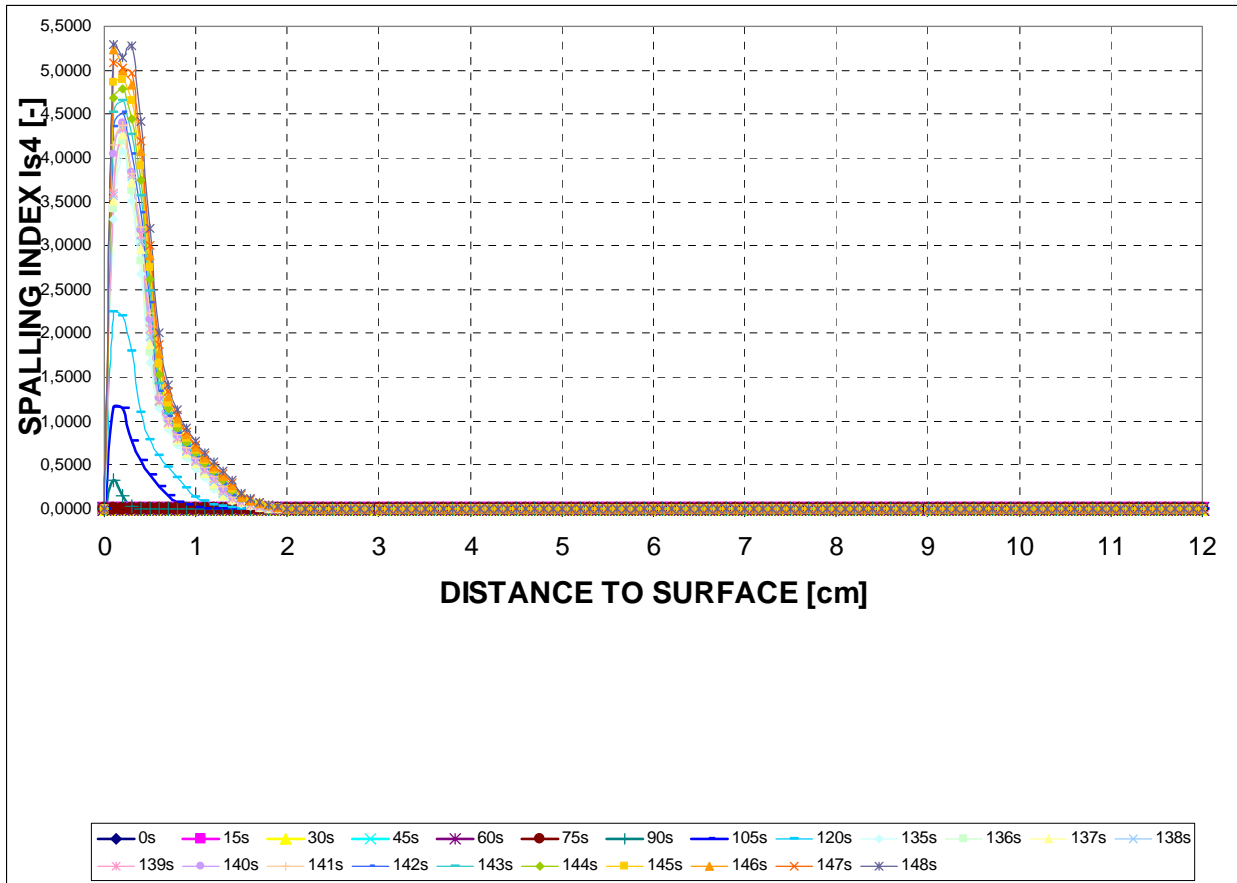


Figure 4A-79. Spalling Index IS_4 evolution for combination 79-TH12K019RH50PAR3C60

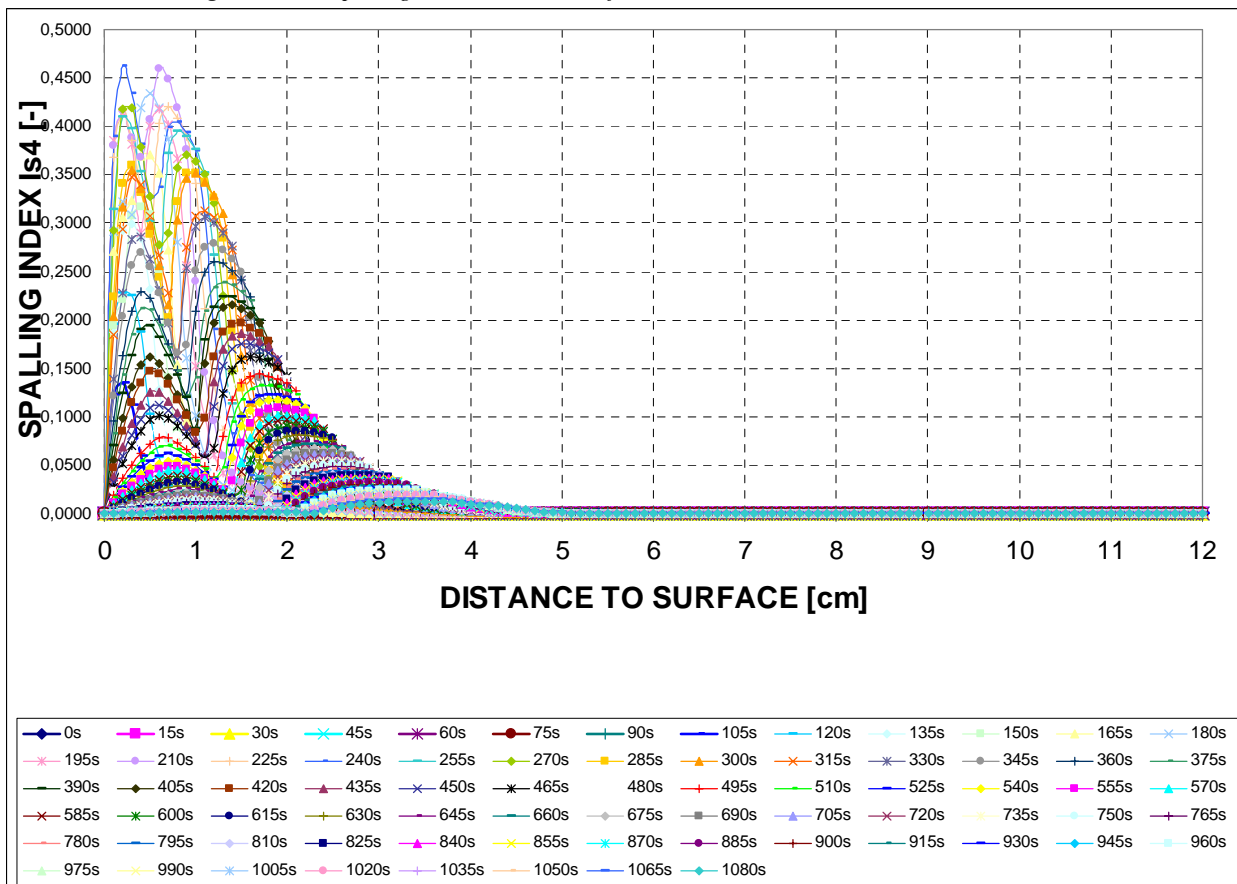


Figure 4A-80. Spalling Index IS_4 evolution for combination 80-TH12K017RH60PAR3C60

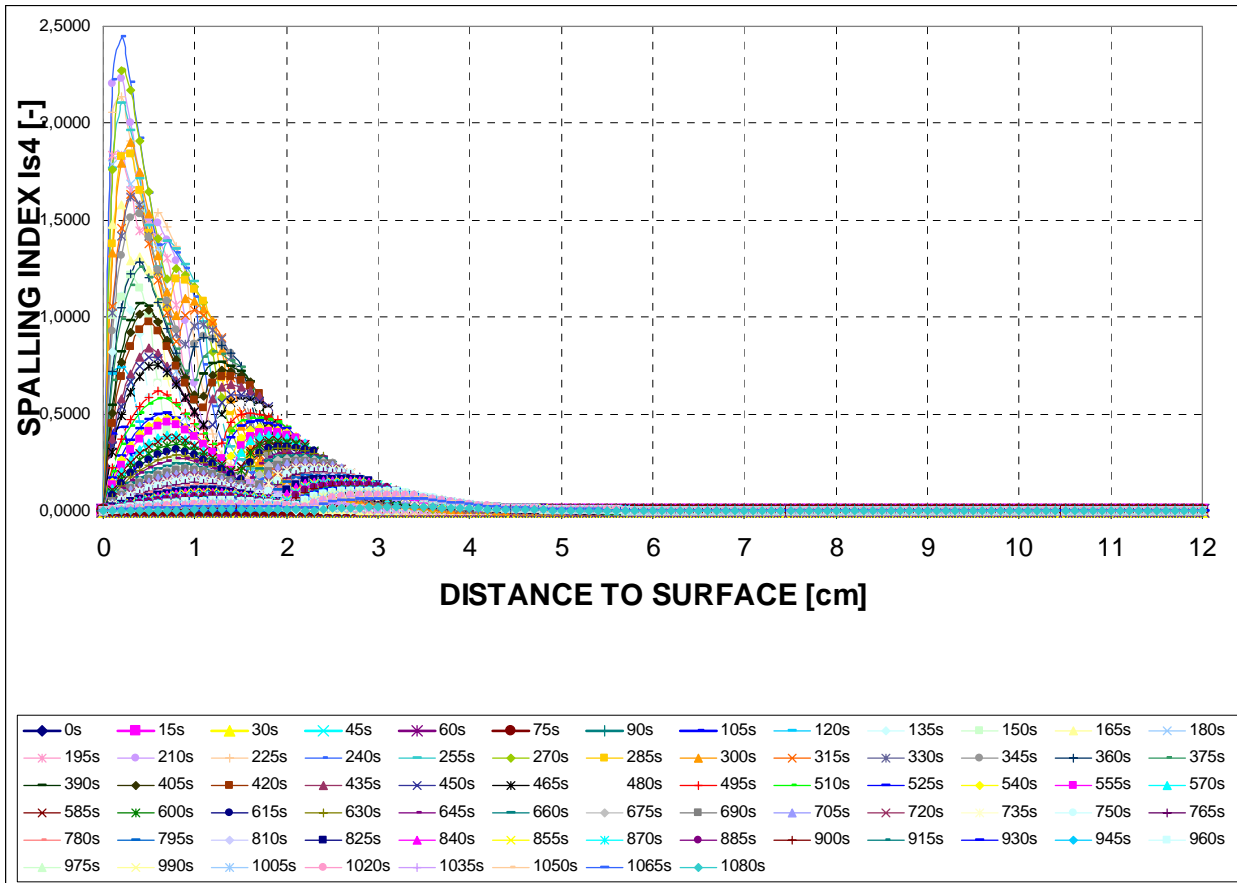


Figure 4A-81. Spalling Index IS4 evolution for combination 81-TH12K018RH60PAR3C60

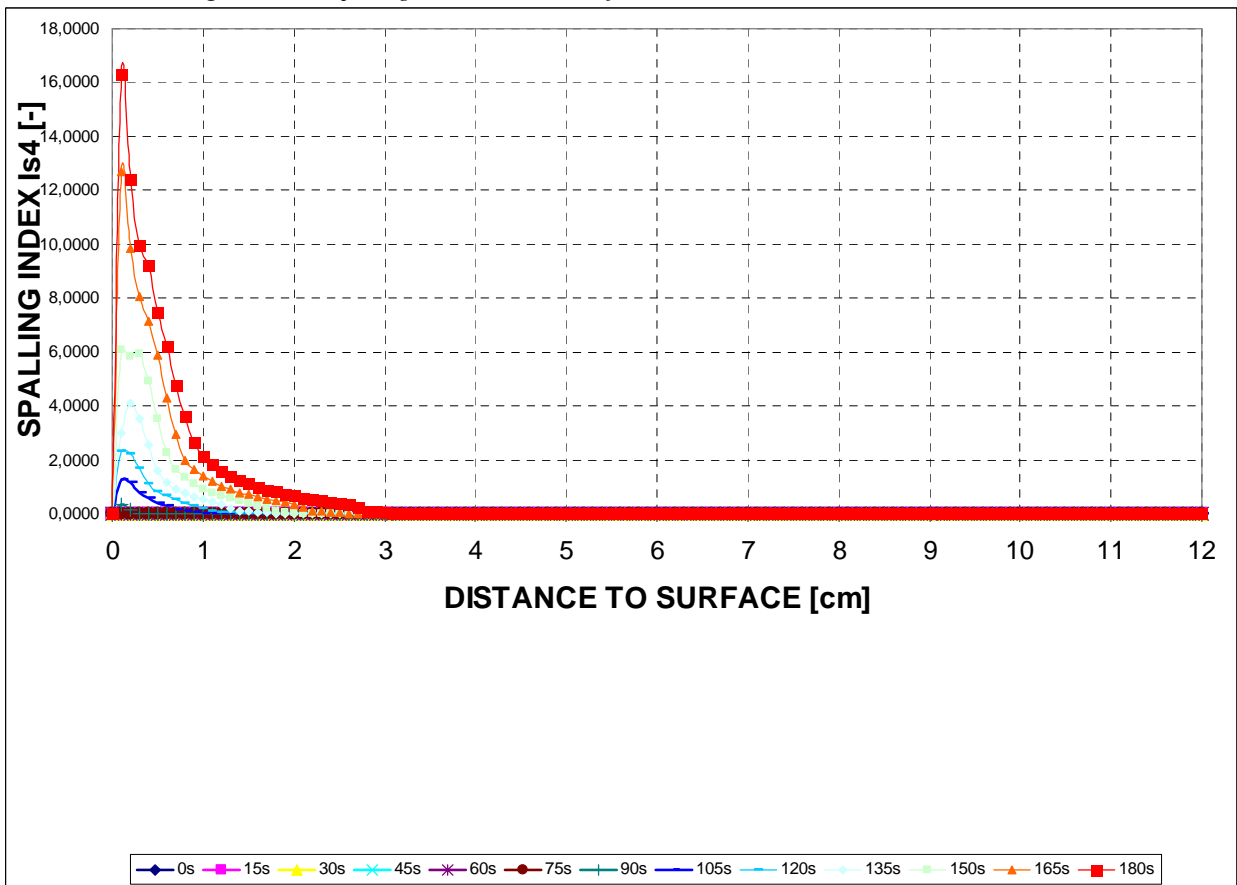


Figure 4A-82. Spalling Index IS4 evolution for combination 82-TH12K019RH60PAR3C60

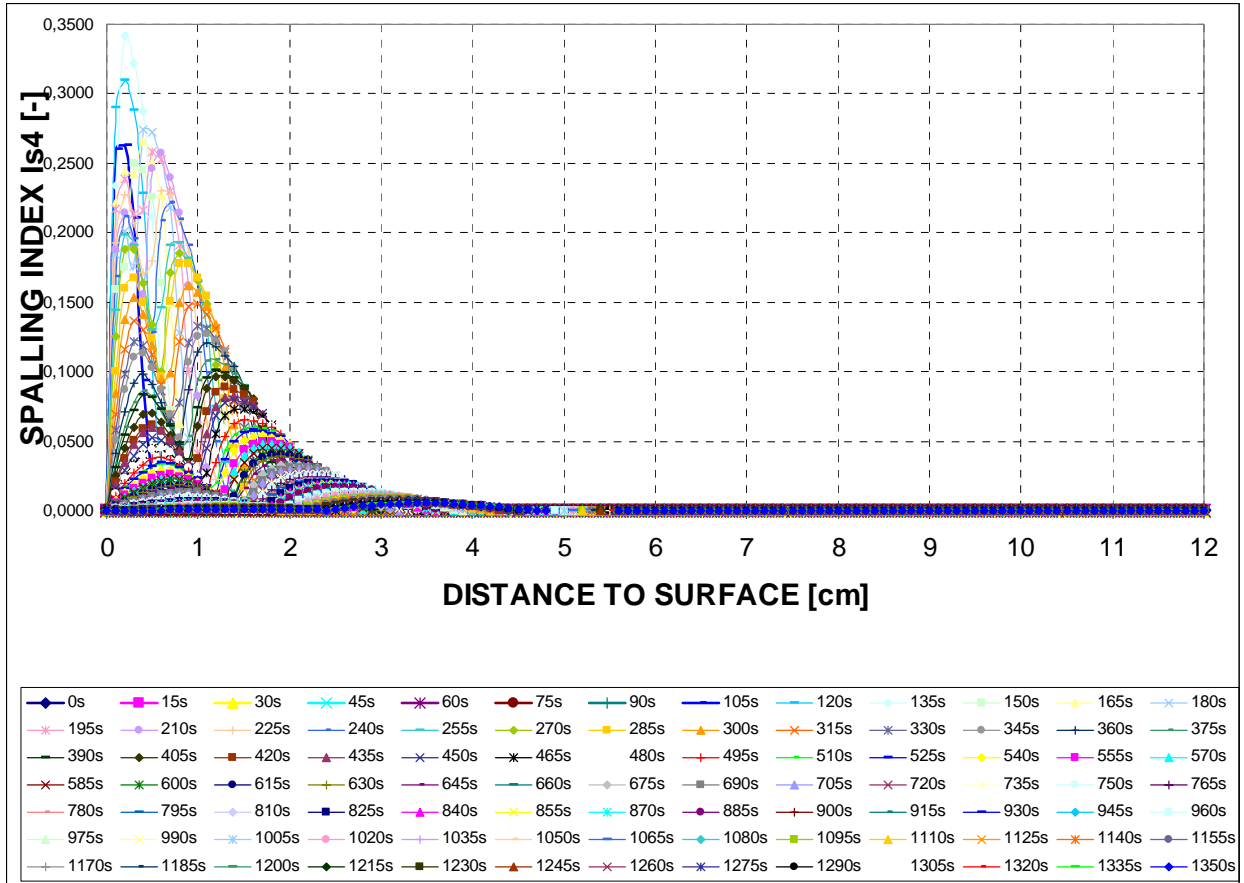


Figure 4A-83. Spalling Index IS_4 evolution for combination 83-TH12K017RH40PAR3C90

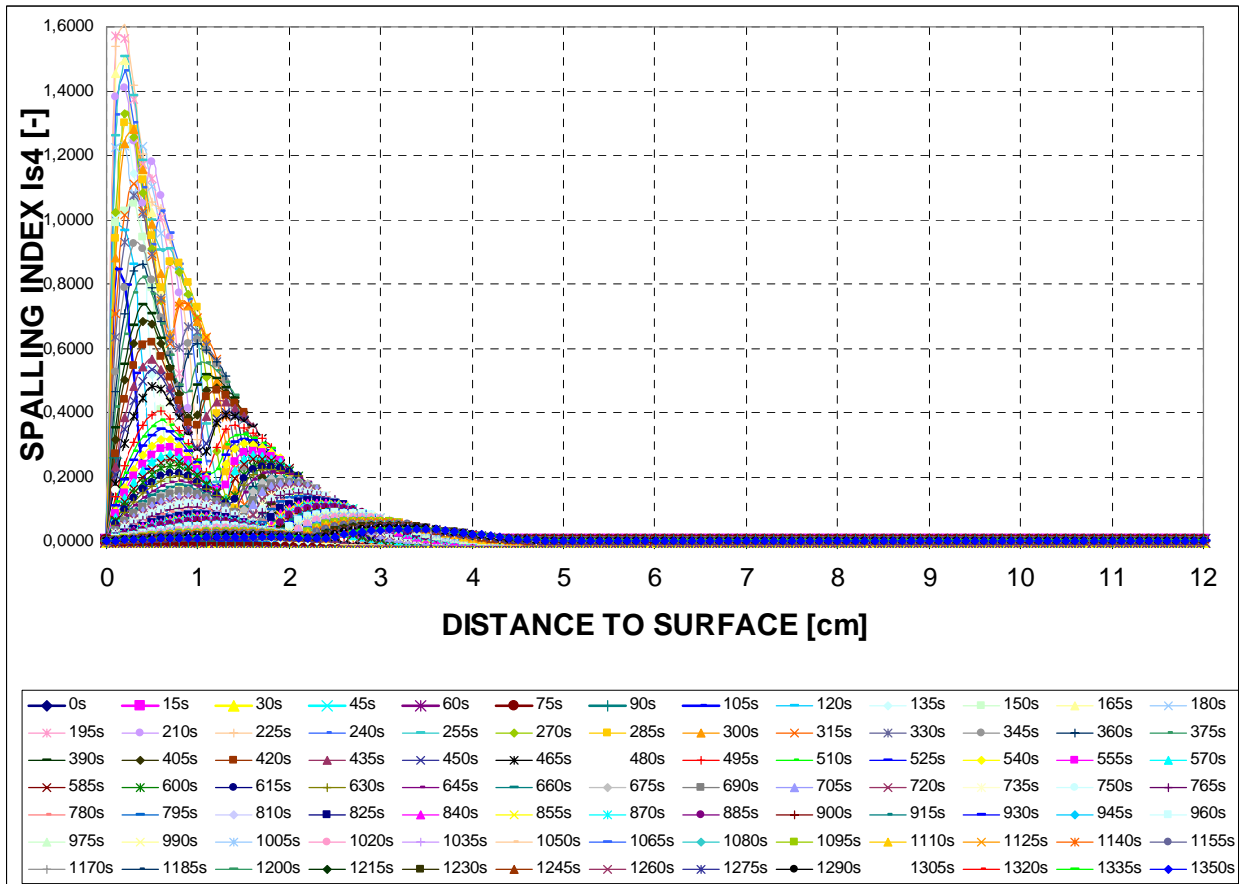


Figure 4A-84. Spalling Index IS_4 evolution for combination 84-TH12K018RH40PAR3C90

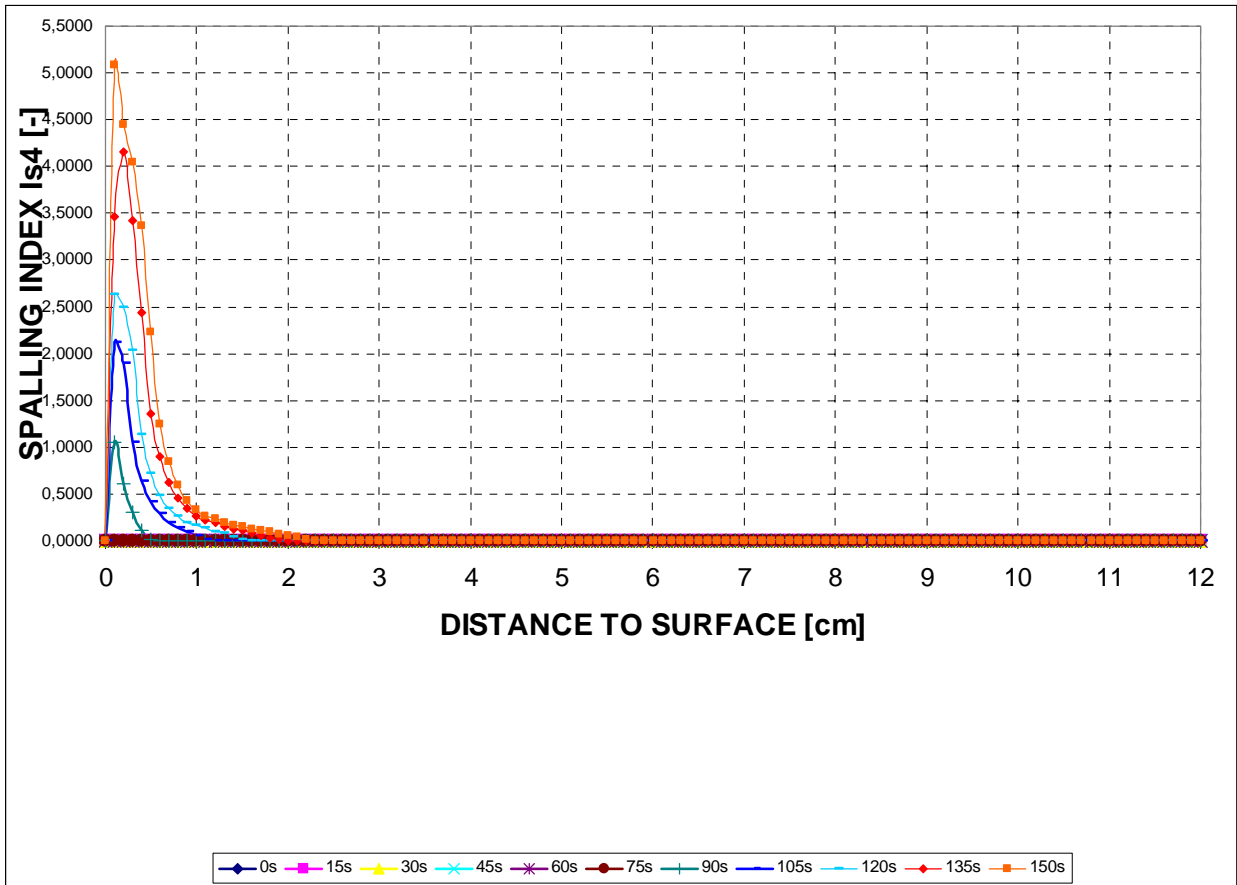


Figure 4A-85. Spalling Index IS4 evolution for combination 85-TH12K019RH40PAR3C90

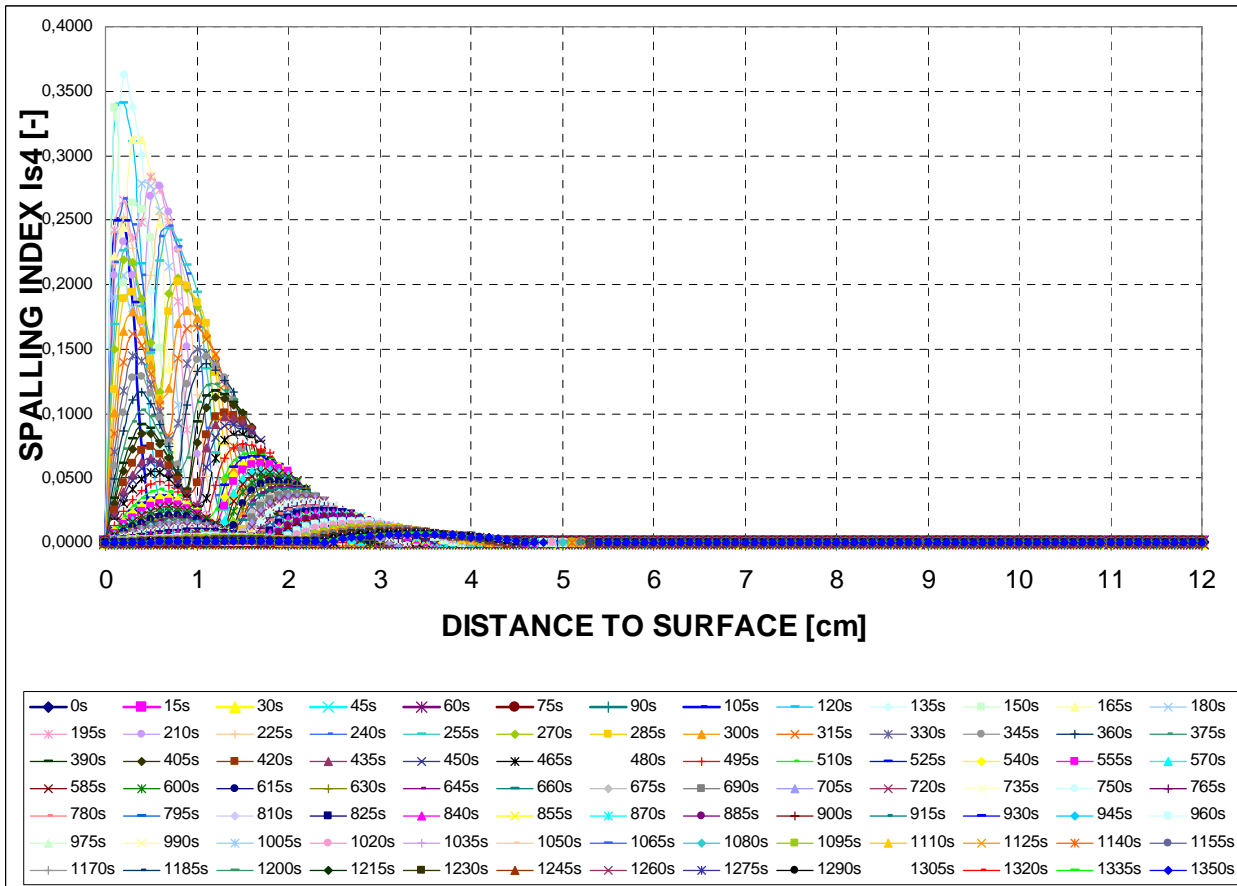


Figure 4A-86. Spalling Index IS4 evolution for combination 86-TH12K017RH50PAR3C90

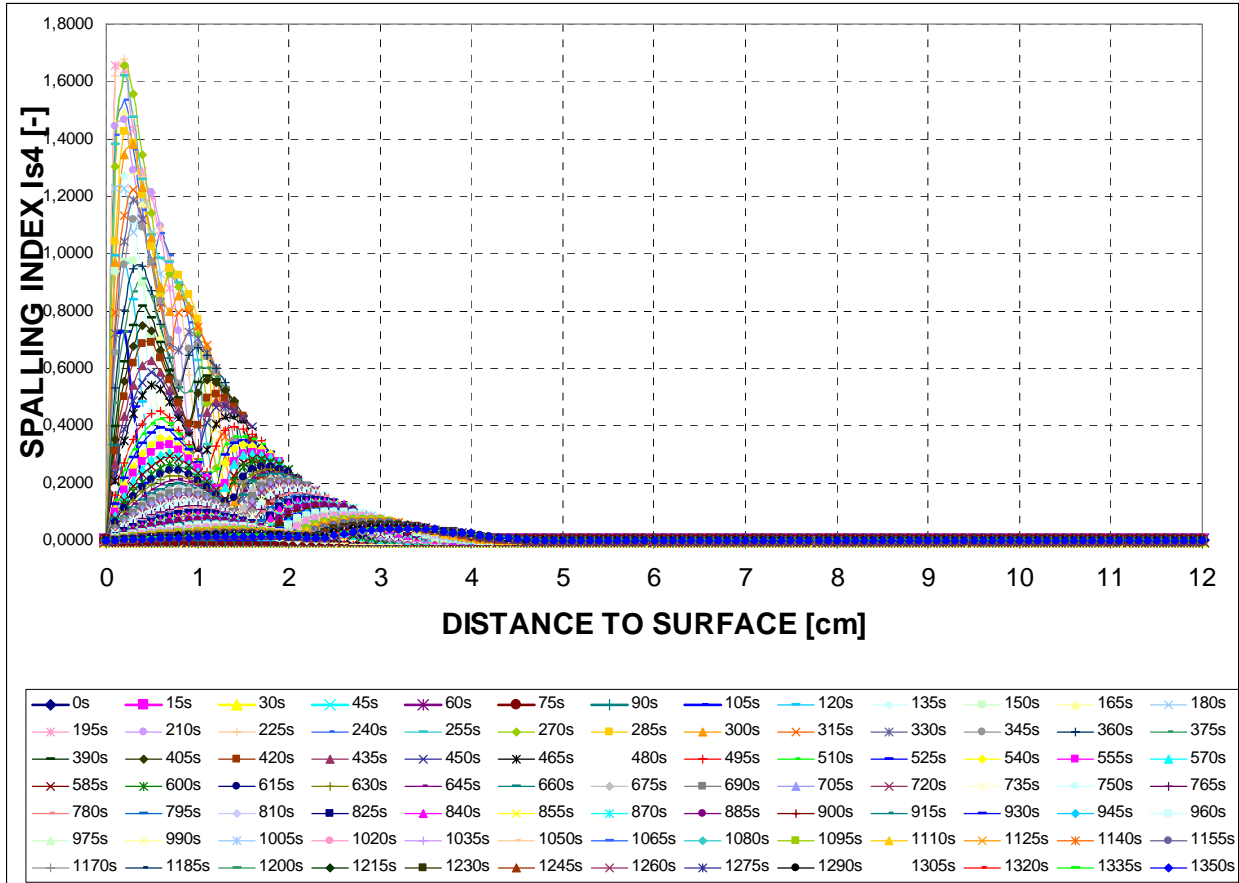


Figure 4A-87. Spalling Index IS4 evolution for combination 87-TH12K018RH50PAR3C90

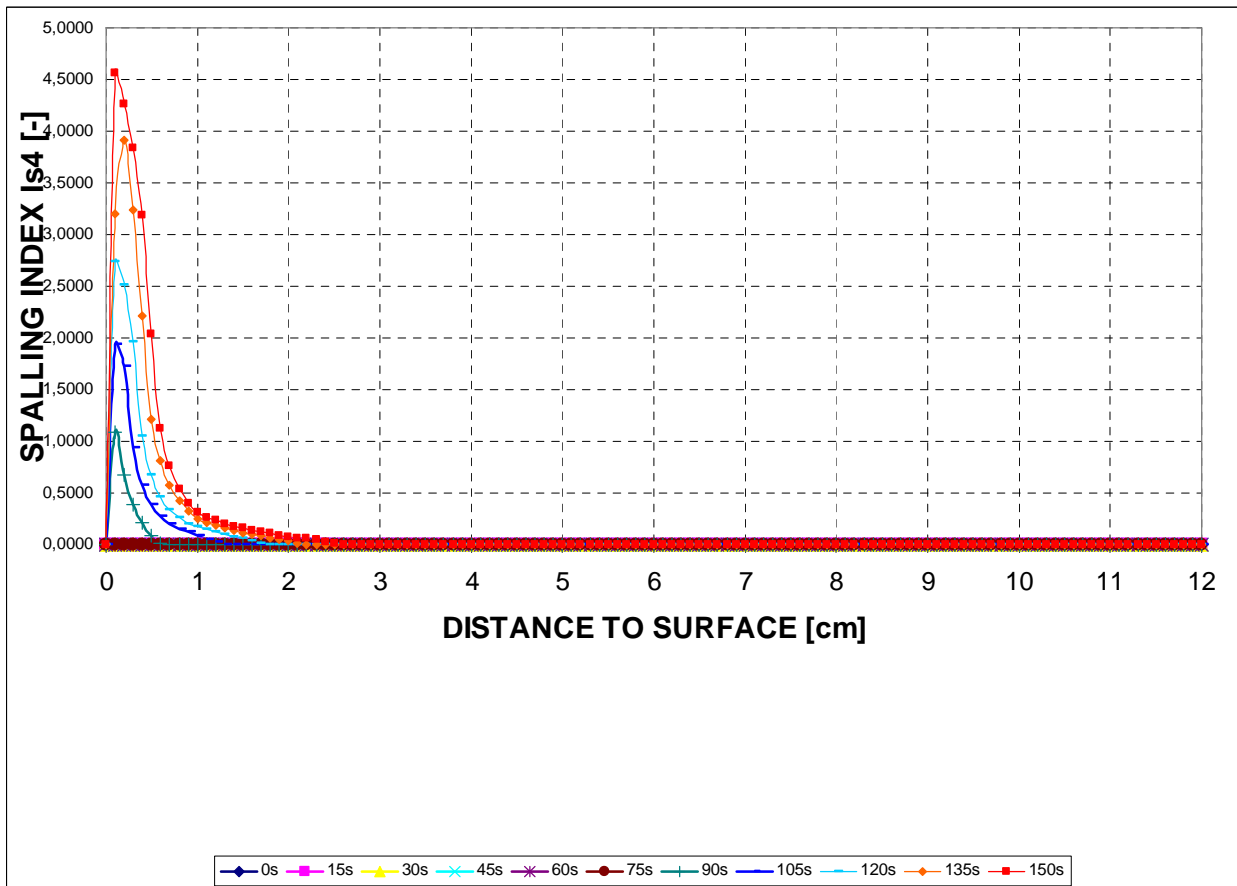


Figure 4A-88. Spalling Index IS4 evolution for combination 88-TH12K019RH50PAR3C90

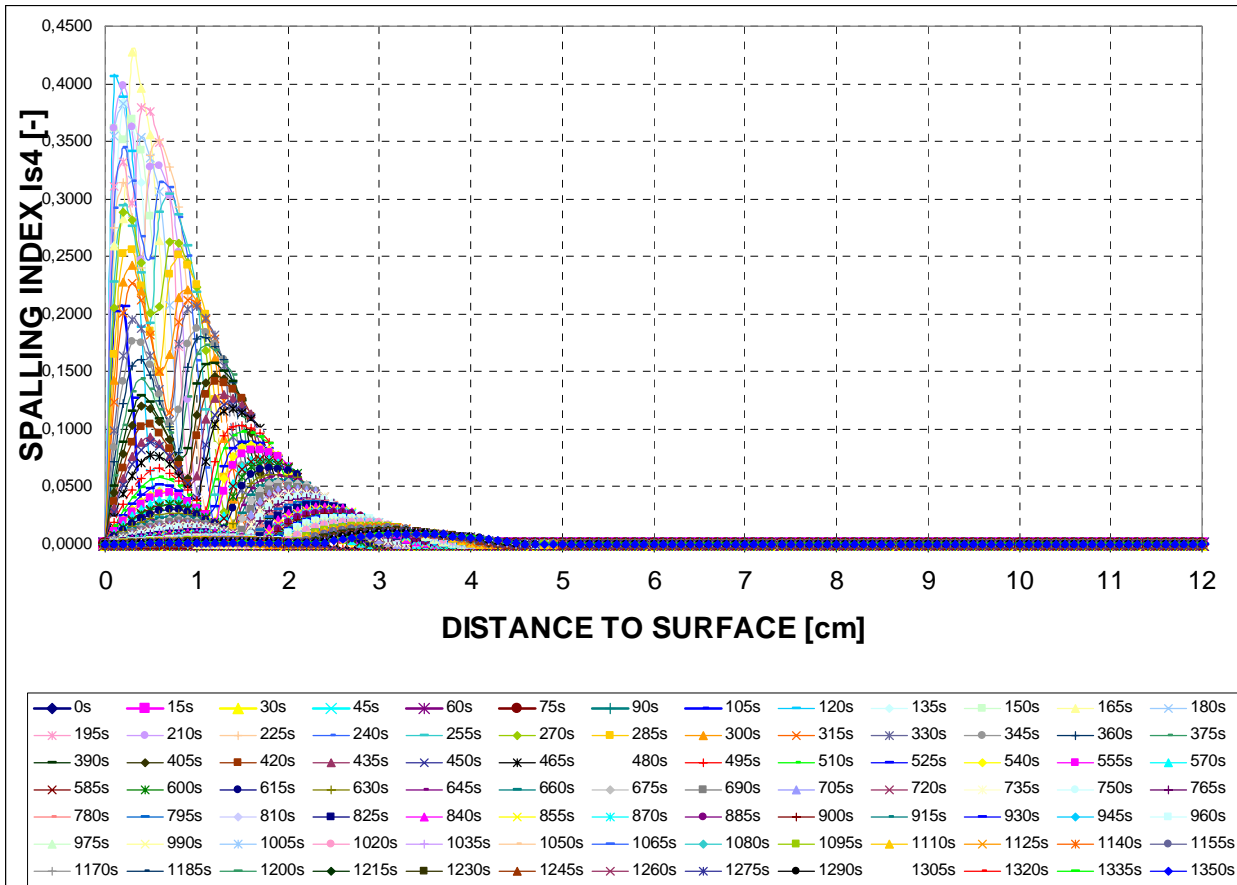


Figure 4A-89. Spalling Index IS4 evolution for combination 89-TH12K017RH60PAR3C90

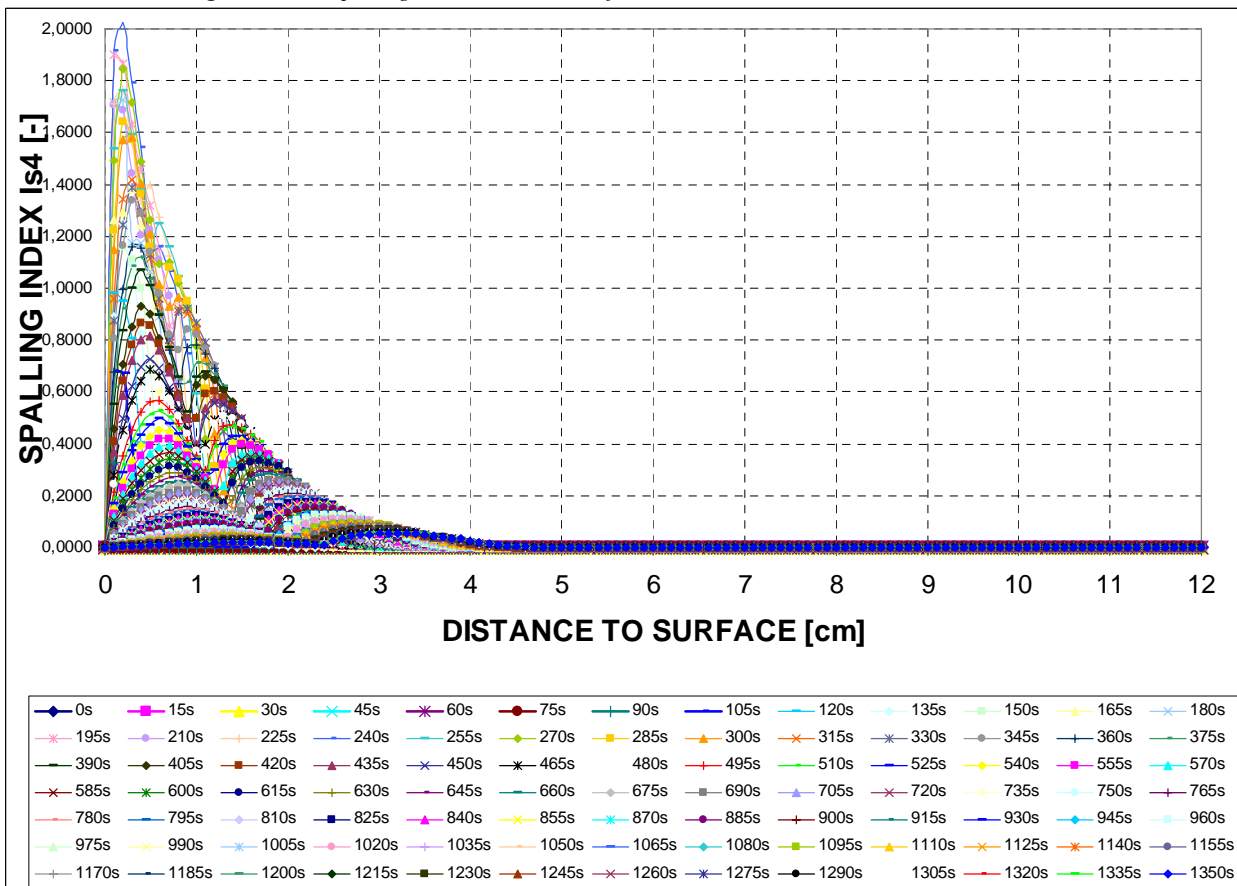


Figure 4A-90. Spalling Index IS4 evolution for combination 90-TH12K018RH60PAR3C90

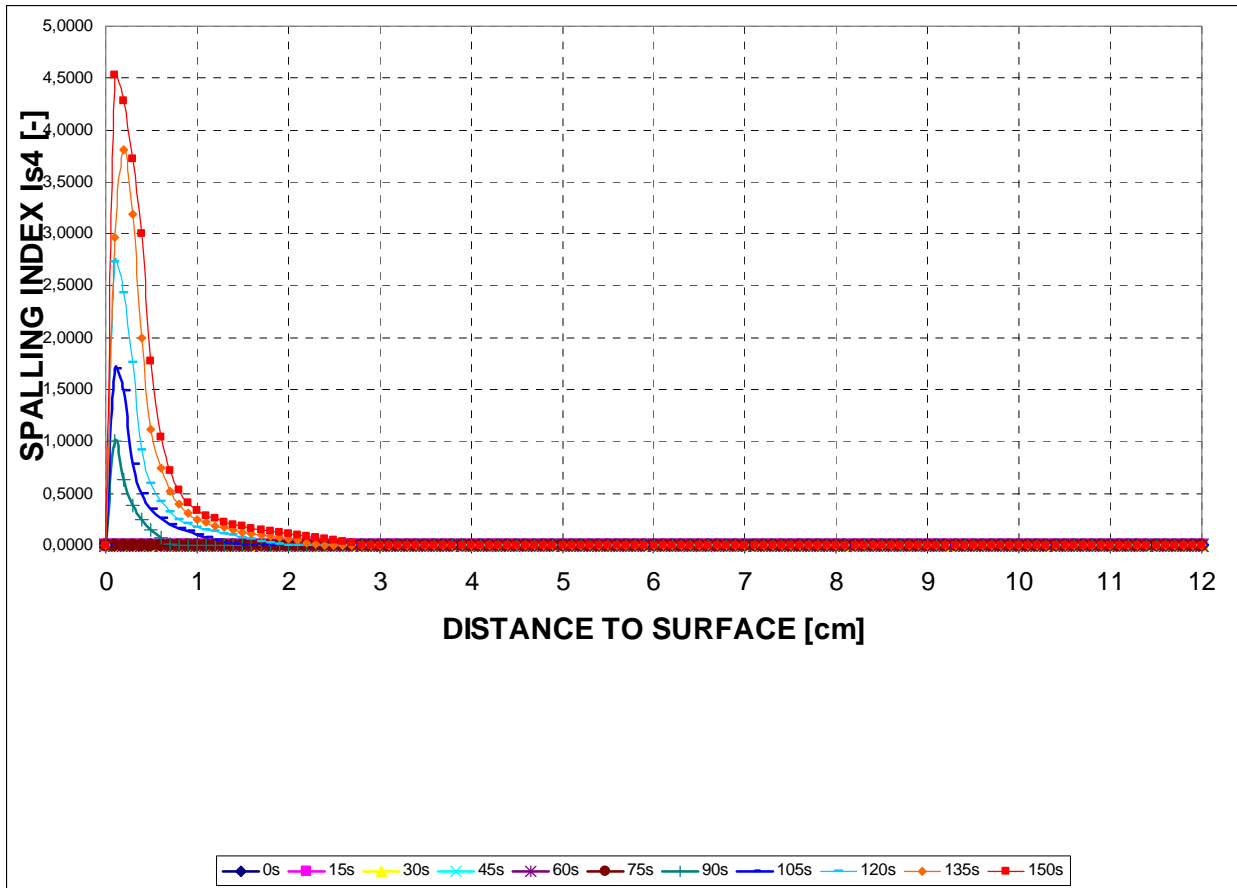


Figure 4A-91. Spalling Index IS4 evolution for combination 91-TH12K019RH60PAR3C90

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