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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Effects of inclusions on the performance of a solid rocket motor / Ponti F.; Mini S.; Fadigati L.; Ravaglioli V.; Annovazzi A.; Garreffa V.. - In: ACTA ASTRONAUTICA. - ISSN 0094-5765. - ELETTRONICO. - 189:(2021), pp. 283-297. [10.1016/j.actaastro.2021.08.030]

This version is available at: <https://hdl.handle.net/11585/832093> since: 2024-05-06

Published:

DOI: <http://doi.org/10.1016/j.actaastro.2021.08.030>

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Effects of Inclusions on the Performance of a Solid Rocket Motor

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Abstract

Some of the most common defects that can be generated during the production of solid propellant are voids and porosity, usually associated with the casting process, and cracks and debonding, typically initiated by the high stresses caused by the curing process. This paper presents the development of an algorithm capable of evaluating the burning surface regression of a solid rocket booster when inclusions are present within the grain. The effects produced by the cavities are evaluated both in terms of performance (i.e., comparison with the behavior of the nominal combustion surface), and in terms of safety (i.e., evaluation of the thermal protection increased exposure). The paper also documents the influence of uncertainties in the knowledge of the real dimension and position of the inclusions detected within the motor. The radiography inspection of the motor is able to detect the presence of cavities within a certain level of accuracy, and the worst combination of these uncertainties has to be determined in order to guarantee, even under such circumstances, the safe and successful firing of the motor. The methodology developed in the paper is adapted in order to identify the worst uncertainty combination, and to subsequently determine the corresponding performance deviation.

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23 KEYWORDS: grain inclusions, solid rocket motor flaws, burning surface regression, spherical cavity
24 effect.

25

26 **1 Introduction**

27 The manufacturing process of a solid rocket motor has to be carefully designed in order to obtain a perfect
28 match between the design specifications and the final geometry, thus ensuring that performance and
29 reliability are aligned with the expectations. Unfortunately, even a perfectly designed process may involve
30 issues that can generate undesired defects and deviations [1] with respect to the expected geometry and
31 properties of the motor [2], [3].

32 One of the procedures typically susceptible to defects affecting both the performance and reliability of a
33 motor is the casting process [4]. While casting, for example, the propellant may not adhere perfectly to the
34 case: in this instance, a portion of the interface surface between propellant and case may detach during the
35 following manufacturing operations (i.e., vulcanization, handling, etc.). Handling and thermal expansion
36 may even cause the solid propellant to crack, increasing its apparent porosity. Another issue may be the
37 presence of cavities within the grain, due, for example, to the high viscosity of the propellant and to a
38 number of voids forming due to the entrapment of air during the casting phase. The entity of the
39 aforementioned defects could even degenerate once the combustion process is initiated, and their stability
40 has to be verified in relation to the loads generated by internal pressure and rocket acceleration [5].

41 For these reasons, every time a motor is manufactured, an extensive monitoring campaign is performed in
42 order to check its integrity and the possible presence of the previously mentioned – and other – defects. For
43 example, the motor may be examined using X-ray, magnetic resonance or ultrasound techniques that allow
44 to identify the presence of inclusions or detachments, and to evaluate their extension and localization within
45 the motor [6–8]. Once a single defect or numerous ones are identified, the following task is to quantify the
46 effects generated by its or their presence, both in terms of performance and reliability, and to determine
47 whether the motor may be safely and efficiently launched or not [9,10].

48 One of the most common defects that are identified during the monitoring campaign is the presence of
49 inclusions within the propellant, resulting from air bubbles, air gaps, and cavities that remain trapped within
50 the high-viscosity propellant during the casting process. The presence of porosities causes two main effects:
51 a faster progression of the combustion process, when each inclusion is reached by the burning surface, and
52 a quicker exposure of the thermal protections, that are reached sooner by the high-temperature gases
53 produced within the combustion chamber. The first effect causes a change in the instantaneous value of the
54 surface exposed to combustion, thus modifying the thrust profile and the performance of the motor, whereas
55 the second one mainly affects the reliability of the motor, since thermal protections are usually designed to

56 last for a definite period of time while exposed to the hot gases in the combustion chamber, and a longer
57 exposure may completely consume the available layer of thermal protection.

58 If numerous inclusions are present within the propellant, investigating their effect on the performance of
59 the motor may become even more complex, due to the mutual influence on the progression of the
60 combustion surface. In addition to this, it should be underlined that the presence of defects is detected
61 through measurements that are affected by inaccuracies; consequently, the evaluation of the modification
62 in the performance profile and the reduction in reliability should be carried out so as to take into account
63 the worst possible effects, identified by combining flaws in the most dangerous possible way.

64 In the past, many approaches were developed in order to determine the 3D evolution of the combustion
65 surface of solid rocket motors; some of them were conceived through the so-called level-set method [11]
66 or by defining a distance function [12–14]. Usually, these types of methodologies are not able to deal with
67 propellant heterogeneities [15–17] and may provide a performance evaluation only under nominal
68 conditions. Some of them have been evolved [18–21] to consider the heterogeneities that may be produced
69 by the casting process [22,23] or by the granulometric composition of the propellant [24–27], whose effect
70 is a local change of the burning speed [28–31]. In other cases, a meshing procedure is used either to
71 represent the 3D grain geometry [32–34] or to discretize the 2D burning surface [35–37]. These approaches
72 may succeed in considering a point-by-point variation of the regression rate, thus simulating the non-
73 isotropic burning of a typical solid propellant [38,39]; some of them, by the same authors of this paper [40]
74 have also proven to be capable to treat inclusions and defects [41]. The expected accuracy of these
75 methodologies is related to the resolution of the meshes generated to describe the 3D or 2D geometries of
76 the grain or of its surface. The attempt to increase mesh resolution results in a very large number of vertices,
77 hence in a large computational effort. If the size of the identified inclusions is small, the need to precisely
78 describe their geometry would subsequently require a really fine mesh, and the number of involved vertices
79 would increase significantly. In the case of a large number of inclusions found in a motor of great size, the
80 problem becomes even harder to be correctly solved, and for this reason the number of inclusions that can
81 be treated with these tools is usually limited to some tenths.

82 The recent evolution of diagnostic systems made it possible to identify an increasing number of defects of
83 reduced dimensions [42]. On the one hand, this advancement allows to determine the thrust profile of each
84 motor with greater precision, and therefore, to assess more accurately if the calculated performance would
85 fall within the acceptance limits; on the other hand, managing many small-sized defects would make the
86 task of estimating the precise performance profile of the actual manufactured – and imperfect – motor
87 harder to be obtained, on account of two conflicting needs, which are: to obtain a good description both of
88 the defects and of the burning surface of the motor, and to maintain the computational effort at a reasonable
89 level. For a very high number of inclusions the solution with the existing tools becomes unpractical.

90 In order to evaluate the consequences generated by a large number of small inclusions precisely, it is
91 therefore necessary to develop a dedicated tool which is able to predict both the performance change and
92 reduction in reliability, given estimates of the dimensions and location of the cavities. This paper illustrates
93 a new geometric approach that is capable of reaching such a goal for an unlimited number of small spherical
94 inclusions that are present into the grain, identifying both the ensuing modifications in the performance
95 profile and the increase in the time of exposure of thermal protections to hot gases. The approach is
96 developed using the 3D nominal regression of the burning surface as input, evaluated through a solid rocket
97 motor tool developed by the authors of this paper, namely ROBOOST. The geometric evolution of the
98 combustion surface provided by ROBOOST is used to assign a web coordinate to each position within the
99 grain. Such coordinate identifies the distance covered by the combustion process on its path to reach that
100 position, starting from the initial combustion surface; the developed methodology ultimately allows to
101 assess the web coordinate variations caused by the presence of the investigated inclusions [43].

102 Another important attribute of the developed algorithm is the capability of assessing the influence of the
103 dimension and position uncertainties of the inclusions on the calculated web difference, focusing on the
104 evaluation of the worst possible combination of the measured uncertainties, both on a global and local scale.
105 The developed approach has been validated using an example in which an analytical solution is known and
106 used to evaluate the effects of a large set of inclusions detected on a real rocket; the algorithm has been
107 finally integrated into ROBOOST in order to increase its capability of simulating solid rocket motors.

108 The paper is divided into three main sections, organized as follows: the first section presents the developed
109 approach; the second shows the validation of the methodology applied to some test cases whose analytical
110 solution is known; the third section discusses the results obtained by applying the algorithm to a real motor
111 with a large number of identified inclusions.

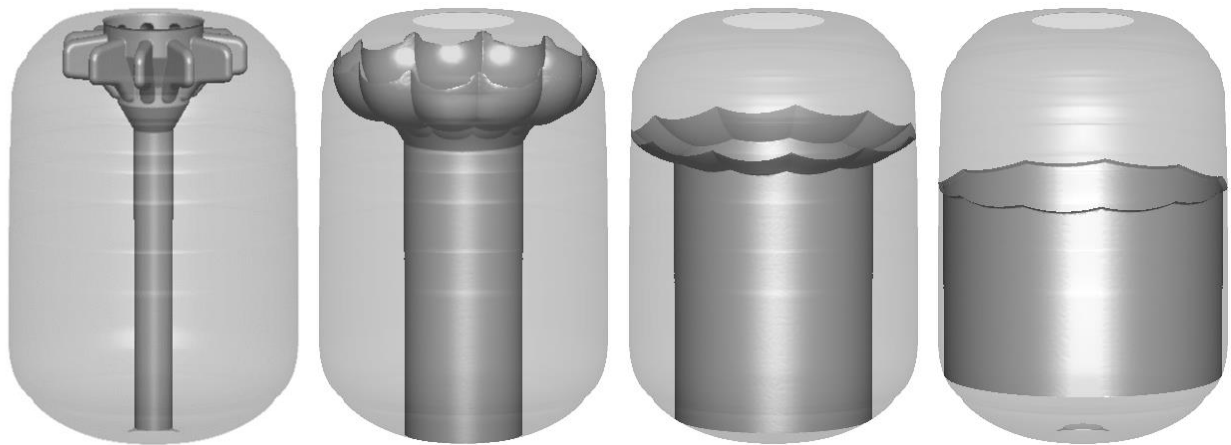
112

113 **2 Methodology Description**

114 *2.1 Combustion surface nominal regression and web coordinate definition*

115 The first step of the developed methodology is the definition of the web coordinate, w , determined using
116 the nominal regression of the combustion surface. Web coordinate is indeed defined, for each position
117 within the grain, as the distance covered by the combustion process on its path, i.e., the total grain thickness
118 burnt to reach that position. If the propellant has an isotropic behavior, without heterogeneities, the web
119 coordinate value (from now on referred to as “web value”) corresponds to the minimum distance measured
120 from the initial combustion surface. If the burning propellant is not isotropic, however, the web value and
121 the minimum distance may differ, due to the dissimilar regression rates that may be applied in the different
122 directions of the combustion progression. For this reason, the calculation of the web value is performed by

123 assigning to the points belonging to the combustion surfaces, evaluated at each instant of time, a web equal
 124 to the integral of the nominal regression rate with respect to time. If the instantaneous combustion surface
 125 has been calculated by taking into account the non-isotropic behavior of the propellant, the web value will
 126 be determined accordingly. The described approach is also valid for isotropic propellants, since the integral
 127 of the nominal regression rate coincides, in this case, with the minimum distance evaluation. Nevertheless,
 128 its application is more general, since it allows to consider even the potential non-isotropic behavior of the
 129 propellant; for this reason, it is the preferred one. A tool that is capable of calculating the combustion surface
 130 regression also under these conditions has been developed by the same authors of this work and is described
 131 in previous papers on the topic [40]. Since the development of that tool (ROBOOST) is well beyond the
 132 scope of the present study, the details of its working mechanism are not described in this paper, and its
 133 outputs are used, as already mentioned, to obtain the web value. An example of this process is described in
 134 the following Figures, in which the surface regression of a finocyl motor is represented in normalized units.



135
 136 a) Norm. web 0.00 b) Norm. web 0.32 c) Norm. web 0.64 d) Norm. web 0.96

137 **Fig. 1: Combustion surface at different normalized web coordinates in a finocyl motor**

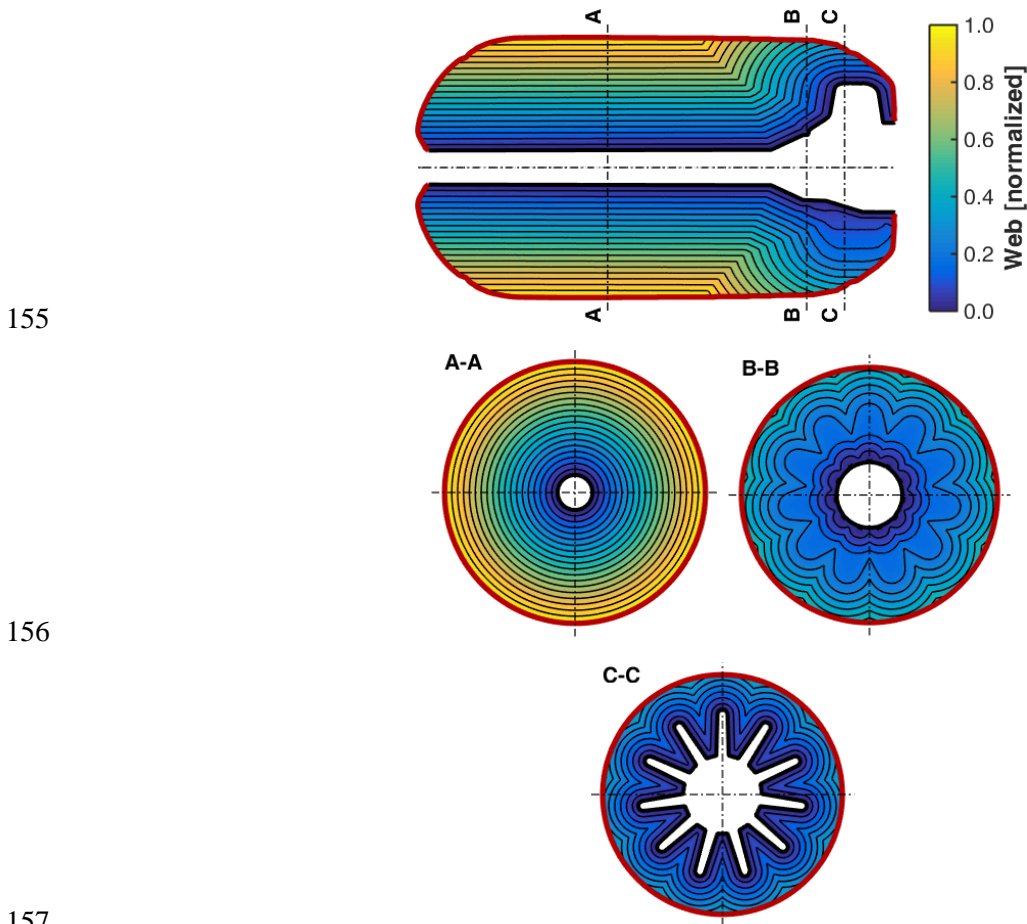
138 Each of the surfaces represented in Fig. 1 is associated to a precise value of the web (expressed in
 139 normalized units). The web distance between two consecutive surfaces has been fixed as equal to $5 \cdot 10^{-4}$
 140 normalized web. The availability of such a large number of combustion surfaces at different web
 141 coordinates allows for the evaluation of the web coordinate value at each internal position of the motor, as
 142 described in Fig. 2, where some characteristic sections are shown.

143 The web value obtained for each position within the motor can be now represented as a function of the
 144 coordinates of that position, as described by the following equation:

145
$$w = w(x, y, z) \tag{1}$$

146 2.2 Evaluation of the path followed to reach the motor case

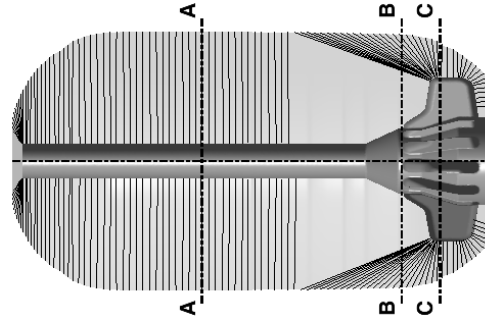
147 The same set of combustion surfaces may also be used to evaluate the path that is followed by the
148 combustion process to reach each of the positions located on the motor case. This can be done by reverse
149 integrating the local normal to the combustion surface, starting from each location on the motor case, until
150 a corresponding position on the initial combustion surface is reached. Some combustion paths, obtained for
151 the same motor geometry considered in the previous figures, are shown as an example in Fig. 3. Knowing
152 the followed path is important for the evaluation of the danger associated to each inclusion, since an
153 inclusion that is located on the path followed by the combustion process to reach a position on the motor
154 case will be more dangerous for that position, with respect to inclusions far from that path.



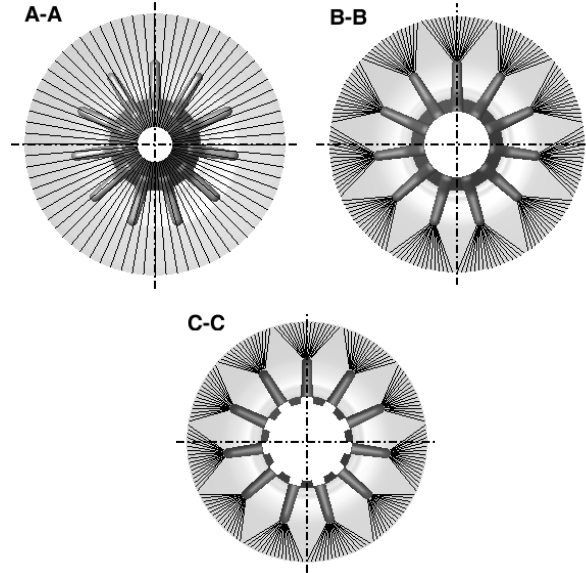
158 **Fig. 2: Web coordinate representation in some characteristic sections of the motor**

159

160



161



162

163

Fig. 3: Combustion paths followed to reach different locations on the motor case

164

2.3 Effect of a spherical cavity on a grain position

165

The second step of the methodology is the evaluation of the effects of a single spherical cavity placed in a

166

generic position within the grain. The spherical inclusion is identified by its diameter D_{cav} and by the

167

position of its center $(x_{cav}, y_{cav}, z_{cav})$; the use of Equation (1) allows to determine the web coordinate w_{cen}

168

in which the center of the cavity would have been reached by a nominal combustion:

169

$$w_{cen} = w(x_{cav}, y_{cav}, z_{cav}) \quad (2)$$

170

The cavity is reached by the combustion process at a web value w_{cav} that is lower than w_{cen} , as clearly

171

displayed in Fig. 4 and reported in Equation (3).

172

$$w_{cav} = w_{cen} - D_{cav}/2 \quad (3)$$

173 As soon as the cavity is reached by combustion, its internal surface becomes part of the burning process
 174 and the regression begins to proceed, propagating in all directions.

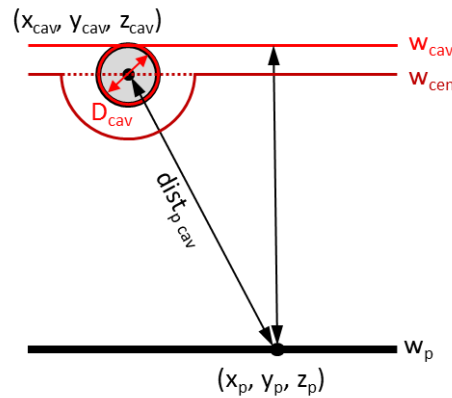
175 A generic point P of coordinates (x_p, y_p, z_p) , under nominal conditions, would have been reached by the
 176 combustion process at a web coordinate w_p :

177
$$w_p = w(x_p, y_p, z_p) \quad (4)$$

178 Due to the presence of the inclusion, the same point could be reached by the combustion process at a
 179 different web coordinate. Following the combustion path that goes through the cavity, it is then possible to
 180 determine that the generic point could be reached by the combustion coming from the inclusion at a web
 181 coordinate $w_{p\ cav}$, which is equal to:

182
$$w_{p\ cav} = w_{cav} + dist_{p\ cav} - D_{cav}/2 \quad (5)$$

183 where $dist_{p\ cav}$ is the distance between the center of the cavity and point P (see Fig. 4).



184

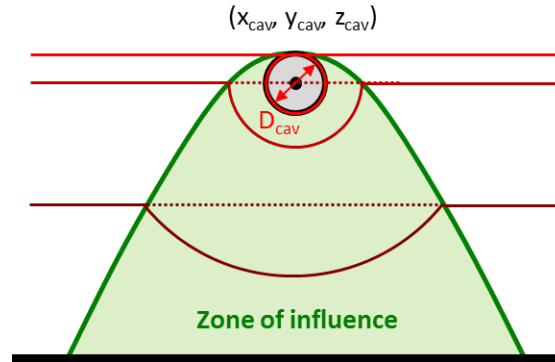
185 **Fig. 4: Graphic representation of the effect of a cavity on a grain position**

186 If $w_{p\ cav} > w_p$, the presence of the cavity does not produce any effect on the combustion timing for the point
 187 P. On the other hand, if $w_{p\ cav} < w_p$, the presence of the inclusion causes an advance ($\Delta w_{p\ cav} = w_p - w_{p\ cav}$)
 188 of the web value in which point P is reached by combustion, as expressed by Equation (6):

189
$$\Delta w_{p\ cav} = \begin{cases} 0 & , \text{ if } w_{p\ cav} > w_p \\ w_p - w_{cen} - dist_{p\ cav} + D_{cav} & , \text{ if } w_{p\ cav} < w_p \end{cases} \quad (6)$$

190 The condition expressed by Equation (6) allows to split the web that is reached by the combustion process
 191 after the incorporation of the cavity into two separate regions: the one that is affected by the presence of

192 the inclusion (characterized by a positive value of the web advance (zone of influence)); the one that is not
 193 affected by the cavity.

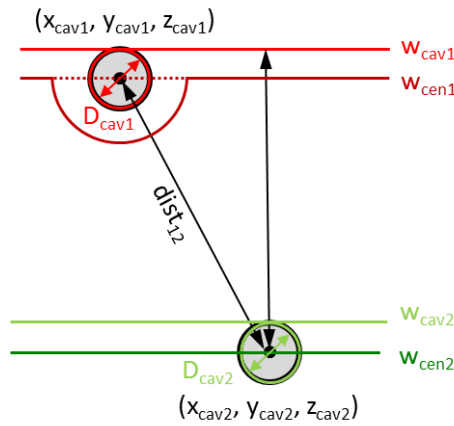


194

195 **Fig. 5: Zone of influence of a cavity**

196 *2.4 Effect of a cavity on another cavity*

197 If more than one cavity is present within the grain, they may exert a mutual influence on each other, and
 198 for this reason, the web in which each inclusion is reached by the combustion process may differ from that
 199 obtained under nominal conditions. This scenario is schematized in Fig. 6:



200

201 **Fig. 6: Graphic representation of the effect of a cavity on another cavity**

202 The second cavity shown in Fig. 6 is reached by the combustion surface under nominal conditions (i.e.,
 203 without any influence from the first inclusion) at a web coordinate:

204
$$w_{cav2} = w_{cen2} - D_{cav2}/2 \tag{7}$$

205 Due to the presence of the first cavity, the combustion process may reach the second inclusion through a
 206 path that crosses the first one, at a web coordinate:

$$207 \quad w_{cav2\ cav1} = w_{cen1} - D_{cav1} + dist_{12} - D_{cav2}/2 \quad (8)$$

208 The presence of the first cavity determines an advance of the web ($\Delta w_{21} = w_{cav2} - w_{cav2\ cav1}$) in which the
 209 second inclusion is reached by combustion only when $w_{cav2\ cav1} < w_{cav2}$, otherwise no mutual influence may
 210 be exerted among the considered inclusions, as expressed by Equation (9).

$$211 \quad \Delta w_{21} = \begin{cases} 0 & , \text{ if } w_{cav2\ cav1} > w_{cav2} \\ w_{cen2} - w_{cen1} - dist_{12} + D_{cav1} & , \text{ if } w_{cav2\ cav1} < w_{cav2} \end{cases} \quad (9)$$

212 2.5 Effect of two cavities on the position of a grain

213 The next step is the study of the effects generated by the two inclusions considered in the previous step on
 214 a generic point P of coordinates (x_p, y_p, z_p) . As can be seen in Fig. 7, point P can be reached by combustion
 215 through 3 different paths:

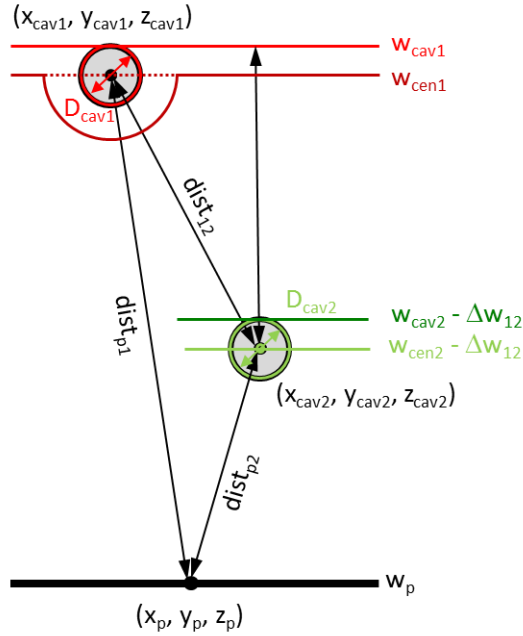
- 216 - Nominal combustion reaches point P at web $w_p = w(x_p, y_p, z_p)$
- 217 - Combustion surface coming from the first cavity at web $w_p - \Delta w_{p1}$
- 218 - Combustion surface coming from the second cavity at web $w_p - \Delta w_{p2}$

219 each of them causing a web advance, as expressed by Equation (10).

$$220 \quad \begin{cases} 0 \\ \Delta w_{p1} = w_p - w_{cen1} - dist_{p1} + D_{cav1} \\ \Delta w_{p2} = w_p - w_{cen2} - dist_{p2} + D_{cav2} + \Delta w_{21} \end{cases} \quad (10)$$

221 The shortest path is the only one to be considered to evaluate the web coordinate in which point P is reached
 222 by combustion; the web advance for point P (Δw_p) can be therefore determined as the maximum of the web
 223 advances associated to each of the possible paths:

$$224 \quad \Delta w_p = \max(0, \Delta w_{p1}, \Delta w_{p2}) \quad (11)$$



225

226 **Fig. 7: Graphic representation of the effects of two cavities on a generic position of the grain**

227 The approach may now be extended to a generic set of inclusions by simply taking into account that the
 228 web advance of a single cavity is determined as the maximum of the mutual influences generated by all the
 229 other inclusions, each of them considered with its own web advance, in turn caused by the other cavities.
 230 For a generic i -th cavity, out of a set of N cavities, the web advance Δw_i can be measured as:

231
$$\Delta w_i = \max(0, \Delta w_{i1}, \dots, \Delta w_{iN}) \quad (12)$$

232 Even if the process seems complex due to the apparent large number of mutual influences to be taken into
 233 account, it can be strongly simplified by considering a tree of influences between cavities built bearing in
 234 mind that if cavity 1 influences cavity 2, it can be stated that cavity 2 does not influence cavity 1. Such tree
 235 can be built simply by looking at the web in which each of the cavities should be reached by combustion
 236 under nominal conditions, referred to as $w_{cav i}$, and then by sorting them using this quantity. The influence
 237 on a specified cavity i by another cavity j is studied only when $w_{cav i} > w_{cav j} - w_{tol}$, where w_{tol} is a tolerance
 238 value that guarantees that the influencing cavities are considered even when the initial order is changed by
 239 the application of the relative influence.

240 Once the web advance Δw_i has been measured for each inclusion, the effect of the N inclusions on a generic
 241 point P within the grain can be obtained as the largest value among the web advances generated by each
 242 cavity on that point:

243
$$\Delta w_p = \max(0, \Delta w_{p1}, \dots, \Delta w_{pN}) \quad (13)$$

244 If point P is located within the grain, the methodology presented above allows to evaluate the burning
245 surface change that is caused by a given set of inclusions and, consequently, also the performance variation
246 of the SRM under study. If point P is located on the thermal protection, the evaluation of the web advance
247 allows to estimate the increase of exposure to the hot gases generated by combustion that the set of cavities
248 is causing on that point of the thermal protection.

249 The methodology described in this paper is based on a scenario involving spherical cavities because they
250 are the most common type of inclusions that can be observed and detected in a solid rocket motor. However,
251 such approach can be extended also to cavities with a generic shape simply by considering their shape as
252 obtained from a combination of elementary inclusions shaped like spheres. Such a process may always be
253 set up to describe generic shapes, the only side effect being the increased number of cavities to be
254 considered.

255 *2.6 Effect of uncertainties*

256 The effects discussed in the previous sections are computed using the nominal diameter and positioning of
257 the cavities. Each cavity is known through experimental observations of the manufactured motor, and
258 nominal diameter and position are affected by uncertainties that can produce different evaluations of the
259 web advance. The goal is to evaluate the worst-case scenario by taking into account all the uncertainties.

260 In order to perform this operation, the effect of a single cavity on the web advance of a generic point is
261 studied, as obtained through Equation (6):

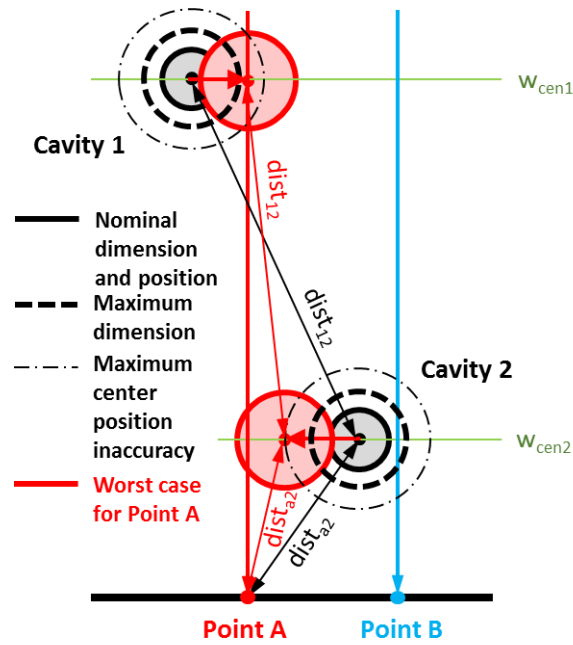
- 262 – The larger the diameter of the cavity, the larger the effect on the exposure map (since it implies a
263 larger value of D_{cav} in Equation (6));
- 264 – The effect generated by a cavity on the point under study is most substantial when the cavity is
265 located along the path followed by the regression surface to reach that point (this implies a lower
266 value of $w_{cen} + dist_p_{cav}$, that appears with a negative sign in Equation (6)).

267 The same considerations may be extended also to a combination of two (or more) cavities:

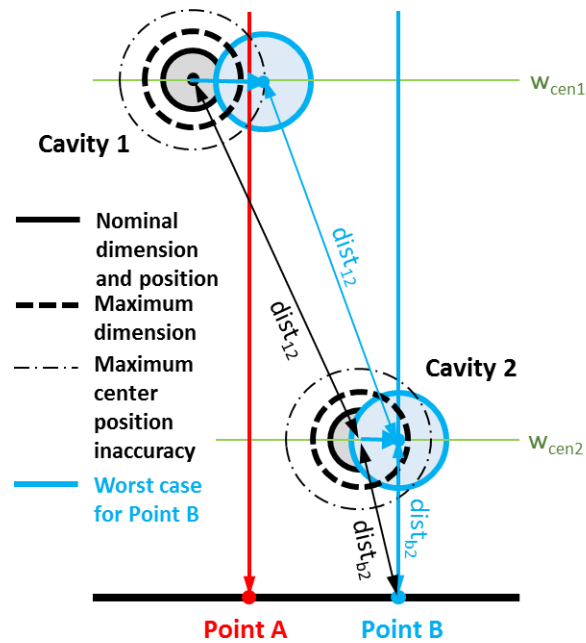
- 268 – The larger the diameter of each cavity, the most pronounced the combined effect;
- 269 – The more the cavities are aligned along the path followed by the regression of the surface, the
270 most pronounced the effect on the point under study.

271 Figure 8 describes the concept of cavity alignment, highlighting that for each position within the grain, the
272 worst condition for that position would be obtained by applying the uncertainties with different
273 combinations.

274



275



276 **Fig. 8: Graphic representation of the worst-case inaccuracy application for two different points A**
277 **and B**

278 Based on these considerations, it can be stated that the absolute worst combination of inaccuracies does not
279 exist, since the worst-case configuration may differ for each point. If these considerations are applied to the
280 motor case, this means that the worst possible web advance should be evaluated independently for each
281 position on the case. By combining the worst-case conditions for each point on a surface (e.g., the thermal

282 protection surface), it is possible to obtain a map that can be referred to as the worst-case map for that
283 surface.

284

285 3 Methodology Validation

286 3.1 Comparison with test cases

287 The developed methodology has been used to determine the variations of the burning surface due to the
288 presence of cavities for three test cases, whose results can be determined through simple geometric
289 considerations. The three cases have been designed to investigate different types of interaction between the
290 burning surface and the inclusions, also considering different mutual influences that may be exerted among
291 cavities. In all test cases, a planar combustion surface has been considered to guarantee a precise evaluation
292 of the ideal surface variation; the planar surface incorporates one or more inclusions in the following way:

- 293 A. A single inclusion;
- 294 B. A sequence of two inclusions placed along the same combustion progression line;
- 295 C. Two identical inclusions located at the same web coordinate.

296 For each test, the nominal combustion surface has been discretized using a triangular mesh, and the effects
297 of the cavities have been evaluated by applying the described methodology to each vertex of the mesh. The
298 extension of the nominal and the modified surface has been determined by summing up all the areas of the
299 mesh triangles. Finally, the difference between nominal and modified areas has been compared with the
300 same difference obtained through geometric computations.

301

302 3.1.1 Test A

303 A single inclusion with a diameter $D_{cav}=16\text{ mm}$ and center $(x_{cav}, y_{cav}, z_{cav}) = (0, 100, 0)\text{ mm}$ is incorporated
304 by a planar combustion surface characterized by a regression direction aligned with the y-axis. When the
305 surface reaches a position in the y direction equal to 140 mm , the effect of the cavity appears as a spherical
306 cap, with radius R equal to 56 mm and cap height h equal to the inclusion diameter of 16 mm . The surface
307 of the spherical cap can be measured as $2\pi Rh$, whereas the surface of the plane that is substituted by the
308 spherical cap is equal to $\pi(R^2 - (R - D_{cav})^2)$. The surface increase due to the cavity is therefore the difference
309 of these surfaces, equal to $\pi h^2 = 804.25\text{ mm}^2$.

310 Figure 9a reports the result of the methodology described in the previous section applied to a triangular
311 mesh with a maximum edge size equal to 0.4 mm . The estimation of the surface increase is 799.50 mm^2 ,
312 with a percent error of 0.59% .

313

314 3.1.2 Test B

315 Two inclusions with diameters $D_{cav1}=16\text{ mm}$ and $D_{cav2}=8\text{ mm}$ and centers $(x_{cav1}, y_{cav1}, z_{cav1}) = (0, 100, 0)$
316 mm and $(x_{cav2}, y_{cav2}, z_{cav2}) = (0, 130, 0)\text{ mm}$ are incorporated by a planar combustion surface, in a similar
317 way to what was described in Test A. When the surface reaches a position in the y direction equal to 140
318 mm , the effect of the cavities appears as a combination of two spherical caps, with radiuses R equal to 56
319 mm and 34 mm respectively, and cap heights h equal to 16 mm and 24 mm respectively. The intersection
320 between the two spherical caps is observed at a height equal to 8 mm , meaning that the first 8 mm of the
321 combined surface are obtained as a portion of the first spherical cap (that becomes a spherical sector of
322 height h_1), while the following 16 mm are the final portion of the second spherical cap of height h_2 (see
323 Fig. 9b for more details).

324 The extension of the described surface can be therefore evaluated as the sum of the area of a spherical sector
325 and a spherical cap, obtaining $2\pi R_1 h_1 + 2\pi R_2 h_2$, whereas the surface of the plane that is substituted by the
326 spherical cap is equal to $\pi(R_1^2 - (R_1 - D_{cav1})^2)$. The surface increase due to the cavity is therefore equal to the
327 difference of these surfaces, amounting to 1407.44 mm^2 .

328 Figure 9b reports the result of the methodology developed in this paper applied to a triangular mesh with a
329 maximum edge size equal to 0.4 mm . The estimation of the surface increase is 1401.20 mm^2 , with a
330 percent error of 0.44%.

331

332 3.1.3 Test C

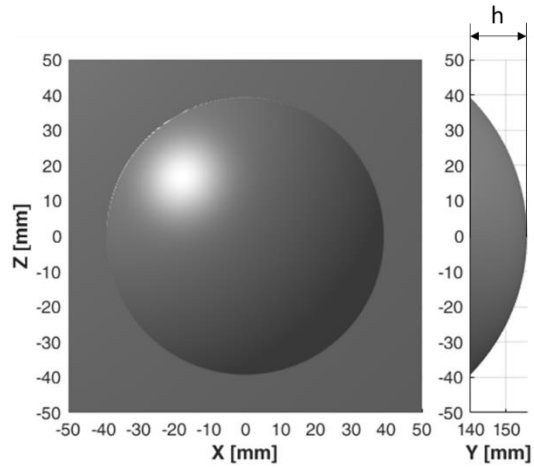
333 Two inclusions, both with diameters of 20 mm and centers $(x_{cav1}, y_{cav1}, z_{cav1}) = (0, 140, 16)\text{ mm}$ and $(x_{cav2},$
334 $y_{cav2}, z_{cav2}) = (0, 140, -16)\text{ mm}$ respectively are incorporated by a planar combustion surface in a similar
335 way to Test A. When the surface reaches a position, in the y direction, equal to 140 mm , the effect of the
336 cavities appears as a combination of two portions of spherical cap, with radiuses R equal to 20 mm , cap
337 heights h equal to 20 mm , with a missing portion of cap whose height is $h_m=4\text{ mm}$ (see Fig. 9c for more
338 details).

339 The extension of the described surface can be evaluated as the sum of two semispherical caps (thus
340 obtaining a spherical cap), whereas the surface of the plane that is substituted can be obtained as the sum
341 of two circular segments. The surface increase due to the cavity is the difference of these surfaces, which
342 is equal to 2141.42 mm^2 .

343 Figure 9c reports the result of the methodology developed in this paper, applied to a triangular mesh with
344 maximum edge size equal to 0.4 mm . The estimation of the surface increase is 2133.70 mm^2 , with a
345 percent error of 0.39%.

346

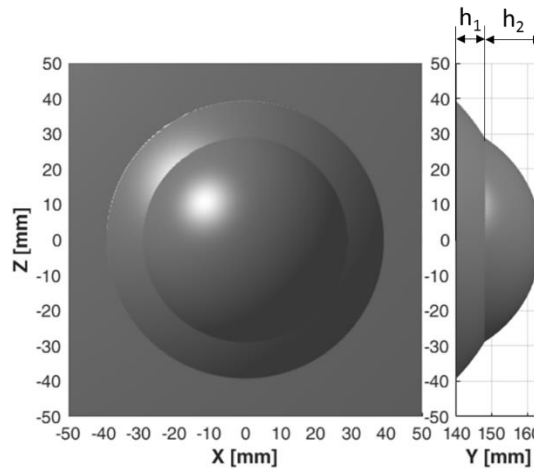
347



Test A

348

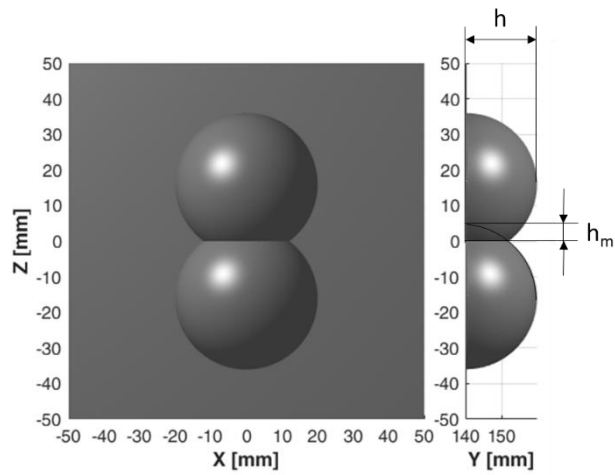
349



Test B

350

351

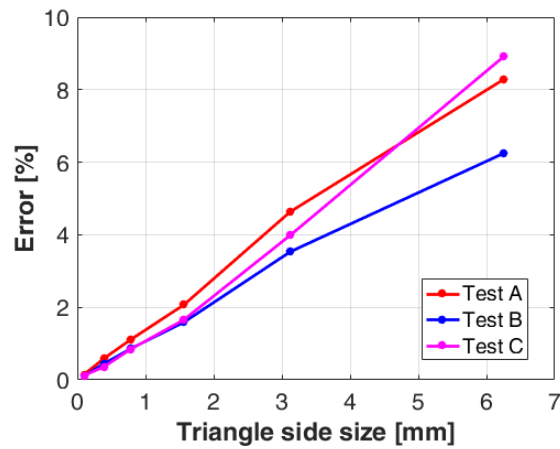


Test C

352

Fig. 9: Results obtained in three different test cases

353 The obtained error for the test cases taken into account is satisfactory and allows to state that the validation
354 of the methodology has been successful. Nevertheless, accuracy depends on the chosen resolution to
355 generate the mesh used to describe the surfaces. An investigation of the effects of the resolution has been
356 carried out obtaining the results shown in Fig. 10. As can be observed, in order to obtain an accurate
357 evaluation of the effects generated by the cavities taken into account, the maximum edge size should be
358 lower than 1 mm. Since the diameter of the inclusions ranges from 8 to 20 mm, it can be stated, as a general
359 rule, that the dimension of the edge size of the mesh should be smaller than 1/10 of the diameter of the
360 cavities under investigation.



361

Fig. 10: Percent error variation as a function of the mesh edge size

362

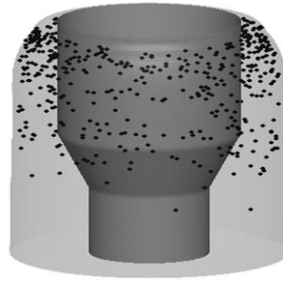
363

364 **4 Results and discussion**

365 The developed methodology has been used to investigate the effects generated by a large number of cavities
366 found on an actual motor. A significant number of cavities (670) had been generated during the casting
367 process of a segment of the Ariane 5 solid rocket motor namely segment S3. The presence of the cavities
368 has been detected through the diagnostic procedures that follow the manufacturing phase, by employing an
369 X-ray instrumentation.

370 Since the detected cavities are localized in a relatively small portion of the motor, the investigation of their
371 effects was focused on that portion, thus neglecting a large part of the original geometry, and considering
372 only the interesting one. The geometry of the part considered in for the present study is represented in Fig.
373 11, together with the location of the detected cavities. Neglecting the portion of the motor with no detected

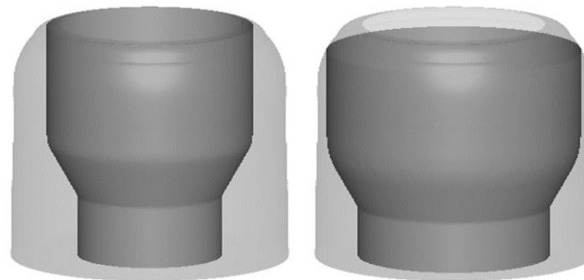
374 inclusions is useful to reduce the computational effort needed (the higher the extension of the motor, the
375 larger the number of triangles to be used to cover the entire combustion surface), and/or increase the
376 accuracy of the evaluations.



377

378 **Fig. 11: Geometry of the investigated portion of the motor with the detected cavities**

379 The portion of the motor has been studied in its nominal configuration to identify the web coordinate and
380 the path followed by combustion to reach the motor case, so as to develop the methodology used to evaluate
381 the effects of the cavities precisely. The process that allows to determine this piece of information requires
382 the knowledge of the combustion surface regression at different web values, obtained through the tool
383 introduced at the beginning of this work (ROBOOST) and displayed in Fig. 12:



384

385

a) Norm. web 0.15

b) Norm. web 0.45



386

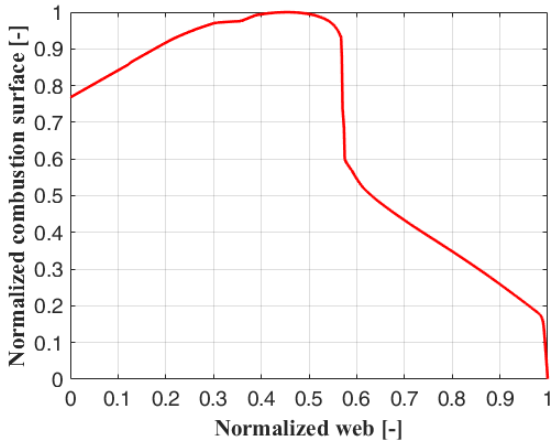
387

c) Norm. web 0.75

388

Fig. 12: Regression of the combustion surface at different web values

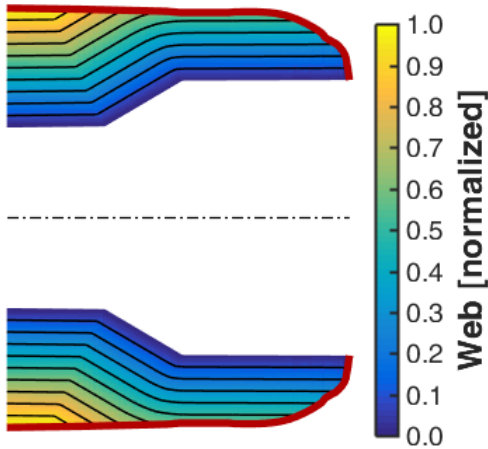
389 The extension of the combustion surfaces measured at different web coordinates by ROBOOST has been
390 displayed in Fig. 13 as a function of the web coordinate, represented in a normalized form for confidentiality
391 reasons. Since the surface is evaluated on a portion of the entire motor, its waveform does not represent the
392 complete generated thrust directly, even if the difference caused by the inclusions is the same as the one
393 that affects the whole motor.



394

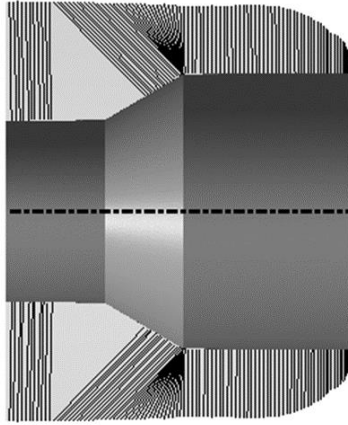
395 **Fig. 13: Combustion surface vs web coordinate**

396 The knowledge of the combustion surfaces reported in Fig. 12 allows to determine the web coordinate
397 value, shown in Fig. 14, following the same procedure already described in a previous section of this paper.
398 As for Fig. 15, it illustrates the lines describing the path followed by the combustion process to reach each
399 of the available positions on the motor case.



400

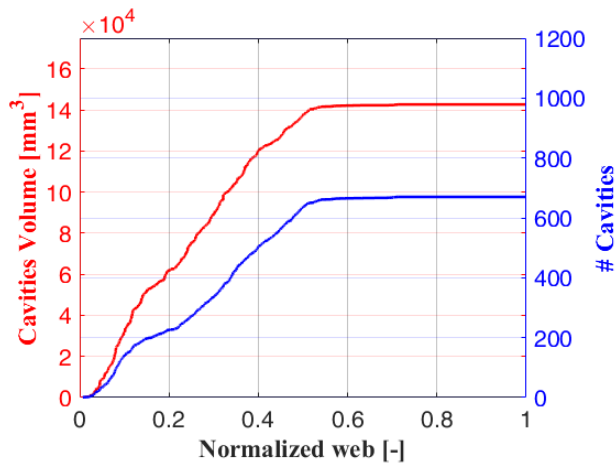
401 **Fig. 14: Web coordinate representation for the longitudinal section of the motor**



402

403 **Fig. 15: Combustion paths followed to reach the different locations on the motor case**

404 As already mentioned, 670 cavities with a diameter ranging from 5 to 14 *mm* have been detected on this
 405 motor; consequently, a very fine mesh was required to describe the surface regression. The location of each
 406 cavity has been used to evaluate the web coordinate of the centers, and to sort them based on the expected
 407 order of incorporation into the combustion surface (i.e., based on the web coordinate). This piece of
 408 information is very useful to determine the mutual influence of the various inclusions efficiently, as already
 409 explained in a previous section. Fig. 16 illustrates the number and total volume of the cavities as a function
 410 of the web coordinate, showing that the largest part of the inclusions is contained in the first half of the web
 411 coordinate (i.e., approximately in the first half of the duration of the combustion).



412

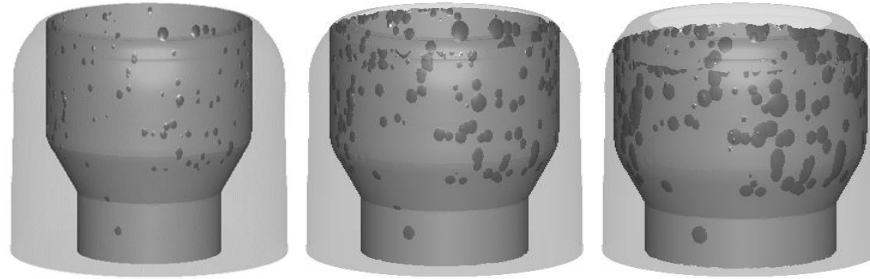
413 **Fig. 16: Number and total volume of inclusions vs web coordinate**

414 The effect of the detected inclusions can now be evaluated both in terms of performance modification (i.e.,
415 combustion surface changes), and in terms of longer exposure of the thermal protections of the motor case
416 (i.e., web coordinate advance).

417 *4.1 Effects on performance*

418 The evaluation of the combustion surface change is performed by applying the methodology to each vertex
419 of the mesh describing the burning surface at the different web coordinate values. Based on the
420 considerations made in the validation phase of the procedure, the chosen edge size is *0.5 mm*. The evaluated
421 web advance has been used to represent the motion caused by the inclusions on each vertex, thus obtaining
422 a geometrical representation of the modified surfaces, some of which are shown in Fig. 17. The regions
423 affected by the inclusions are represented in a darker gray in order to better highlight them. As it can be
424 noticed, even if the initial dimension of the inclusions is relatively small (see Fig. 17a), the extension of
425 their effect spreads around due to the regression process (see Figures 17b and 17c).

426 Figures 17a-f show that all the inclusions generate effects within the portion of the motor that has been
427 selected, thus confirming that the choice of taking into consideration only a portion of the original motor
428 with the purpose of reducing the computational effort was right. Another aspect to be highlighted is the
429 effect produced by adjacent surfaces characterized by different regression directions, such as the one that
430 occurs in the lower part of the selected portion of the motor. Due to this, the initial circular shape of the
431 inclusion located lowest in the drawings is progressively cut and modified by the advancement of the
432 inclined burning surface connecting the cylindrical surfaces at the bottom and top of the motor.



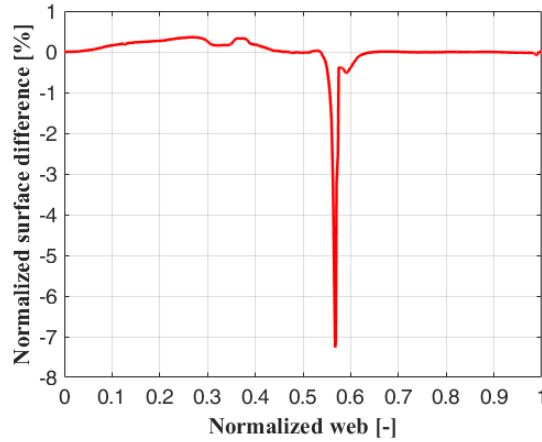
a) Norm. web 0.15 b) Norm. web 0.30 c) Norm. web 0.45



d) Norm. web 0.60 e) Norm. web 0.75 f) Norm. web 0.90

Fig. 17: Combustion surfaces at different web coordinates affected by the inclusions

The evaluation of the change of the regression area is reported in Fig. 18. The instantaneous absolute value can be as high as 7% of the maximum nominal combustion surface, even if the dimension of the inclusions is small. The maximum instantaneous absolute difference is located at approximately 55% of the web coordinate, in the region where the largest cylindrical portion of the motor's internal surface reaches the thermal protection layer. Such a large difference is due to the advance with which the thermal protection is hit, and to the corresponding reduction of the burning surface that disappears when the case is reached. It should be underlined that this large value is obtained because only a portion of the entire motor is represented. The value would have been lower than 1% (and, therefore, acceptable) if the total motor had been taken into consideration.



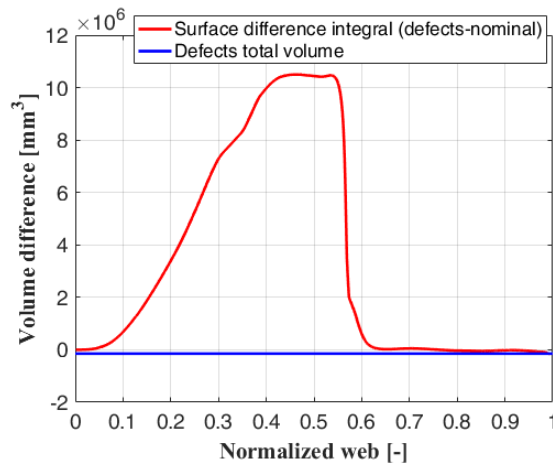
448

449

Fig. 18: Combustion surface percent variation vs web coordinate

450 During the first half of the propulsion phase, the combustion surface variation is positive, meaning that the
 451 amount of propellant burnt during that phase is larger than the nominal one. This is due to the propagation
 452 of the combustion surface, starting from the cavities, that increases the extension of the burning area and
 453 also the amount of propellant involved in the combustion process. In order to quantify this effect, the
 454 volume increase of burnt propellant with respect to the nominal condition is reported in Fig. 19.

455



456

457

Fig. 19: Burned volume vs web coordinate

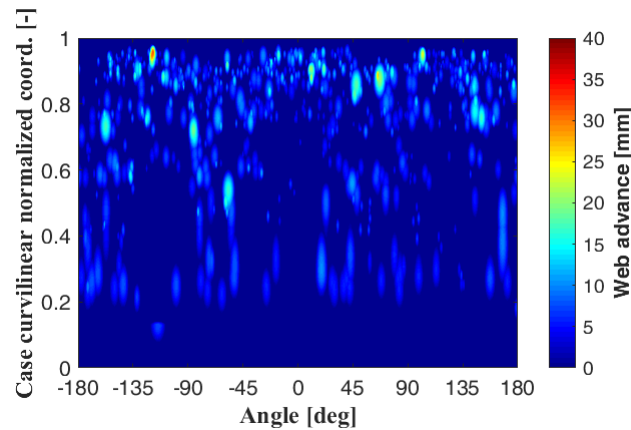
458 As can be observed in Fig. 19, the volume difference is quite high in the first half of the propellant's burning
 459 phase, with a peak in volume difference that is a lot higher than the total volume of the cavities. As already
 460 mentioned, this is due to the spreading of the burning surface of the cavities once they have been
 461 incorporated into the combustion process. At a normalized web equal to 0.55, this effect disappears since

462 most cavities are located in the upper region of the portion of the motor, characterized by a larger internal
463 diameter and therefore a shorter burning time. The final value of the volume difference will be negative
464 and equal to – in absolute value – the total volume of the cavities (reported in blue in Fig. 19), since the
465 volume of the inclusions is filled with propellant in the nominal case, and empty in the real case.

466 4.2 Effects on the exposure time of thermal protections

467 The evaluation of the exposure time increase for the thermal protections is studied by applying the
468 developed methodology to each vertex of the mesh describing the thermal protection surface. The smaller
469 the mesh edge size, the higher the accuracy of the web advance obtained, as already discussed in previous
470 sections. For this reason, the chosen mesh edge size is 0.5 mm. Fig. 20 shows the web advance value for
471 the thermal protection surface, represented as a function of its curvilinear and angular coordinates (Fig.
472 20a) and reported on a 3D representation of the surface (Fig. 20b).

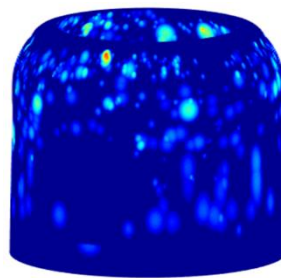
473



474

475

a) Web advance represented in curvilinear and angular coordinates



476

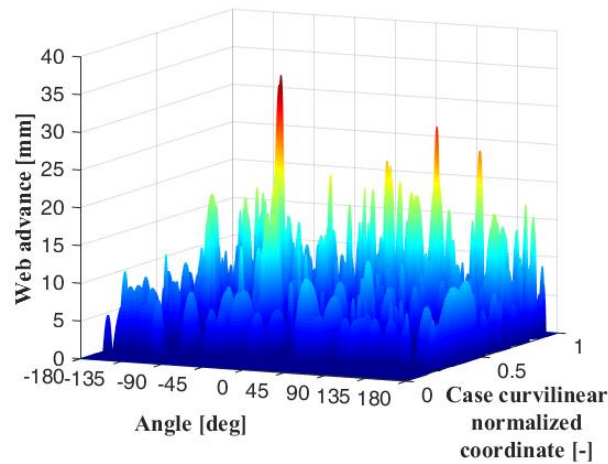
477

b) Web advance reported on the thermal protection surface

478

Fig. 20: Web advance obtained on the thermal protection surface

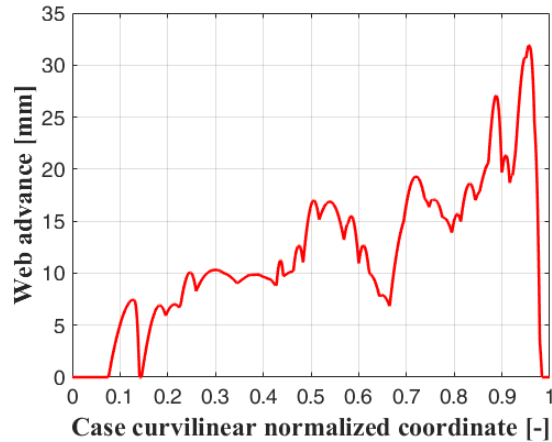
479 The same values are also reported on a waterfall representation in Fig. 21 in order to highlight the peak
480 values, which appear to be as high as to 32 *mm*. Each web advance value obtained should be now checked
481 to verify if the thermal protection is able to survive to the additional exposure to the high-temperature hot
482 gases in the combustion chamber. Since the thickness of the thermal protection for this motor is a function
483 of the curvilinear coordinate of the case only (i.e., the thickness does not vary in the angular direction), the
484 piece of information that is needed to complete this check is the maximum web advance for each value of
485 the curvilinear coordinate, as reported in Fig. 22.
486



487

488 **Fig. 21: Waterfall representation of the web advance**

489 The values reported in Fig. 22 have been obtained by simply considering the maximum web advance
490 estimated for each case curvilinear coordinate. Since the maximum diameter of the detected cavities is equal
491 to 14 *mm* approximately, and the maximum web advance is more than twice that value, there is a strong
492 effect of mutual influence between inclusions. In particular, the highest value is the effect of the
493 combination of 5 cavities (with a maximum nominal diameter of 11.5 *mm*) which are almost aligned on
494 the line that describes the path followed by combustion to reach the corresponding position on the thermal
495 protection.



496

497

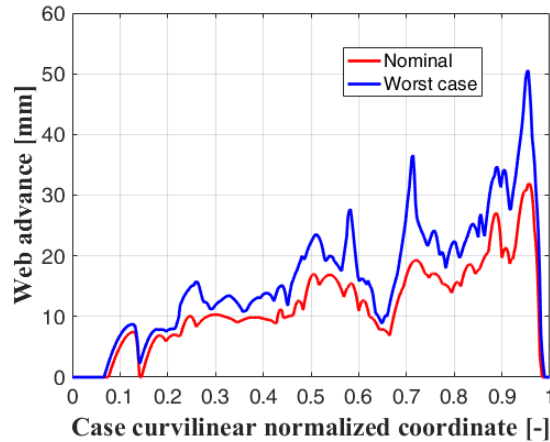
Fig. 22: Maximum value of web advance as a function of case curvilinear coordinate

498 *4.3 Effect of uncertainties*

499 The final point to be evaluated in the present study was the effect of the uncertainties on the properties of
 500 the cavities. The assumption is that the maximum uncertainty on the diameter of each cavity is 1 mm,
 501 whereas the knowledge of the position is less accurate, and the inaccuracy can be as high as 10 mm. This
 502 larger inaccuracy stems from the fact that the position of each cavity is obtained by matching together
 503 different views of the same cavity, obtained through X-ray investigations of the same grain portion seen
 504 from different view angles.

505 The methodology described in the previous section has been employed to determine the worst condition for
 506 each point on the thermal protection surface. As already mentioned in the methodology description, each
 507 thermal protection surface point has its own worst condition, determined by a dedicated application of the
 508 inaccuracies (especially in terms of position). For this reason, the worst global condition is the collection
 509 of all the worst results determined for each position on the investigated surface and obtained with different
 510 cavity configurations. The worst global condition represents a collection of web advances that can be
 511 obtained locally but cannot be obtained with the same intensity starting from a single cavity configuration.
 512 The comparison between the maximum web advance for each value of the curvilinear coordinate under the
 513 nominal cavity configuration and the one resulting from taking into consideration the collection of the worst
 514 cases is shown in Fig. 23.

515



516

517

Fig. 23: Comparison between nominal inclusion configuration and worst case

518

The total number of simulations performed to determine the worst condition for each point of the thermal protection surface was equal to 275 000 and required approximately 70 hours of work to be completed.

519

520

The highest value of the web advance is still in the same position, even if its value is higher by 20 mm,

521

amounting to a 60% increase. That increase cannot be explained simply by considering the diameter growth

522

introduced with the uncertainties, since the 5 cavities involved in the nominal configuration to generate the

523

maximum web advance level would have generated a 5 mm increase maximum. This means that other

524

cavities exert an influence for that position once they have been considered in their most dangerous position:

525

as a matter of fact, the total number of cavities playing a role rises to 9.

526

The difference obtained between nominal cavity configuration and worst-case application of the

527

inaccuracies highlights the importance of considering this effect. The increment of the highest web advance

528

is indeed substantial, and its exact evaluation is crucial in guaranteeing the safety of the motor under study.

529

530 5 Conclusions

531

A methodology to evaluate the effects of cavities inside the grain of a solid rocket motor has been developed

532

and validated. The methodology has been presented in detail by taking into account inclusions with a

533

spherical shape, however, it may be extended to cavities with a generic shape by simply considering them

534

as being composed of a set of spherical inclusions. The output of the developed procedure is the change in

535

burning surface (linked to the change in internal pressure and generated thrust), and the variation of

536

exposure time of the thermal protection surface. This set of information is needed each time a set of

537

inclusions is detected inside a manufactured rocket to make sure that the motor can be safely launched. In

538

the validation phase, the methodology was proven effective as long as the dimensions of the edge size of

539 the mesh employed to describe the burning surface and/or the thermal protection surface is small enough.
540 Under these conditions, it is indeed possible to guarantee an accuracy that remains under 1% of the
541 variations generated by the presence of the cavities.

542 The procedure has been extended to assess the effects generated by the inaccuracies in the measuring of the
543 dimension and position of the cavities – usually detected through X-ray inspection of the grain. The
544 outcome of the methodology is in the collection of the local worst-case scenarios, obtained as the result of
545 the combination of the most dangerous positioning and sizing of the inclusions within the inaccuracy limits.
546 The algorithm has been applied to an actual motor containing a large number of inclusions (670), produced
547 during the manufacturing process. The methodology was proven effective in the evaluation of the
548 consequences caused by the presence of the cavities, highlighting their mutual interactions that would not
549 have been otherwise considered. The highest exposure advance of the thermal protection surface was
550 located in a region in which 5 different inclusions were interacting, generating an advance approximately
551 3 times higher than the maximum diameter of the largest cavity of the cluster. The methodology can be
552 applied to any motor simply by knowing its geometry and dimension and location of its cavities.

553

554 **Nomenclature**

555 D_{cav} = diameter of the cavity [m]

556 $dist_{12}$ = distance between the centers of cavity 1 and cavity 2 [m]

557 $dist_{p1}$ = distance between point P and the center of cavity 1 [m]

558 $dist_{p2}$ = distance between point P and the center of cavity 2 [m]

559 $dist_{pcav}$ = distance between the center of the cavity and the generic point P [m]

560 w = web coordinate [m]

561 w_{cav} = web coordinate in which the cavity is incorporated into the burning surface [m]

562 $w_{cav2cav1}$ = web coordinate in which cavity 2 is reached by the combustion coming from cavity 1 [m]

563 w_{cen} = web coordinate of the cavity center [m]

564 w_p = web coordinate on a generic point P [m]

565 w_{pcav} = web coordinate in which point P is reached by the combustion coming from the cavity [m]

566 x = coordinate of points along x-axis [m]

567 y = coordinate of points along y-axis [m]

568 z = coordinate of points along z-axis [m]

569 Δw_{21} = web advance caused by cavity 1 on cavity 2 [m]

570 Δw_i = web advance on the i-th cavity caused by a set of cavities [m]

571 Δw_p = web advance on point P caused by a set of cavities [m]

572 Δw_{p1} = web advance caused by cavity 1 on point P [m]

573 Δw_{p2} = web advance caused by cavity 2 on point P [m]

574 Δw_{pcav} = web advance caused by a cavity on point P [m]

575

576 **Declaration of competing interest**

577 The authors declare that they have no known competing financial interests or personal relationships that
578 could have appeared to influence the work reported in this paper.

579

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681 **Vitae**



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