Research Article

Linking Processing Parameters with Melt Pool Properties of Multiple Nickel-Based Superalloys via High-Dimensional Gaussian Process Regression

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Table 1. Composition of the 58 nickel-based superalloys

Nickel-based superalloys contain up to 40 wt. % of a combination of five to ten elements in addition to Nickel (Ni) to optimize their performances for high-temperature applications. Table 1 lists the composition of the fifty-eight superalloys as obtained from the Cannon Muskegon[1]. The base element is Ni with about 46-75 wt. %. Other component elements include Chromium (Cr), Cobalt (Co), Aluminum (Al), Tungsten (W), Tantalum (Ta), Titanium (Ti), Rhenium (Re), Iron (Fe), and Molybdenum (Mo), that are added between 0-20 wt. %. Trace amounts of Carbon (C), Boron (B), Zirconium (Zr), Niobium (Nb), Hafnium (Hf), Silicon (Si), Manganese (Mn), Vanadium (V), and Yttrium (Yt) are also present. The composition of every Ni superalloy is represented as constituent fractions of the aforementioned 19 elements as shown below.

Table 1. Composition of nickel-based superalloys.

	C	Cr	Ni	Co	Mo	W	Nb	Ta	Ti	Al	B	Zr	Hf	Fe	Re	Mn	Si	V	Y
AM-1	0	8	62.6	6	2	6	0	9	1.2	5.2	0	0	0	0	0	0	0	0	0
AM-3	0	8	67	6	2	5	0	4	2	6	0	0	0	0	0	0	0	0	0
B 1900	0.1	8	64.565	10	6	0	0	4.25	1	6	0.015	0.07	0	0	0	0	0	0	0
B 1900 +HF	0.1	8	63.435	10	6	0	0	4.25	1	6	0.015	0.1	1.1	0	0	0	0	0	0
B 1910	0.15	10	62.235	10	3	0	0	7.25	1.25	6	0.015	0.1	0	0	0	0	0	0	0
C 1023	0.16	15.5	58.034	10	8.5	0	0	0	3.6	4.2	0.006	0	0	0	0	0	0	0	0
C 263	0.06	20	51.339	20	6	0	0	0	2.15	0.45	0.001	0	0	0	0	0	0	0	0
CM 186 LC	0.07	6	62.61	9	0.5	8	0	3	0.7	5.7	0.015	0.005	1.4	0	3	0	0	0	0
CM 247 LC	0.07	8	61.505	9	0.5	10	0	3.2	0.7	5.6	0.015	0.01	1.4	0	0	0	0	0	0
CM 681LC	0.1	5.5	66.24	9	0	8.5	0	6	0.15	0	0	0.01	1.5	0	3	0	0	0	0
CMSX-10K	0	2	69.57	3	0.4	5	0.1	8	0.2	5.7	0	0	0.03	0	6	0	0	0	0
CMSX-10N	0	1.5	69.12	3	0.4	5	0.05	8	0.1	5.8	0	0	0.03	0	7	0	0	0	0
CMSX-2	0	8	65.8	5	0.6	8	0	6	1	5.6	0	0	0	0	0	0	0	0	0
CMSX-3	0	8	65.7	5	0.6	8	0	6	1	5.6	0	0	0.1	0	0	0	0	0	0
CMSX-4	0	6.5	61.7	9	0.6	6	0	6.5	1	5.6	0	0	0.1	0	3	0	0	0	0
CMSX-486	0.07	5	61.31	9	0.7	9	0	4.5	0.7	5.7	0.015	0.005	1	0	3	0	0	0	0
CMSX-6	0	10	70.4	5	3	0	0	2	4.7	4.8	0	0	0.1	0	0	0	0	0	0
GMR 235	0.15	15.5	63.09	0	5.3	0	0	0	2	3	0.06	0	0	10	0	0.3	0.6	0	0
GTD 111	0.1	14	60.268	9.5	1.6	3.8	0	2.8	4.9	3	0.012	0.02	0	0	0	0	0	0	0
GTD 222	0.1	22.5	51.083	19	0	2	0.8	1	2.3	1.2	0.005	0.012	0	0	0	0	0	0	0
GTD 444	0.1	9.75	62.52	7.5	1.5	6	0	4.8	3.6	4.23	0	0	0	0	0	0	0	0	0
IN 100	0.16	10	60.735	15	3	0	0	0	4.75	5.5	0.015	0.04	0	0	0	0	0	0.8	0
IN 625	0.2	21.6	65.2	0	8.7	0	3.9	0	0.2	0.2	0	0	0	0	0	0	0	0	0
IN 713 LC	0.06	12	75.073	0	4.3	0	2	0	0.7	5.8	0.007	0.06	0	0	0	0	0	0	0
IN 713C	0.1	13.5	73.03	0	4.5	0	2	0	0.8	6	0.01	0.06	0	0	0	0	0	0	0
IN 738C	0.17	16	61.52	8.5	1.7	2.5	0.8	1.7	3.5	3.5	0.01	0.1	0	0	0	0	0	0	0
IN 792	0.12	12.4	61.16	9	1.9	3.8	0	3.9	4.5	3.1	0.02	0.1	0	0	0	0	0	0	0
IN 792 Hf	0.11	12.2	61.275	9	2	3.8	0	4	4	3.5	0.015	0.1	0	0	0	0	0	0	0
IN 939	0.15	22.4	48.74	19	0	1.6	1	1.4	3.7	1.9	0.01	0.1	0	0	0	0	0	0	0
MC-2	0	8	64.5	5	2	8	0	6	1.5	5	0	0	0	0	0	0	0	0	0
Mar M 200+Hf	0.14	9	60.845	10	0	12	1	0	2	5	0.015	0	0	0	0	0	0	0	0
Mar M-002	0.15	9	59.785	10	0	10	0	2.5	1.5	5.5	0.015	0.05	1.5	0	0	0	0	0	0
Mar M-247	0.16	8.2	59.975	10	0.6	10	0	3	1	5.5	0.015	0.05	1.5	0	0	0	0	0	0
Mar M 002	0.15	9	59.785	10	0	10	0	2.5	1.5	5.5	0.015	0.05	1.5	0	0	0	0	0	0
Mar M 004	0.05	12	73.585	0	4.5	0	2	0	0.6	5.9	0.015	0.05	1.3	0	0	0	0	0	0
Mar M 200	0.15	9	59.485	10	0	12.5	1.8	0	2	5	0.015	0.05	0	0	0	0	0	0	0
Mar M 246	0.15	9	59.785	10	2.5	10	0	1.5	1.5	5.5	0.015	0.05	0	0	0	0	0	0	0
Mar M 421	0.15	15.5	60.885	9.5	2	3.8	2	0	1.8	4.3	0.015	0.05	0	0	0	0	0	0	0
Ni-X	0.1	21.75	46.55	1.5	9	0.6	0	0	0	0	0	0	0	18.5	0	1	1	0	0
PWA 1480	0	10	62.497	5	0	4	0	12	1.5	5	0.003	0	0	0	0	0	0	0	0
PWA 1484	0	5	59.75	10	1.9	5.9	0	8.7	0	5.65	0	0	0.1	0	3	0	0	0	0
PWA 1487	0	5	59.887	10	1.9	5.9	0	8.4	0	5.65	0	0	0.25	0	3	0	0	0	0.013
PWA-1426	0.1	6.5	58.855	12	2	6	0	4	0	6	0.015	0.03	1.5	0	3	0	0	0	0
RR-2000	0	10	61.5	15	3	0	0	0	4	5.5	0	0	0	0	0	0	0	1	0
Rene 125	0.11	9	59.223	10	2	7	0	3.8	2.5	4.8	0.017	0.05	1.5	0	0	0	0	0	0
Rene 220	0.02	18	57.47	12	3	0	5	3	1	0.5	0.01	0	0	0	0	0	0	0	0
Rene 41	0.09	19	55.355	11	9.75	0	0	0	3.15	1.65	0.005	0	0	0	0	0	0	0	0
Rene 77	0.07	14.6	58.475	15	4.2	0	0	0	3.3	4.3	0.015	0.04	0	0	0	0	0	0	0
Rene 80	0.16	14	60.295	9.5	4	4	0	0	5	3	0.015	0.03	0	0	0	0	0	0	0

Rene 95	0.15	14	61.29	8	3.5	3.5	3.5	0	2.5	3.5	0.01	0.05	0	0	0	0	0	0	0
Rene N4	0	10	60.6	8	2	6	0.5	5	3.5	4.2	0	0	0.2	0	0	0	0	0	0
Rene N5	0	7	62.6	8	2	5	0	6	0	6.2	0	0	0.2	0	3	0	0	0	0
Rene N6	0	4	59	12	1	6	0	7	0	5.8	0	0	0.2	0	5	0	0	0	0
SC-180	0	5	60.2	10	2	5	0	8.5	1	5.2	0	0	0.1	0	3	0	0	0	0
SR-99	0	8	66.3	5	0	10	0	3	2.2	5.5	0	0	0	0	0	0	0	0	0
U 500	0.07	19	52.923	18	4	0	0	0	3	3	0.007	0	0	0	0	0	0	0	0
U 700	0.07	15	53.505	18.5	5	0	0	0	3.5	4.4	0.025	0	0	0	0	0	0	0	0
Waspaloy	0.07	19.5	58.325	13.5	4.2	0	0	0	3	1.35	0.005	0	0	0	0	0	0	0	0
Weldable Waspaloy	0.06	12.1	67.69	12.3	3.7	0	0	0	3	1.15	0	0	0	0	0	0	0	0	0

[1] https://cannonmuskegon.com/

Figure 1. Convergence results for Sobol sensitivity calculations

The Sobol analysis is carried out using the sensitivity analysis package, SALib, for which samples are generated using the Saltelli sampler. The number of samples to be generated is determined via a convergence test. The evolution of first order and total order indices with an increasing number of samples is observed until the Sobol calculations converge without any computing errors.

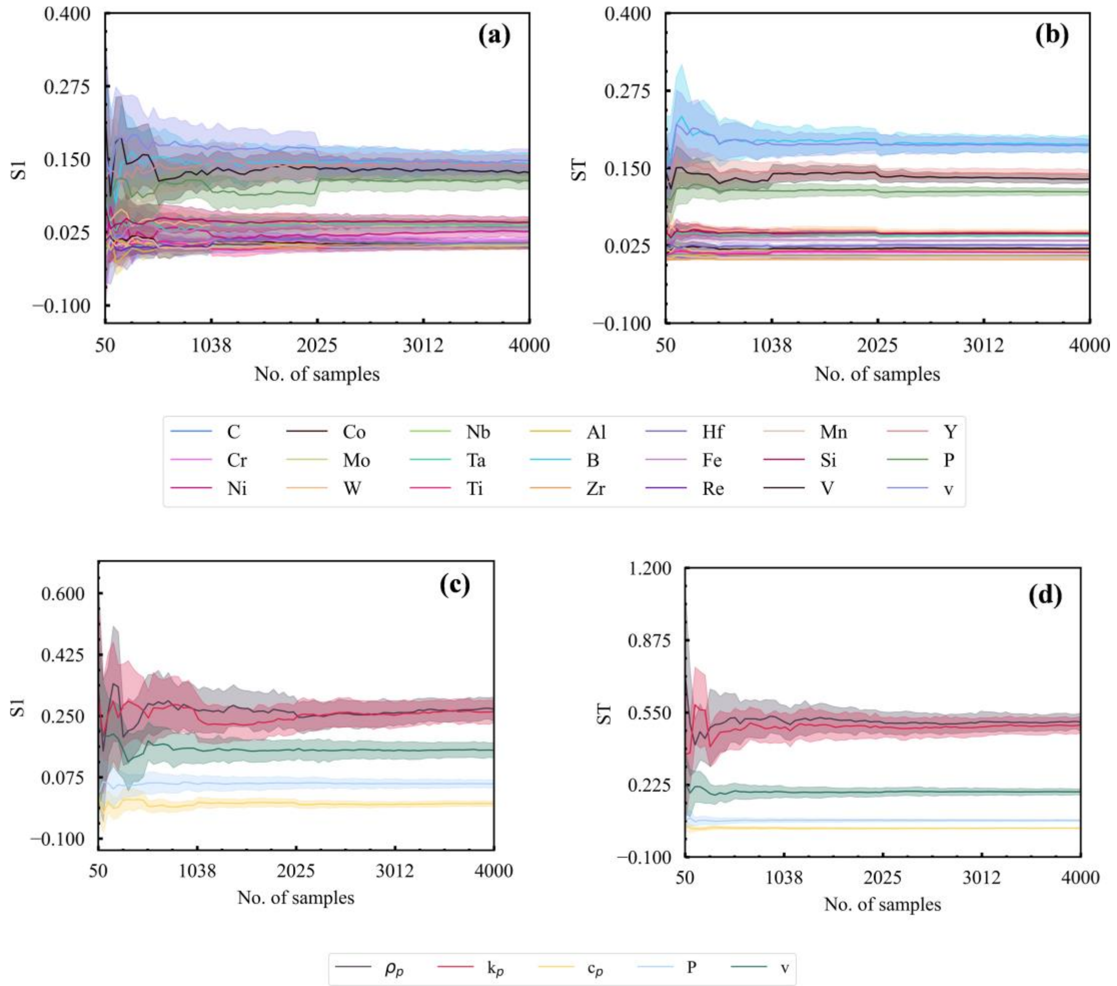

Figure 1. Convergence of Sobol sensitivity analyses using GP_{OneStep} for (a) first-order ($S1$) and (b) total-order sensitivities (ST). Convergence of Sobol sensitivity analyses using $GP_{\mathrm{TwoStep}_{[\delta]}}$ for (c) first-order ($S1$) and (d) total-order sensitivities (ST).

Table 2. $S2$ sensitivities for $GP_{OneStep}$

The pairwise interactions, indicated by $S2$ values are listed in Table 2. $S1$ sensitivities alone summed up to 0.96 indicating the effect of $S2$ on the total sensitivity, measured by ST, is marginal.

Table 2. $S2$ sensitivities for $GP_{OneStep}$

C	-2.79E-05	0.000114	3.06E-05	6.90E-05	6.96E-05	3.86E-05	7.44E-05	1.62E-05	5.06E-05	3.23E-05	3.65E-05	4.69E-05	2.85E-05	0	2.85E-05	2.85E-05	2.61E-05	0	0.000294	0.002445
Cr		8.59E-05	0.000104	-2.33E-05	0	2.65E-05	0	6.07E-05	1.83E-05	5.00E-05	5.64E-05	0	3.21E-05	0	3.21E-05	3.21E-05	0	0	0.000224	0.003706
Ni			0.000182	7.43E-05	0.000124	6.31E-05	0.000226	0.000139	0.000111	8.27E-05	6.97E-05	0.00013	2.13E-05	3.28E-05	0	2.13E-05	2.18E-05	0	0.000458	0.00227
Co				-1.35E-05	0	2.34E-05	6.97E-05	8.69E-05	0.000182	0	3.99E-05	9.76E-05	0	9.30E-05	0	0	1.31E-05	0	0.000261	0.001561
Mo					0	4.69E-05	0	0.00011	1.56E-05	6.06E-05	9.99E-05	3.19E-05	1.63E-05	0	1.63E-05	1.63E-05	0	0	0.000341	0.001219
W						0	0	2.46E-05	5.12E-05	0	0	4.83E-05	0	0	0	0	0	0	0.000266	0.002243
Nb							0	6.08E-06	4.08E-05	0	0	0	0	0	0	0	0	0	0.000208	0.001152
Ta								0	5.23E-05	0	9.60E-06	0	0	4.05E-05	0	0	0	1.21E-05	0.000211	0.002325
Ti									0.000159	0	7.63E-05	9.61E-05	0	0	0	0	2.38E-06	0	0.000251	0.001829
Al										0	0.000171	0.000113	0	6.07E-05	0	0	1.73E-05	1.65E-05	0.000346	0.001799
B											0	0	5.96E-06	0	0	5.96E-06	0	0	0.000369	0.002194
Zr												1.06E-05	0	0	0	0	0	0	0.000443	0.002409
Hf													0	0	0	0	0	0	2.18E-05	0.001257
Fe														0	1.09E-08	1.09E-08	0	0	0.000173	0.000256
Re															0	0	0	0	-0.00022	0.003106
Mn																1.09E-08	0	0	0.000173	0.000256
Si																	0	0	0.000173	0.000256
V																		0	0.000168	0.00013
Y																			5.58E-05	0.000228
P																				0.035438
v	Cr	Ni	Co	Mo	W	Nb	Ta	Ti	Al	B	Zr	Hf	Fe	Re	Mn	Si	V	Y	P	v