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AN OVERVIEW OF NUMERICAL OPTIMIZATION APPLICATIONS FOR FRICTION STIR WELDING

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Abstract

Recent advances in the computational power, and at the same time, the software that is capable of taking advantage of the new hardware architecture promote numerical modelling activities for the Friction Stir Welding (FSW) process as in parallel with other engineering applications. All these developments provide a stronger basis for understanding of the FSW process by enabling inclusion of more detailed multi-physics phenomena, i.e. complex interaction among material behaviour, microstructure evolution, material flow, heat generation, etc. A source of motivation behind all these efforts is the increasing demand for the FSW process mainly in aerospace and automotive industries. However the list of unknowns for the success of the process (e.g. defect free welds) is not yet cleared up. Tool design and process parameter optimization studies are in general limited by design of experiments and those rarely supported by the statistical analysis tools. One of the main reasons for the lack of the autonomous optimization studies, in which the numerical FSW simulations are used for response evaluations, is still the high computational cost. Here in this review paper, a brief overview of remarkable achievements together with the discussion of the limitations in the numerical FSW optimization studies are laid on the table.

Key words: friction stir welding, process optimization, tool design, evolutionary computation, meta-modelling

1. INTRODUCTION

The FSW process is getting more attractive especially in aerospace and automotive industries where there is a high demand for lightweight structures built of materials having high strength-to-weight ratio such as aluminum alloys (Mishra & Ma, 2005; Thomas, 1999; Ma, 2001). First and foremost, the mechanical properties of the metal are preserved as much as possible since there is no melting during the process. It is also advantageous in case of welding large structures which cannot be heat treated afterwards. The process starts with clamping the work pieces on to a backing plate to avoid abutting surfaces spread apart. Then a rotating wear-resistant tool is submerged and traversed along the joint line while stirring the two pieces of metal together. The frictional heating, together with the plastic work provided by the forging and stirring motions, softens the material and makes the FSW tool move forward easier. The process is finalized by removing the tool out of the two work pieces and let it cool down to form the weld. These steps have been schematically shown in figure 1.

Since the development of the process in 1991, FSW modeling studies involving several research areas such as heat transfer (Chao & Qi, 1998; Schmidt & Hattel, 2005; Zhu & Chao, 2004), material flow (Colegrove & Shercliff, 2005; Nandan et al., 2008), material science and metallurgy (Robson et al., 2007), solid mechanics (Chao & Qi, 1998; Zhu & Chao, 2004; Chen & Kovacevic, 2006; Richards et al., 2008; Feng et al., 2007) are increasing every year. However, the common ground behind those models is the requirement for high demanding computation time. Therefore the number of numerical optimization studies is limited and design improvements mostly were performed by experimental works (Cox et al., 2012; Rajakumar & Balasubramanian, 2012; Kumar et al., 2011).

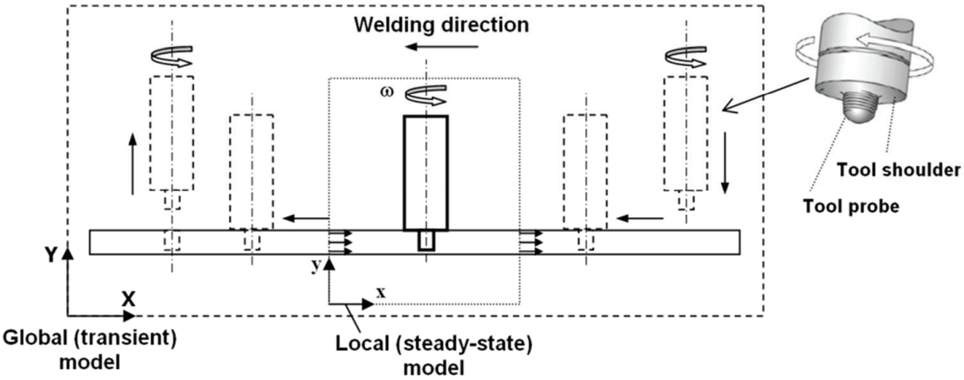

Fig. 1. Schematic view of the FSW process and a typical FSW tool.

This paper is organized in the following manner. Section-2 briefly introduces the multi-physics involved in the FSW process as well as the importance of correct and efficient solution of the transient or steady-state thermal field. Four substantially different multi-objective optimization applications of their first kind in the field of numerical FSW process optimization are provided in short.

2. NUMERICAL OPTIMIZATION OF THE FSW PROCESS

In FSW, heat is generated by friction mainly at the interface between the tool shoulder and the upper surface of the workpiece and plastic deformation by the tool probe or pin in the plunging stage as well as during the welding period via stirring the two workpiece materials along the joining line. The heat flows into the workpiece as well as the tool. The amount of heat conducted into the workpiece influences the quality of the weld, distortion and residual stress in the workpiece (Mishra & Ma, 2005). Insufficient heat generation from the tool shoulder and the probe could lead to failure of the tool pin as the workpiece material is not soft enough. Therefore, understanding the heat aspect of the FSW process, which is the main driving force for all subsequent coupled simulations, e.g., microstructure and solid mechanics models, is extremely important, not only for understanding the physical phenomena, but also for improving the process efficiency, e.g., welding faster and safer (Tutum et al., 2007; Tutum et al., 2010). As aforementioned, some of the limited numerical optimization applications in the FSW research field are briefly presented in the following four subsections in a chronological order (Tutum & Hattel, 2011).

2.1. Optimization of FSW process parameters to reduce residual stresses

The maximum tensile stresses are typically found on, or at either side of, the weld line. These, so-called residual stresses, lower the loading capacity of the component and the compressive plastic misfit situated at the end of the welding process causes distortion, i.e. shrinkage, in the plate unless some removal techniques, i.e. thermal and mechanical tensioning, shot peening and local-dynamic cooling are applied. Figure 2 and 3 show the effect of different welding speeds on the temperature and the residual stress distribution respectively on the plate. Higher welding speed obviously results in higher thermal gradients and eventually in higher magnitudes of peak residual stresses. From manufacturer viewpoint, it is desired to weld faster (i.e. higher production rate), but on the other hand to reduce the manufacturing defects such as residual stress and distortion evolved during the process in the final product. This is clearly a conflicting optimization problem of which solution involves multiple trade-off solutions.

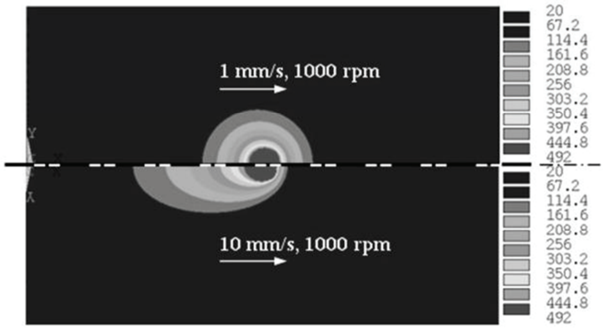

Fig. 2. Comparison of the effect of two different welding speeds on the transient thermal field.

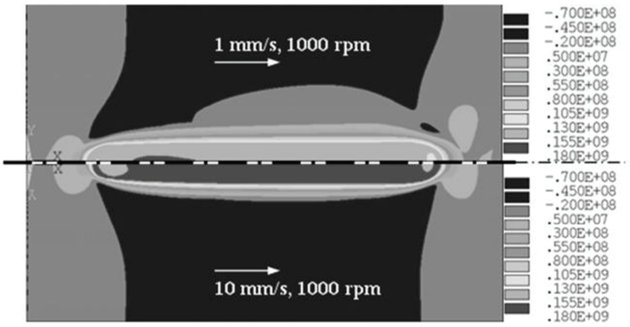

Fig. 3. *Comparison of the effect of two different welding speeds on the residual stress distribution.*

Two design variables, i.e. welding speed and tool rotational speed, are considered for this problem. Non-dominated sorting genetic algorithm (NSGA-II) (Deb et al., 2002), which is an evolutionary multi-objective optimization (EMO) algorithm has been coupled with the residual stress model implemented in commercial finite element analysis (FEA) software ANSYS. The second case converts the first objective (i.e. maximization of the welding speed) into a so-called wear criterion. The resulting Pareto-optimal fronts are presented below in figures 4 and 5. More details are given in the original papers (Tutum & Hattel, 2010a,b).

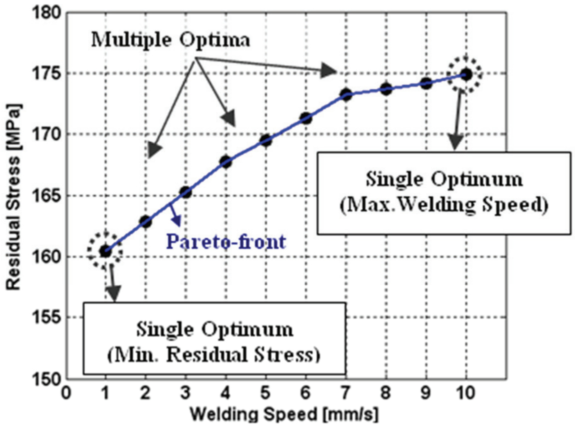

Fig. 4. *Pareto-front for the case-1.*

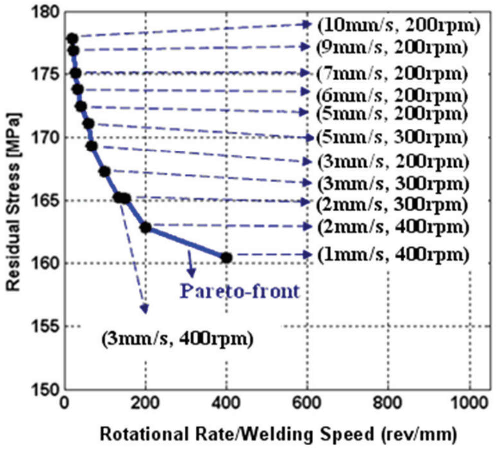

Fig. 5. *Pareto-front for the case-2.*

2.2. Hybrid search using NSGA-II, clustering and a gradient based optimization algorithm

In this section, optimum process parameters and tool geometries in FSW are investigated to minimize the temperature difference between the leading edge of the tool probe and the work piece material in front of the tool shoulder (the computation domain is shown in figures 6 and 7), i.e. to soften the material enough to move the tool probe forward without failure, and simultaneously to maximize traverse welding speed, hence production rate, subjected to hot and cold weld conditions (Tutum et al., 2010).

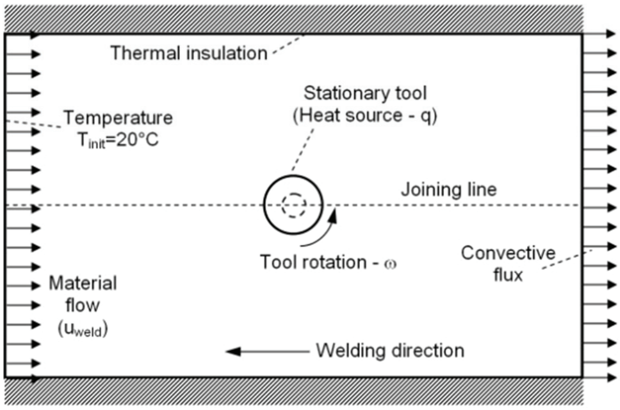

Fig. 6. *2-D Eulerian steady state thermal model.*

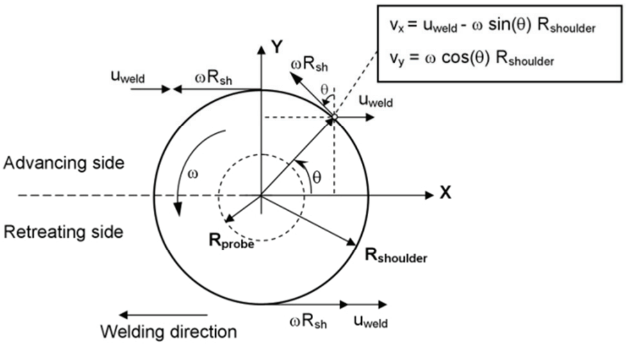

Fig. 7. *Mathematical modeling of the flow field under the tool shoulder in detail.*

A 2-D Eulerian steady state thermal model is implemented in commercial multi-physics software COMSOL and it is coupled with the NSGA-II implemented in MATLAB. The non-dominated solutions found with NSGA-II are clustered based on their Euclidean distances in the objective space (*see* figure 8) and consequently each solution is used as the starting guess (*see* figure 9) having one of the objectives converted to a equality constraint for the gradient-based optimization algorithm Sequential Quadratic Optimization (SQP). More details are given in the paper by Tutum et al., 2010.

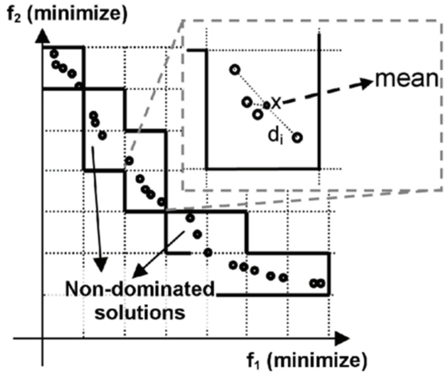

Fig. 8. *Clustering scheme*

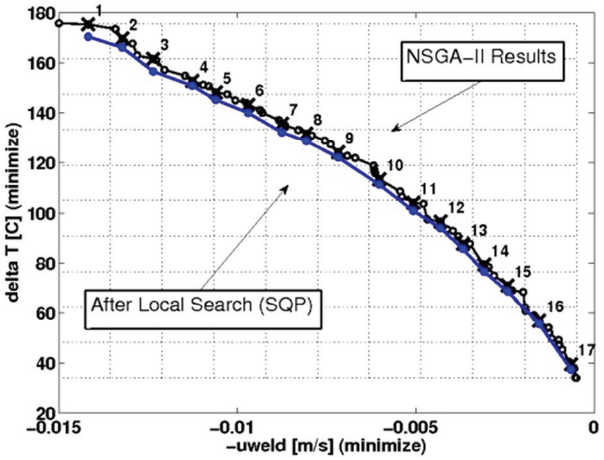

Fig. 9. *Pareto-optimal front modified after the local search on each clustered non-dominated solutions.*

2.3. Automatic discovery of design principles using Pareto set

Deb and Srinivasan, 2006, introduced the methodology so-called *innovization* (innovation through optimization) in which the common design principles among the Pareto-optimal solutions regarding their design variables, objectives or constraint values. While innovization deals with deciphering design principles from a given trade-off front, the higher-level innovization concerns the effect of varying a problem parameter, previously kept constant, on the design principles. In this optimization study, the problem considered in section 2.2 has been used as the original FSW problem and the thickness of the workpiece, which was considered as a constant previously, is converted to a design variable and its effect on the Pareto fronts (i.e. the non-dominated front referring to the modified FSW problem in figure 10 is obtained by converting the plate thickness constant in the original FSW problem into a design variable) and the discovery of the design rules (*see* figure 11) are investigated (Bandaru et al., 2011).

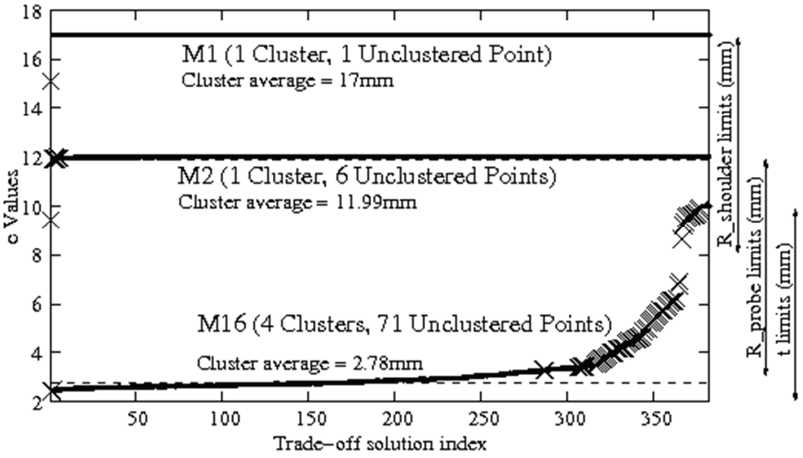

Fig. 11. *Cluster plot for the design principle numbered as 23.*

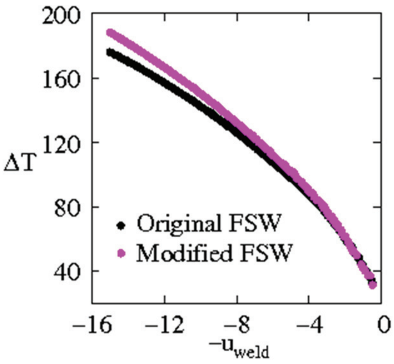

Fig. 10. *Comparison of the trade-off fronts. Original FSW has 287 non-dominated solutions and modified FSW has 382.*

Table 1 shows the obtained design principles and their significance. A few striking aspects of the FSW problem that are revealed by these principles are:

- $R_{shoulder}$(tool shoulder radius) takes the same values for about 95% of the trade-off solutions and this value turns out to be the upper bound of the variable.
- Similarly, O10 and the *c*-values indicate that R_{probe} (tool probe radius) too takes its maximum allowed value of 12 mm for 90% of the front.
- Except for O1 and O10, u_{weld} appears in all the principles making it a very important variable for optimization.
- O23 indicates that for most solutions, $T_{average}$ is (approximately) directly proportional to u_{weld}.

Table 1. *Design principles for original FSW model.*

i	$R_{shoulder}$ $a_{i1}b_{i1}$	R_{probe} $a_{i2}b_{i2}$	u_{weld} $a_{i3}b_{i3}$	n_{rev} $a_{i4}b_{i4}$	ΔT $a_{i5}b_{i5}$	T_{probe} $a_{i6}b_{i6}$	T_{ahead} $a_{i7}b_{i7}$	$T_{average}$ $a_{i8}b_{i8}$	$S_i(\%)$
1	1.000000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.12
2	0.0	0.0	-0.533003	0.0	1.000000	0.0	-0.030123	0.122853	93.38
3	0.0	0.0	-0.532979	0.005812	1.000000	0.0	0.0	0.0	93.38
4	0.0	0.0	-0.529824	0.0	1.000000	0.161206	0.0	0.0	93.03
5	0.0	0.0	-0.529909	-0.000108	1.000000	0.145736	0.0	0.0	92.68
6	0.0	0.0	-0.530625	0.006289	1.000000	0.0	0.023284	0.0	91.99
7	0.0	0.0	-0.530449	0.0	1.000000	0.161227	-0.003067	0.0	91.64
8	0.0	0.0	-0.531469	0.0	1.000000	0.0	0.000197	0.0	90.94
9	0.0	0.0	-0.531470	0.0	1.000000	0.0	0.0	0.0	90.94
10	0.0	1.000000	0.0	0.0	0.0	0.0	0.0	0.0	89.90
11	0.0	0.0	-0.530964	0.0	1.000000	0.002263	0.0	0.091096	88.85
12	0.0	0.0	-0.530514	-0.000296	1.000000	0.0	0.0	0.107888	87.80
13	0.0	0.0	-0.530622	0.0	1.000000	0.0	0.0	0.108271	87.80
14	0.0	0.0	-0.092097	-0.021700	0.0	1.000000	-0.479464	0.0	80.84
15	0.0	0.0	-0.969780	-0.409886	0.0	0.0	-0.377738	1.000000	80.84
16	0.0	0.0	-0.943839	-0.454088	0.0	0.0	0.0	1.000000	80.84
17	0.0	0.0	-0.092097	0.0	0.0	1.000000	-0.479464	0.0	80.14
18	0.0	0.0	-0.559903	-0.912156	0.0	1.000000	0.0	0.0	80.14
19	0.0	0.0	-0.741674	-0.461080	0.0	0.589618	0.0	1.000000	80.14
20	0.0	0.0	-0.963256	0.0	0.0	1.000000	-0.483385	0.032360	80.14
21	0.0	0.0	-0.989152	0.0	0.0	0.0	-0.000057	1.000000	80.14
22	0.0	0.0	-0.989152	0.0	0.0	0.012628	0.0	1.000000	80.14
23	0.0	0.0	-0.989152	0.0	0.0	0.0	0.0	1.000000	80.14

More details can be found in the paper by Bandaru et al., 2011.

2.4. Multi-Criteria Optimization Using a Thermal Model with Prescribed Material Flow

In this last optimization study, a three dimensional steady-state Eulerian thermal model involving a temperature dependent heat source term (Schimidt & Hattel, 2008) incorporating with the prescribed material flow (schematically shown in figure 12) has been implemented in COMSOL (Tutum et al., 2012).

This thermal simulation of the FSW process is used for optimizing the process parameters and the tool geometry simultaneously to maximize the production rate and minimize the risk of tool failure. The average temperature is desired to have above 450 °C to avoid tool pin failure and below 500 °C to reduce tool wear. The effect of the tool rotation on the distribution of the temperature field is also taken into account (asymmetric resulting thermal field under the tool shoulder area is shown in figure 12). The objectives mentioned above are conflicting, hence the solution of this optimization problem re-

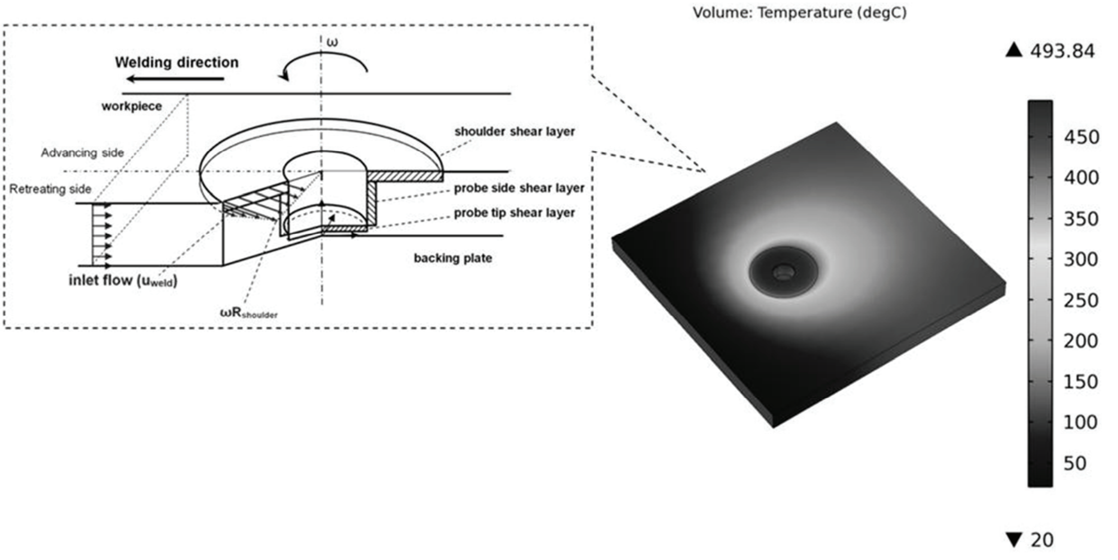

Fig. 12. *Three dimensional steady-state thermal FSW model with prescribed material flow.*

sults in multiple trade-off solutions. For this purpose NSGA-II is used with 65 generations and 50 individuals. The results found so far (see figure 13) are further investigated to unveil existing common design rules as functions of the process parameters (i.e. see figure 14 for the relations for the probe height and the tool rotational speed variation along the Pareto front). Crucial information has been discovered for the generic FSW optimization problem at hand:

- The tool probe radius and the height are found to have their lower design limits whereas the tool shoulder radius is kept constant at its upper design limit.
- Most importantly, the MOP mentioned above having two practical objectives are met by choosing a proper rotation speed for each feed rate set-up (i.e. exponential variation has been observed) without changing the tool design.

More details can be found in the paper by Tutum et al., 2012.

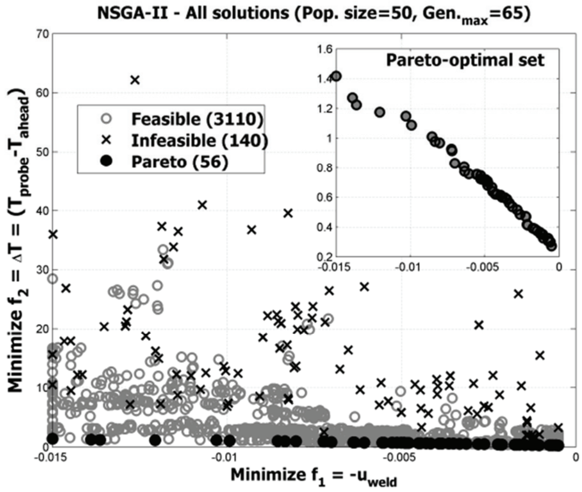

Fig. 13. *All solutions obtained using NSGA-II. The Pareto-optimal front is shown in the inset figure.*

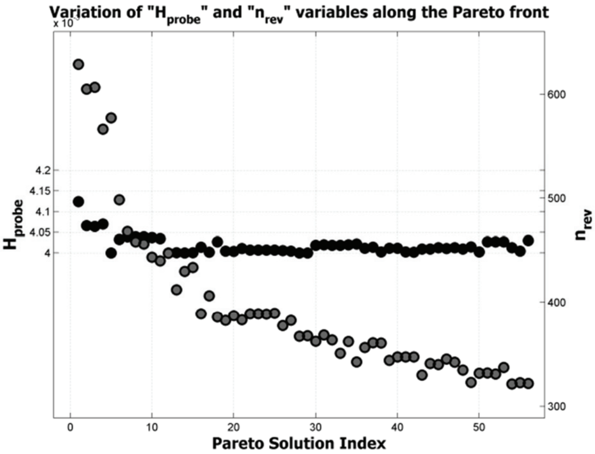

Fig. 14. *H_{probe} and n_{rev} variables of the Pareto-set sorted from u_{weld}=15 mm/s to 0.5 mm/s.*

3. SUMMARY

This paper briefly introduced the multi-physics involved in the FSW process. The limited number of optimization studies in FSW are exemplified with four substantially different multi-objective optimization applications in short. One of the main reasons for the lack of the autonomous optimization studies utilizing FSW simulations is the high computational cost. Readers are referred to the original papers for details.

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PRZEGLĄD APLIKACJI OPTYMALIZACJI PROCESU SPAWANIA TARCIOWEGO WYKORZYSTUJĄCYCH MODELOWANIE NUMERYCZNE

Streszczenie

Rozwój komputerów i oprogramowania, które wykorzystuje nową architekturę sprzętową umożliwia obecnie modelownie numeryczne procesu spawania tarciowego (ang.: Friction Stir Welding - FSW). Modelowanie zjawisk zachodzących w trakcie spawania prowadzi do lepszego zrozumienia procesu FSW poprzez wprowadzenie do modelowania złożonych zależności pomiędzy zachowaniem się materiałów, zmian mikrostruktury, płynięcia materiału, generowania ciepła. Motywacją do tych badań jest coraz szerzej stosowany proces FSW głównie w przemyśle samochodowym i lotniczym. Modelowanie tego procesu jest skomplikowane, a liczba niewiadomych decydujących o własnościach spawu (np. spawy wolne od defektów) nie jest do końca znana. Możliwości optymalizacji projektowania narzędzi oraz parametrów procesu FSW są ograniczone, ponieważ nie stosuje się metod projektowania doświadczenia i analizy statystycznej ze względu na wciąż wysokie koszty obliczeniowe numerycznej symulacji tego procesu. W niniejszym artykule przedstawiono krótki przegląd najważniejszych osiągnięć wraz z dyskusją o ograniczeniach w optymalizacji procesu FSW wykorzystującej numeryczne modelowanie.

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