Optimization of a pipe end upsetting process

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ABSTRACT: This paper discusses the application of Design of Experiments, Response Surface Methodology and Robust Optimization techniques for efficient optimization of pipe end upsetting with a non-uniform and transient temperature field. First, target pipe end shape and objective functions are defined, and constraints on the final shape, forging pressures, temperatures and strain rates are specified. Second, parametric initial work piece shape and initial temperature distributions are defined. Material data are obtained from independent compression tests. Third, a Box-Behnken experimental design (BBD) is defined for a set of shape and temperature variables. A set of ABAQUS simulations is run according to the BBD. The results from the simulation runs are processed by a MATLAB-script. The script calculates regression relations for all essential responses and estimates the value of the object functions and constraints in the entire design space. Further, it performs both standard and robust constrained optimization. The robust optimization considers the effects of variability in design variables. Finally, MATLAB plots several 2D cross-sections of objective and constraints functions in the multi-dimensional design space. Such process windows make prediction of the capability of the upsetting process possible and are very valuable input to the design and quality assurance work.

Key words: Design of Experiments, optimization, numerical simulation, upsetting

1 INTRODUCTION

The objective of the work described in the article has been to establish and assess a method for optimizing the pipe end shape after a single step hot upsetting process. Moderate upsetting is here employed prior to machining of bevels for welding to compensate for significant dimensional variability related to pipe manufacture (both with respect to the thickness and diameter variability). The increase in wall thickness during upsetting is usually less than 30 %, and the extension and shape of the expanded section are determined by the temperature distribution and the initial shape of the pipe-end. No complex tools are needed for the upsetting process. The pipe is simply pressed towards a properly lubricated flat faced tool. A non-uniform transient temperature distribution has first been applied by electric resistance or induction heating. Figure 1 describes the set-up with dashed lines indicating circumferential thickness variations.

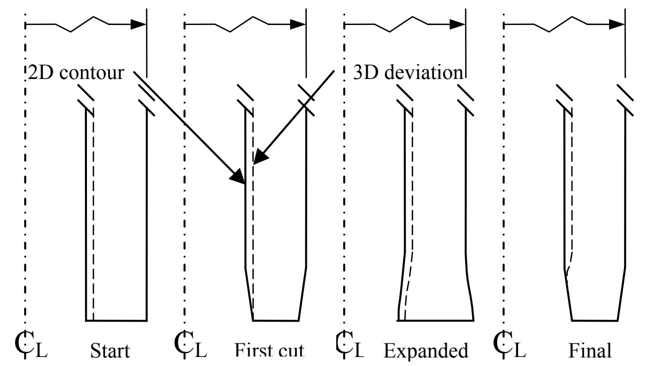

Fig. 1. The initial and the final shape of the pipe end. The problem is here assumed to be purely axisymmetric (2D), but the dashed lines indicate possible 3D thickness differences around the pipe circumference and to be reduced.

The optimisation method combines the well-known Design of Experiments (DoE) and Response Surface Method (RSM) tools [1] with techniques for robust optimization [2,3]. The main results of the work are 2D process charts which clearly indicate the process window or envelope for the process.

2 PROBLEM AND DESIGN OF EXPERIMENTS

2.1 Variables

The numerical analysis described in this paper is purely 2D (axisymmetric) even though the actual problem of pipe end shape variability by nature is a 3D problem (i.e. variations in pipe thickness or ovality). Figure 2 shows the basic pipe end design and the temperature distribution prior to upsetting.

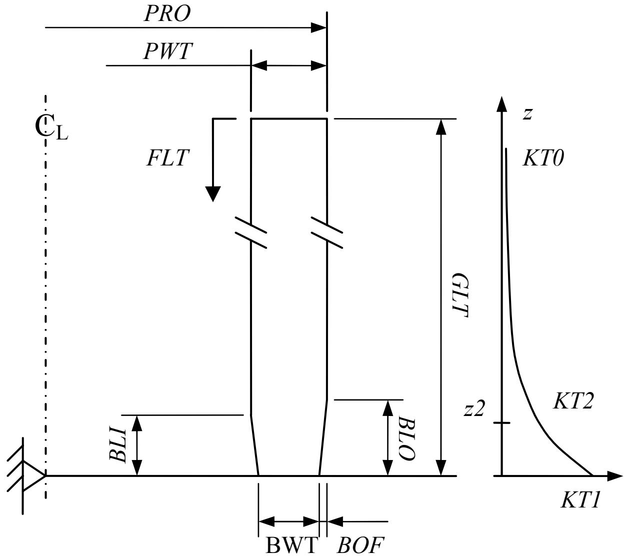

Fig. 2. The shape and temperature variables of the study

In this study we assume that the pipe thickness, *PWT*, the radius, *PRO*, and the distance to the clamping tools, *GLT*, are constant. In addition we assume that the inner and outer bevel length are equal, *BLO = BLI*. To simplify analysis a set of dimensionless variables are defined:

- Bevel width ratio: *BWR* = *BWT / PWT*
- Bevel length ratio: *BLR* = *BLO / PWT*
- Bevel offset ratio:

$$BOR = \frac{2BOF}{PWT - BWT} - 1 \qquad (1)$$

If *BOF = 0*, *BOR = -1*. On the other hand, if *BOF = PWT – BWT*, *BOR = 1*. The forging length, *FLT*, is regarded as a process variable in addition to the duration of the movement, *FTM*. The forging speed is constant. The forging length ratio *FLR = FLT / PWT* is a non-dimensional measure. The temperature distribution at the onset of upsetting is defined by the function:

$$T(z) = KT0 + (KT1 - KT0) \cdot \exp(-Bz) \qquad (2)$$

$$B = -\frac{1}{z_2} \ln\left(\frac{KT2 - KT0}{KT1 - KT0}\right) \qquad (3)$$

KT0 is set to 25 °C in this study. z_2 is here arbitrarily set equal to $0.8 \cdot PWT$. Hence, *KT1* and *KT2* are uniquely describing the temperature distribution. Totally there are 7 free variables or factors in the study: *KT1*, *KT2*, *BWR*, *BLR*, *BOR, FLR* and *FTM*. Table 1 lists maximum and minimum values of these factors assessed in the study as well as the assumed experimental standard deviation.

Table 1. Variables with maximum coded (*) and natural values

#	Factor	Min*	Max*	Min	Max	Var
x_1	*KT1 [°C]*	-1	1	1000	1400	1
x_2	*KT2 [°C]*	-1	1	500	800	1
x_3	*BWR [-]*	-1	1	0.5	0.9	0.005
x_4	*BLR [-]*	-1	1	0.5	1.5	0.005
x_5	*BOR [-]*	-1	1	-0.2	0.2	0.001
x_6	*FLR [-]*	-1	1	0.4	1.0	0.005
x_7	*FTM [s]*	-1	1	0.2	0.4	0.005

2.2 Responses

The main shape responses from the analysis are *RI* and *RO,* the inner and outer radii at $n = 31$ positions along the pipe axis from 0 to 10 mm. The pipe wall thickness and mean radius, *WT* and *RM*, are deduced from *RI* and *RO (RM = (RI + RO)/2, WT = RO – RI). RI* and *RO* are measured after upsetting and cooling. Other responses are max and min axial stress, *SX* and *SN*, max and min contact pressure, *PX* and *PN*, and max and min temperature, *TX* and *TN*, and max and min plastic strain *EX* and *EN*. All responses are expressed on terms of polynomials including linear and quadratic terms as well first order interaction terms. For example, the wall thickness $WT(0) = y$ is:

$$y = b_0 + \sum_{i=1}^{7} b_i x_i + \sum_{i=1}^{7} b_i x_i^2 + \sum_{i=1}^{6} \sum_{j>i}^{7} b_{ij} x_i x_j \qquad (4)$$

Coefficients b_i and b_{ij} are determined by regression.

2.3 Objectives

The objective of the analysis is to obtain an upset pipe end with a target shape. Here, we express the target shape in terms of *WT* and *RM*:

$$WT_t(z) = WT_{t0} \cdot \exp\left(-C_{WT} z^2\right) \qquad (5)$$

$$RM_t(z) = RM_{t0} \cdot \exp\left(-C_{RM} z^2\right) \qquad (6)$$

WT_{t0} and RM_{t0} are the target wall thickness and mean radius at z = 0. RM_{t0} can be negative. C_{WT} and C_{RM} are the elongation of the upset regions. Here we require $WT_{t0} = 1.4 \cdot PWT$, $RM_{t0} = 0.03 \cdot PWT$ and $C_{WT} = C_{RM} = 8/PWT^2$. The objective function is a weighted sum:

$$f = \frac{1}{n}\sum_{i=1}^{n} krm_i \left(\frac{RM(z_i) - RM_t(z_i)}{\sigma_{RM}} \right)^2 + \frac{1}{n}\sum_{i=1}^{n} kwt_i \left(\frac{WT(z_i) - WT_t(z_i)}{\sigma_{WT}} \right)^2 \quad (7)$$

Values for standard variation σ_{RM} and σ_{WT} are usually determined experimentally. The vectors krm_i and kwt_i indicate the relative weight of each term. The total weight of all terms should equal n:

$$\sum_{i=1}^{n} krm_i = \sum_{i=1}^{n} kwt_i = n \quad (8)$$

In the case of robust optimization it is customary to minimize the variability in the objective function as well as the objective function itself, In such a case the minimum of $f_v = f + k\,\sigma_f^2$ is sought. The deviation σ_f can be calculated by using Eq. 4.

2.4 Constraints

In this study we impose explicit constraints for all x_i, ($x_{imin} < x_i < x_{imax}$). In addition, we require that process responses are within certain bounds, i.e. the nominal axial compressive stress is in a range $S22_{min}$ to $S22_{max}$:

$$c_1 = -SN + S22_{\min} < 0\,,\ c_2 = SX - S22_{\max} < 0 \quad (9)$$

Table 2 lists the upper and lower limits of upsetting force, contact pressure, equivalent plastic strain and temperature at the bevel face. The data are based on experiments, and more complex requirements can be introduced. Additional constraints relate to the shape of the upset, i.e. for all z_i, $RI_{min} < RI < RI_{nom}$.

Table 2. The constraints used in this study

	SN/SX [MPa]	*PN/PX* [MPa]	*EN/EX* [-]	*TN/TX* [ºC]	*RI* [mm]	*RO* [mm]
Min	80	60	0.7	900	86.7	-
Max	250	250	1.8	1200	-	105.0

The constraints limit the design space and define the process window. In the deterministic analysis the requirement is that Eq. 9 and similar are satisfied. In reality and the stochastic analysis, process variability causes response variability. To ensure a satisfactory outcome, stricter requirements must be posed. In the case of robust optimization, a thorough evaluation of the likelihood of satisfying constraints can be made by assuming that variables x_i and responses y are stochastic and normally distributed ($x_i \sim N(\mu_{xi}, \sigma_{xi})$, $y \sim N(\mu_y, \sigma_y)$). Furthermore, the requirement to satisfy should be $C_i = c_i + k_c\,\sigma_{ci} < 0$ instead of $c_i < 0$. If $k_c = 3$, the probability of a failure is less than 0.1 %. σ_{ci} is determined from Eq. 9, the chain rule and Eq. 10:

$$\sigma_y^2 = \sum_{i=1}^{7} \left(\frac{\partial y}{\partial x_i} \right) \sigma_{x_i}^2 \quad (10)$$

In this study we consider only the variability related to design variables. Table 2 contains estimates.

2.5 Finite element modelling and post-processing

Numerical data have been obtained by running 57 simulations in ABAQUS Standard ver 6.5 according to a Box-Behnken Design (BBD) [1]. The ABAQUS model is coupled thermo-mechanical using element CAX4RT. The initial temperature is applied as a load in a step before upsetting. After upsetting the loads are released and the part cools slowly.

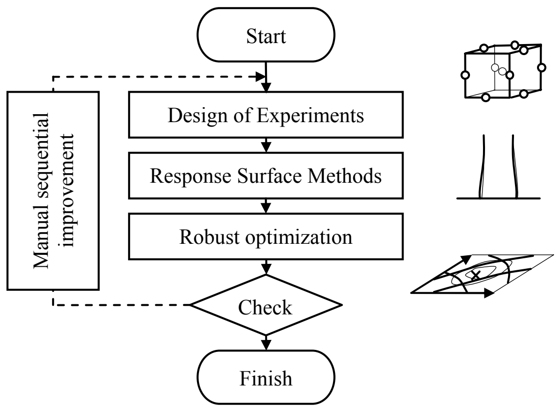

Fig. 3 The principle of the program used for optimization

Post-processing of data is performed by a simple MATLAB-script as shown in Figure 3. Data from simulation (or experiment) according to BBD are read and used to establish regression relations, i.e. meta-models expressed as polynomials. The models are tested by calculating the average squared bias (ASB) [1] for various 2D cross-section of the design space. Generally, the bias is small, and all selected responses can be expressed as 2nd order polynomials. Finally, constrained optimization and plotting of results for 2D cross-sections of the design space is performed within the MATLAB environment.

3 RESULTS AND DISCUSSION

Figure 4 shows the compressive nominal axial stress responses for the 56 runs of the design matrix and the average response. Main effects are also plotted. Generally, the compressive stresses are low at high temperatures and higher for longer forging lengths. Similar plots exist for all other relevant data. Figure 5 shows the various shapes for the BBD runs.

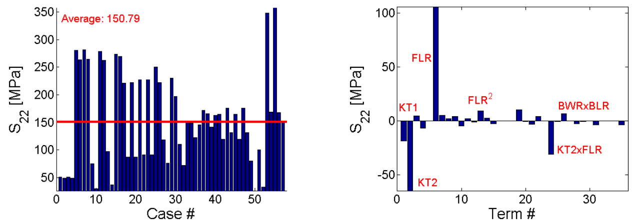

Fig. 4 The pressure responses for BBD runs and main effects

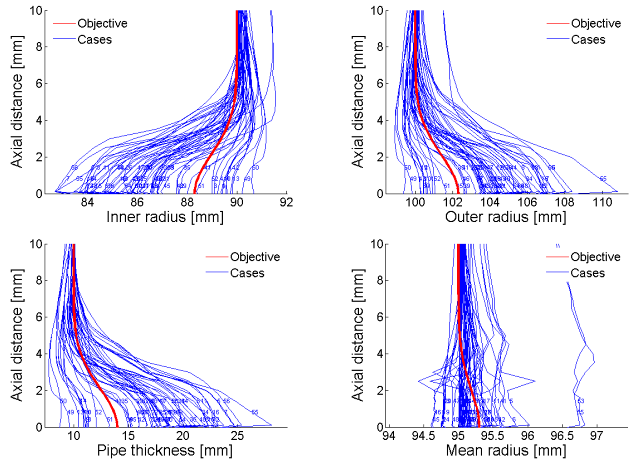

Fig. 5 *RO*, *RI*, *WT* and *RM* responses for all 57 BBD runs

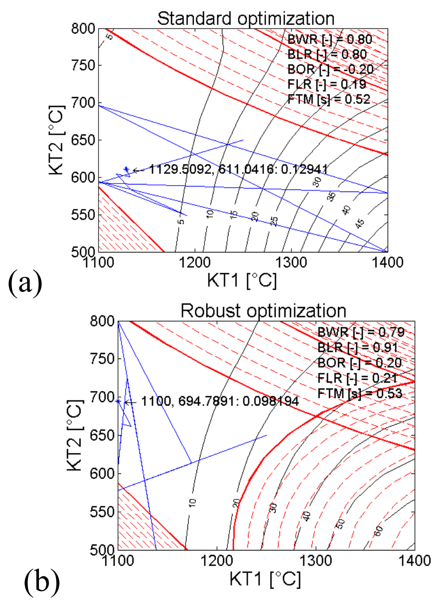

Fig. 6 2D process window plots for the standard and robust analysis. All parameters apart from *KT1* and *KT2* are fixed.

Figure 6 (a) shows a *KT1-KT2* cross-section of the 7D design space. The MATLAB-program determines the optima, then sets all variables equal to optimum values and systematically varies only two variables (here *KT1* and *KT2*). The procedure is repeated for all combinations of two variables. The thick lines in the plot are the constraints for standard optimisation. Figure 6 (b) shows the corresponding plot for a robust analysis with a 3σ constraints applied. Only the thickness *WT* has been optimised in this case. In both cases valid solutions are only those in the area defined by implicit and explicit constraints. Optima are plotted as crosses, and search paths are shown. Figure 7 compares the target shapes (objectives) and optimum shapes for 2D (*KT1*, *BOR*), 3D (*KT1*, *BOR*, *FLR*) and 7D analysis. Generally, satisfactory results are achieved with 7D optimisation. Often it may be sufficient to vary as few as 3 to 4 variables (e.g. *KT1*, *KT2*, *FLR* and *BOR*) in order to perfectly match the target shape. Numerical noise is always present, but it does not significantly affect conclusions.

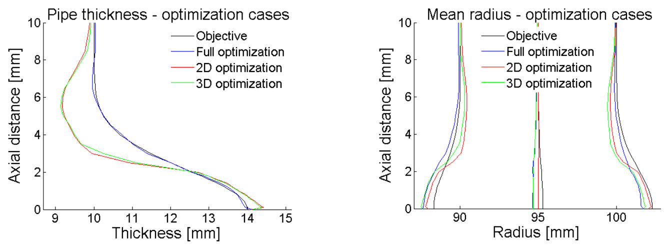

Fig. 7 The target and optimal RI, RO, RM and WT responses for 2D, 3D and 7D robust analysis (3σ analysis).

4 CONCLUSION

Robust optimization techniques combined with DoE can be efficiently used in order to optimize pipe end shape after moderate upsetting. Upsetting is a simple technique for moderately expanding pipe ends.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support provided by TubeFuse Technologies Ltd. and AMR Engineering AS.

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