Effects of tension levelling process parameters on cold rolled strip characteristics using a designed factorial analysis approach

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Tension levelling is a process used in the steel industry to remove any shape defects (i.e. out of flatness) present in coiled material. It is generally the final process before the cold rolled product is dispatched to the customer, and is therefore a process which plays an important role in delivering the desired material properties and the product standards required by the customer. In this paper a designed factorial analysis has been employed to study the effect of tension levelling process parameters on the shape characteristics of the levelled product. These characteristics include residual flatness (longitudinal curvature, referred to as longbow), centreline elongation and residual (or internal) stress imbalances; criteria that determine whether the customer accepts the material or not. It has been identified that in a basic five roll leveller the final (adjustable) roll wrap angle has the most significant influence on these characteristics in over 70% of cases. It has also been recognised that final flatness is dictated by many second order process interactions.

Keywords: Coiled material, Tension levelling, Shape defects, Process parameters, Material properties

Introduction

Manufacturers of material in coil form require that the finished product be fit for purpose according to customers' individual tolerances. In the steel industry, the application used for the product may necessitate stringent tolerances, as is the case in shape critical office furniture applications. Conversely, such tolerances may be relatively relaxed, as in deep pressed applications in automotive panels, for example. In the latter case, visible shape defects can sometimes be tolerated in the product despatched to the customer. For the former, however, shape defects that are manifest in coil and slit form (for example, any edge to edge length differential, such as so called 'edge waves') are highly undesirable.

'Shape' can generally be classified into two groups – latent and manifest. Latent shape appears visible when coil or sheet is slit or cut. This latent property can make the material appear flat prior to a cutting operation, and can be attributed to residual (or internal) stress imbalances. Manifest shape is associated with defects that appear visibly (either in coiled form or under line tension) such as edge waves. Surface area defects such as longbow (permanent longitudinal curvature) can be classed as latent since this defect is, in general, only visible when the coil material is reduced into sheet form.

The associated shape tolerances and flatness specifications quickly become superseded in the marketplace of today. Further processing is required to recover the added value of the product and to achieve the near dead flat sheet properties required for some applications. It is not possible to guarantee dead flat strip after temper rolling, and in order to meet these requirements the strip is tension levelled. Tension levelling, or stretch-bend levelling, is an operation that attempts to achieve the removal of shape in its manifest form. Figure 1 shows a schematic layout of a basic five roll tension leveller in a three over two formation (roll units 1, 3 and 5 are fixed at the pass line, rolls 2 and 4 are adjustable). By subjecting the material to an alternating series of bends under significant front and back line tension, the shortest longitudinal 'fibres' of the product are elongated preferentially. Since material with defects such as edge waves possess differential fibre length across the width, this process ensures that fibre length equalisation takes place in the material.

Roller levelling or multiroll levelling is a process used to remove out of flatness shape defects in its various latent forms. In contrast to tension levelling, this process is restricted in its use by the nature of the incoming shape defect. In general, roller levellers are best suited to remove defects of latent shape characteristics such as longbow (i.e. longitudinal curvature) due to power restrictions, specifically frontline tension capabilities. The roller leveller may contain more than twice the number of work rolls compared with that of its tension levelling counterpart, with only sufficient line tension to pull the material through the machine. The two processes can be used in tandem,[1] in order to produce material that is required to be perfectly flat, and to produce acceptable residual stress distributions 'through

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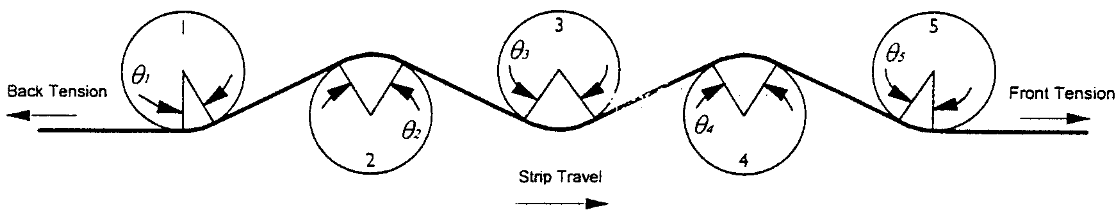


1 Schematic layout of general five roll tension leveller showing contact wrap angle θ at each bend roll

gauge'. In this situation, the tension leveller is predominantly used upstream to remove manifest defects, while the roller leveller, with its low line tension and smaller diameter work rolls, is used to obtain perfectly flat strip with balanced internal stresses.

These processes have been analysed extensively, both by empirical[2,3] and numerical[4–13] methods. Analytical solutions have been proposed,[14,15] mainly as a development tool or guide, in order to determine process characteristics. Analytical solutions of residual curvature are not known to exist, and it is necessary, therefore, to perform such an analysis with the aid of a numerical solution based on constitutive plasticity laws.[16,17] A finite element approach can also be adopted, although this method is restricted to development and analysis due to expensive contact search algorithms (except where novel approaches exist[18,19]), as opposed to real time prediction. These methods are generally computationally expensive and are also time consuming to develop, especially when finite element solutions are required.

Robust design

It is becoming ever more important to understand and, ultimately, control process parameters that affect the residual flatness of the coiled product. In order to achieve flat material across the product range using tension levellers, it is often necessary to perform some form of parametric study to obtain a gauge/width matrix. Frequently this matrix will be chemistry dependent. This method, however, is extremely labour intensive. Moreover, it does not offer a robust theoretical consistency that is applicable from machine to machine. A process tool employed for such an analysis is the area of statistical process control known as 'robust design'.

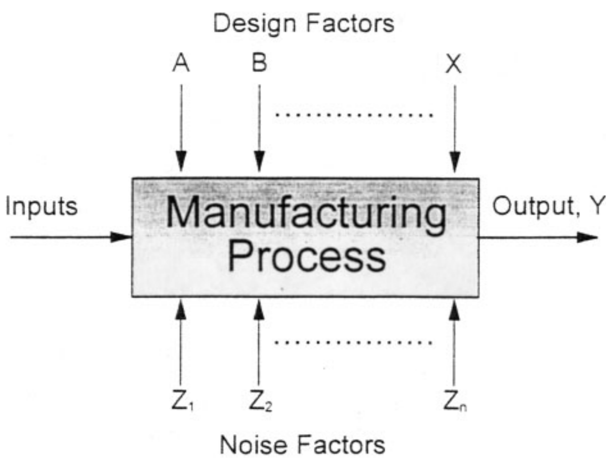
Experimental or robust design is a tool used by statistical process control engineers in order to determine those process variables that affect the quality and consistency of a product. Figure 2 gives a simplified view of robust design. Any manufacturing process can be thought of as a device that converts raw materials (or inputs) into some form of usable, secondary object (or output) Y. This process will probably involve a number of adjustable variables (design and noise factors) that determine the response (the output). The design factors A, B,.., X, are controllable variables which can be set according to specification, such as soak temperature in an annealing cycle. On the other hand, noise factors Z_1, Z_2,…, Z_n are variables which cannot be controlled at the point of manufacture although, for the purpose of an experiment, they may easily be controlled under laboratory conditions.

Robust design was developed in the early 1950s by Taguchi.[20] In Taguchi methodology, the experiments are not 'designed'. Instead, so called 'orthogonal arrays' are given for a particular process, such as the popular $L_8(2^7)$ array. This particular design is capable of analysing up to seven process variables, with each variable set at two levels. Unfortunately, there are major shortcomings of this method associated with the interaction effects between process variables.[21] In contrast with the Taguchi method, statistically designed experiments involve planning the whole analysis. This results in a more controlled and systematically designed set of experiments, including a full analysis of interacting variables, and this is the method chosen here to analyse the tension levelling process. This approach has been previously used by Biggs *et al.*[22] and the reader is referred to their paper for more detailed information on the methodology.

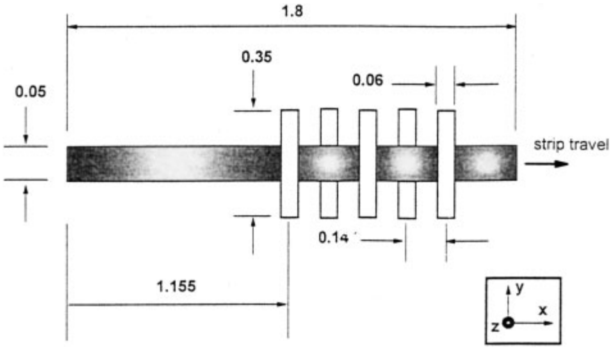
Statistically designed experiments

An engineering experiment has been designed in order to investigate the effect particular variables of the tension levelling process have on the characteristics of the levelled product. The aim is to find levels of the controllable variables of the process that are least influenced by noise factors, and to reduce variability around a mean target value or response Y. Each experiment has been carried out using a fully validated ABAQUS finite element (FE) model, the details of which can be found elsewhere.[23] Figure 3 shows the levelling configuration and material geometry used in the FE simulations.

The response Y takes several forms, although each test response shares the same base and test design. The six identified responses are flatness (residual curvature),



2 General model of a manufacturing system



3 Levelling configuration and material geometry used for factorial experiments: centreline symmetry has been assumed giving a total strip width of 100 mm; gauge used is 0·7 mm

elongation, three top–bottom surface residual stress imbalances (i.e. at the edge, at the centre, and the whole surface average) and centreline residual stress (normalised with respect to yield stress). Residual curvature (flatness) is taken from a fully levelled, 600 mm length of strip, with elongation response taken as the centreline elongation of the material. The stress balances were calculated by taking the sum of the difference in stress magnitudes at each element integration point across width. A description of the factors and their associated levels is given in Table 1.

Estimated location effects and interactions

The statistical procedure used to analyse the estimated effects of each process variable (referred to as the estimated location effects) is based on the assumption that all estimates follow an approximate normal distribution with a mean of zero and an equal standard deviation.[21,24] This is achieved by ranking each estimated location effect from most negative to most positive. From this, it follows that each effect has exactly the same normal distribution, and thus, each effect represents a point under this distribution. A cumulative probability (CP) is then assigned for each location effect. The CP associated with each location effect is given by the formula

$$CP_{\mathrm{i}} = \frac{100(i-0{\cdot}5)}{M-1} \tag{1}$$

where M is the number of test conditions, i is a rank index equal to 1 for the most negative location effect, 2 for the next most negative and so on up to M for the most positive location effect. Important location effects in subsequent probability plots are seen as those factors that deviate from a linear regression line drawn through location effects that have a mean or net effect of zero. The probability plots of estimated location effects for the six identified responses are shown in Fig. 4. A summary of these results can also be found in Table 2.

Table 1 Selected process parameters (factors) and their levels

Factor	Definition	Levels: High	Levels: Low
A	Roll 2 wrap angle$^{\infty}$	24°	18°
B	Roll 4 wrap angle	12·5°	6°
C	Line speed	100 m min^{-1}	60 m min^{-1}
D	Elongation	0·6%	0·3%
E	Yield stress	230 MPa	190 MPa

Flatness

From the probability plot in Fig. 4*a*, it can be seen that five location effects deviate significantly from the linear regression and hence flatness is affected by a total of five factors (the rank of each factor is given in Table 2). Roll 4 wrap angle (factor B) has the largest effect on final flatness, followed by interactions of factors Roll 4 wrap angle/yield stress, Roll 4 wrap angle/elongation, Roll 2 wrap angle/Roll 4 wrap angle and line speed/yield stress (factors BE, BD, AB and CE respectively). This indicates that not only does Roll 4 wrap angle by itself have the greatest effect on flatness, but also its interaction with Roll 2 wrap angle, elongation and yield stress, play similarly important roles in the levelling process; the most notable of these being material yield stress, which is a noise factor. A simplified model using these important effects may be stated as:

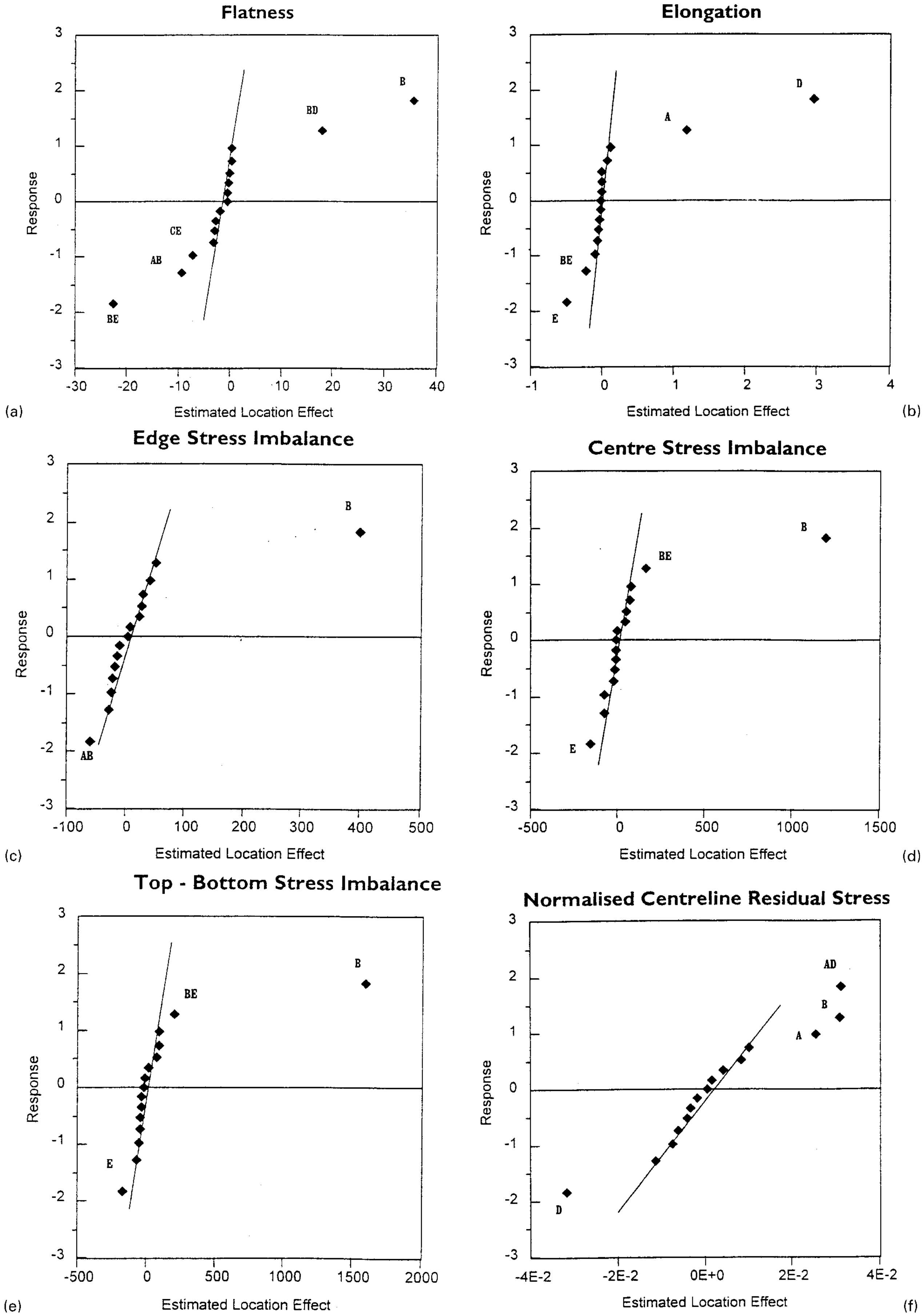
$$Y = -1{\cdot}06 + 17{\cdot}81B - 11{\cdot}32BE + 9{\cdot}98BD - 3{\cdot}55CE \tag{2}$$

Figure 5 shows two way diagrams of flatness; a graphical method of interpreting and quantifying the interaction effects of factors BE, BD, AB and CE. In Fig. 5*a* the plot shows the Roll 4 wrap angle–yield stress interaction. This interaction clearly has the largest impact on flatness in this analysis. Consequently, it shows also that by setting Roll 4 wrap angle and the yield stress to their higher levels a flatter product is obtained. Similarly, in Fig. 5*b*, by ensuring that the elongation remains at its lowest level while setting the wrap angle on Roll 4 to its higher value, slightly improved flatness results are achieved. Moreover, setting the elongation (essentially, a function of the overall line tension) to its higher level results in the largest variability in flatness out of all the individual interaction factors, as shown by the slope of the line in Fig. 5*b*.

It becomes extremely difficult, therefore, to control the final curvature if the elongation is set at its higher level due to the range experienced in the response. Another interaction factor that affects the variability in flatness is the interaction effect between Roll 2 and Roll 4 wrap angles. Again, the two way diagram in Fig. 5*c* shows that setting Roll 2 wrap angle to its lowest level

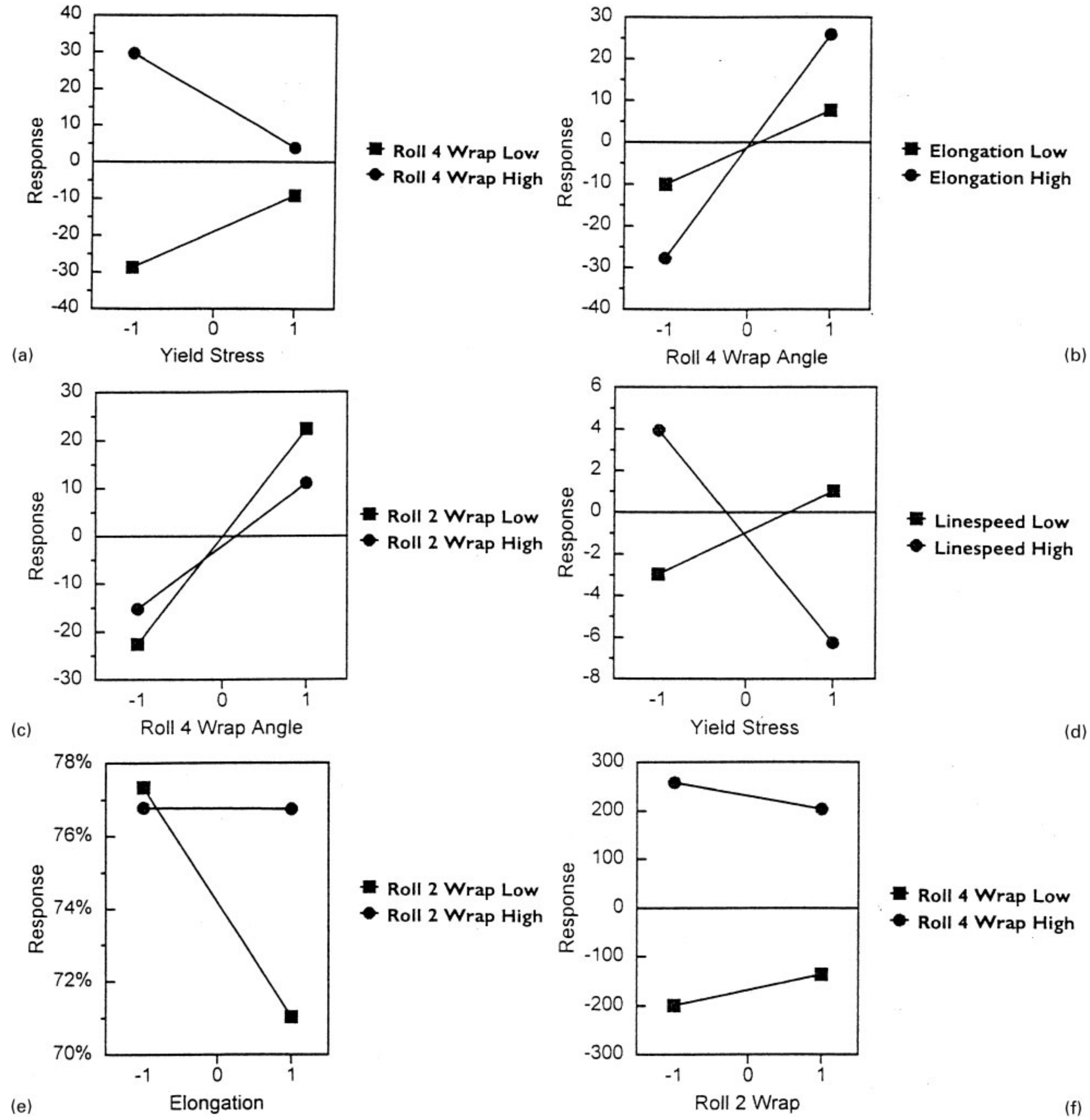
Table 2 Summary of results

Response	Individual factor rank: *A*	*B*	*C*	*D*	*E*	Interaction rank: *AB*	*AD*	*BD*	*BE*	*CE*
Flatness		1				4		3	2	5
Elongation	2			1	3				4	
Edge stress imbalance		1				2				
Centre stress imbalance		1			3				2	
Top–bottom stress imbalance		1			3				2	
Centreline residual stress	4	3		1			2			



a flatness; *b* elongation; *c* edge stress imbalance; *d* centre stress imbalance; *e* top–bottom stress imbalance; *f* normalised centreline residual stress

4 Probability plots of estimated location effects



a Roll 4 wrap–yield stress (BE); *b* Roll 4 wrap–elongation (BD); *c* Roll 4 wrap–Roll 2 wrap (AB); *d* yield stress–linespeed (CE); *e* elongation–Roll 2 wrap (AD); *f* Roll 4 wrap–Rol 2 wrap (AB)

5 Two way diagrams showing how flatness characteristic of the strip (*a–d*) and residual stresses at the centreline (*e*) and edge (*f*) are influenced by interactions between process factors

results in a large variability in flatness. Finally, the yield stress–line speed interaction is demonstrated in Figure 5*d*, from which it is clear that a combination of high yield stress and low line speed provides the best flatness response.

Elongation

Figure 4*b* shows that four factors affect the centreline elongation of the levelled product. Obviously, the elongation (factor D), as a function of the applied tension, has the greatest effect. This is followed by Roll 2 wrap angle, yield stress and the Roll 4 wrap angle - yield stress interaction (factors *A*, *E*, and *BE*, respectively). In this test, line speed had no net effect on the elongation, either as a single factor or as part of any interaction. However, the yield stress, both individually and as part of the interaction with Roll 4 wrap angle, does have an effect. Since yield stress is a noise factor and, as a consequence, difficult to control, the target elongation will be difficult to control precisely in the levelling process. In addition, this will have consequences on final mechanical properties.

Residual stress imbalances

Figure 4*c–f* show probability plots for the residual stress imbalances. In three out of the four cases considered, the Roll 4 wrap angle (factor *B*) was found to have the greatest influence. The exception to this was found to be the test involving normalised centreline residual stress levels (Fig. 4*f*), in which case the centreline elongation (factor *D*) was found to have the greatest effect. In this case, the interaction between Roll 2 wrap angle and elongation (the *AD* interaction) also influences the residual stress levels at the centre. However, Fig. 5*e* shows that this interaction influences stress magnitudes at a relatively low level ($\pm$ 6% influence of the normalised stress).

The edge stress imbalance is also slightly affected by the interaction between each roll wrap angle (the *AB* interaction). Figure 5*f* shows that when the Roll 4 wrap angle is set at its lower level, the residual stress levels at the strip edge are influenced by compressive stresses only. The converse is also the case when Roll 4 wrap is set at its higher level. This indicates that both settings used for Roll 4 wrap angle do not produce desirable stress balances. In order to analyse this phenomena and to find the precise level that produces optimum stress distributions, a further analysis is required using wrap angle levels with narrower band limits.

Concluding remarks

Designed fractional factorial experiments have been employed in order to quantify the influence and effects of a number of variable process parameters, in a five roll tension leveller, on the characteristics of the levelled product. The analysis has indicated that the second adjustable roll wrap angle has a significant effect on many characteristics of the levelled product. It has the largest influence in over 70% of the responses (5 out of 6) including final flatness and many residual stress imbalances. It also has the largest influence on longitudinal curvature (longbow). Several other factors also significantly affect final flatness, although only as interactions. Many process interactions occur between the factors analysed, the most influential interaction on flatness response being between the yield stress (an uncontrollable or noise factor) and the Roll 4 wrap angle. Variability in flatness can be eliminated by setting those process factors that transmit noise to appropriate levels.

This noise factor, both as an individual factor and as part of an interaction with Roll 4 wrap angle, also affects target elongation. This relationship has further implications, notably that this will affect the resulting mechanical properties of the levelled product.

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