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Effects of flow forming parameters on dimensional accuracy in Cr-Mo-V steel tubes

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Abstract

Flow forming is a near-net shape forming process used to produce a range of tubular components. Advantages of the process include increased mechanical properties, grain refinement and high production rates. The cost effectiveness of the process stems from a reduction in input weight and a reduction in final machining time as compared to machine from solid routes. Careful selection of flow forming parameters, such as feed rate and spindle speed, is needed to ensure that the dimensional requirements of component design are met. The main purpose of this work was to explore the effects of machine parameters on geometrical outputs of flow formed trial parts in Cr-Mo-V steel, which is used in aerospace applications. Cr-Mo-V steel was flow formed in the annealed and the hardened and tempered conditions to assess the formability of the material across a range of input hardness. Results including inner diameter growth, formed wall thickness and material sectional hardness are presented. Forming trials were conducted at the Advanced Forming Research Centre on a WF STR600/3 flow former, which is equipped with force sensors on all three of the forming axes. The required forming loads are a significant aspect of managing tool life in an industrial setting, therefore the roller loads generated during forming have been studied. Experiments showed that there is a clear link between machine parameters and geometrical outputs. Slower feed rates and faster spindle speeds resulted in larger inner diameter growth and reduced wall thicknesses. Increased spindle speeds also caused a significant reduction in forming load. The hardness of the material was found to be proportional to the thickness reduction imposed on the trial parts in the annealed condition. Overall, it was observed that varying parameters in flow forming produced clear trends in the outputs, which can be used to predict tolerances in the design of components.

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1. Introduction

Flow forming is a near-net shape forming process used to produce a range of tubular components. Advantages of the process include increased strength properties, grain refinement, improved material utilization, and excellent surface finish [1]. Work has previously been carried out to investigate the effects of flow forming parameters on the residual stress [2] and texture [3] of flow formed Cr-Mo-V steel, and fatigue properties in high-strength steel alloys [4]. However, understanding and controlling the accuracy of flow formed components has not been reported to the same extent, but is important to the implementation of the process into a large scale production environment.

Nomenclature

FR	feed rate, mm/min
SS	spindle speed, revolutions/min, RPM

2. Experimental set-up

Experiments were conducted at the Advanced Forming Research Centre (AFRC), Glasgow, UK, using Cr-Mo-V steel in the annealed and the hardened and tempered conditions. These trials were conducted as part of the Innovate UK (I-UK) funded project SAMULET II (Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies). The purpose of these trials was to test various spindle speeds and feed rates to assess their effects on geometrical features, material hardness, and force required to deform the material. The experiments were carried out using Cr-Mo-V steel, with the nominal composition of the material used given in Table 1.

Table 1. Chemical composition of Cr-Mo-V steel [TATA, 2014] [5].

C	Cr	Mo	V	Si	Mn	Fe
0.40	3.24	0.92	0.19	0.25	0.53	Rem

The AFRC's production scale flow former, the STR 600-3/6 shown in Fig. 1 (left), was used during the experiments. The STR 600-3/6 is a horizontal, three roller machine which can forward flow form components up to 2500 mm and reverse flow form components up to 4000 mm in length [6]. A test part, shown in Fig. 1 (right) and Fig. 2, was designed to include material reductions of 30, 55 and 65% to enable information to be gained about several different reduction rates from a single formed part. For the experimental trial, axial feed rate and spindle speed were adjusted to determine their effect on the formed part. The feed rate ranged from low to high for the annealed parts, and low to medium for the hardened parts, with the feed rate adjusted in increments of 10 mm/min per part. The hardened parts were not formed to the highest feed rates of the annealed parts because harder material requires to be formed slower than softer material. The spindle speed range had an upper limit of 500 RPM for the annealed parts, and 400 RPM for the hardened parts.

Hardness testing, of both the preforms and formed parts, was carried out on a Vickers Macro-Hardness tester with a weight of 30kg and a pyramid diamond indenter. The tests were carried out following Vickers hardness (HV) standard. For the preforms, testing was carried out on the front end of the part nearest the flange (shown as the right hand side of the part in Fig. 2), to avoid contact with the area to be flow formed. Five readings were taken and an average hardness value was obtained. For the formed parts, three readings were taken on each wall section at 120° intervals, and the average value recorded.

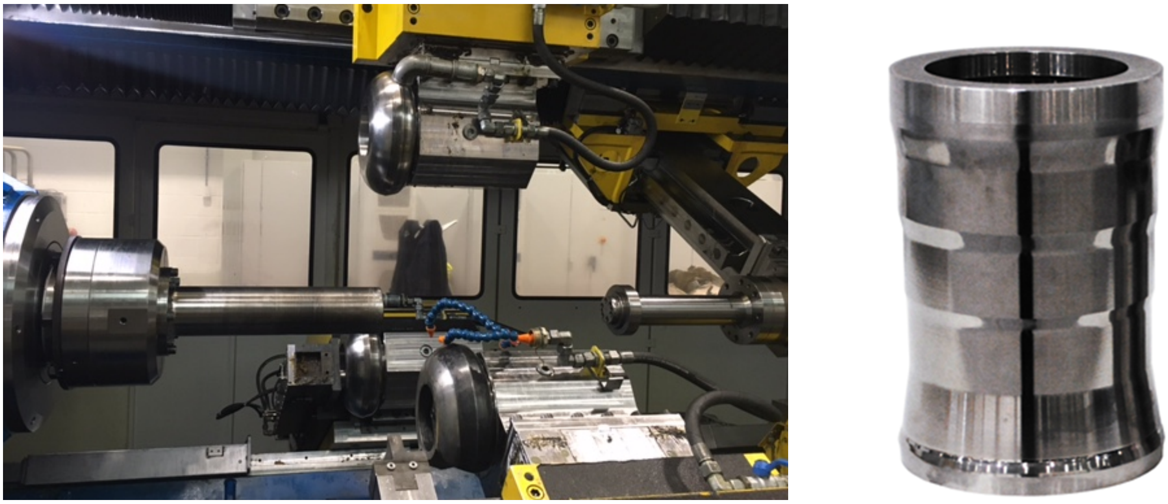

Fig. 1. AFRC's STR 600-3/6 horizontal flow former (left), and flow formed test geometry (right).

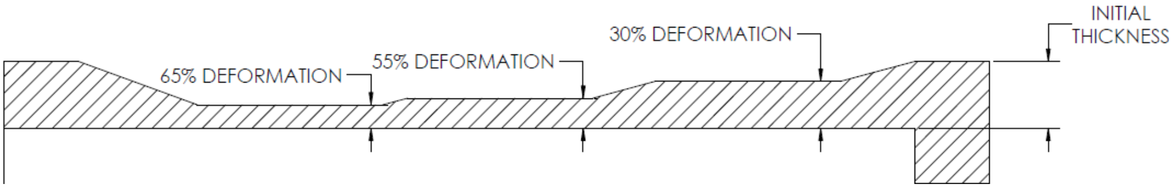

Fig. 2. Schematic of flow formed test component

To assess the effect of feed rate and spindle speed on the work piece three experiments were conducted per material condition: the first two experiments kept the spindle speed constant whilst adjusting the feed rate, whereas the third experiment maintained a constant feed rate and varied the spindle speed. Each experimental trial is detailed in Table 2. It can be seen that hardening and tempering was carried out to produce hardness values in the range 543-575HV to investigate the formability of material at the upper limit for Cr-Mo-V steel.

Table 2. Experimental set-up for Cr-Mo-V steel parts.

Experiment	No. of parts	Preform hardness (HV)	Feed rate (mm/min)	Spindle speed (RPM)	Final material reduction
1	7	234-245	Low-High	Low	Max 65 %
2	7	234-249	Low-High	Intermediate	Max 65 %
3	8	234-244	Intermediate	Low- High	Max 65 %
4	3	543-559	Low-Int.	Low	Max 65 %
5	3	536-563	Low-Int.	Intermediate	Max 65 %
6	6	556-575	Low	Low- High	Max 65 %

3. Results and discussion

For the purposes of this paper, the technical focus will be on the results obtained from the annealed components since there is a larger data set to analyse. Reference will be made to the hardened and tempered components for comparison in the appropriate sections.

3.1. Dimensional accuracy

An important factor in flow forming being cost competitive is to produce parts that negate the need for final machining in the bore. This requires the inner diameters produced along the length of a part are understood and that the design calls out appropriate tolerances. A major aim in flow forming is to induce predominantly axial material flow, which contributes to the elongation of the preform, and restrict tangential flow. In practice tangential flow will occur during flow forming which manifests itself as inner diameter growth. Variables that affect inner diameter growth include material, reduction rates, and machine parameters. Increased levels of inner diameter growth have a number of disadvantages which include a reduction in the achievable straightness [7]. A practical aspect of inner diameter growth is that the manufacturer will size the preform inner diameter so that the nominal inner diameter of the part is achieved after the growth that occurs during flow forming. Also, the final part tolerances have to account for the differences in inner diameter growth that occurs, for example, between regions of the component that are reduced in thickness the most and least during flow forming.

In order to aid the understanding of achievable tolerances on flow formed parts, several geometrical features were measured after forming including inner diameter and wall thickness. Representational graphs are shown for the thinnest wall section for each of the features, which corresponds to a material reduction of 65%. In Fig. 3 the blue points represent Experiment 1, the orange points represent Experiment 2, and the green points represent Experiment 3 from Table 2. From Fig. 3 it can be seen that the feed rate and spindle speed have differing effects on both the wall thickness and inner diameter. As the feed rate is increased, the output wall thickness of the formed parts also increased, however as the spindle speed was increased, the wall thickness decreased. Slower feed rates result in a thinner formed section, which is consistent with the material having been worked for a longer time by the forming rollers. In a similar manner, a faster spindle RPM also resulted in the material being worked more times per minute, hence more material compression and a thinner formed section.

The hardness range for the annealed material is within a narrow range, which has reduced the potential for variation in the outputs between parts, and clear trends have emerged. For these trials, an increase in feed rate resulted in smaller component inner diameters. The difference in recorded inner diameter from the low and high reed rate was approximately 0.4 mm, which is a significant in comparison with a typical tolerance of ±0.4 mm applicable to many industrial applications. An increase in the spindle speed resulted in a slight increase in the formed inner diameter, approximately 0.1 mm difference from low to high spindle speed. From these initial experiments the feed rate has a greater impact than spindle speed when considering inner diameter growth. The choice of a low fixed feed rate for evaluating the effect of the spindle speed on inner diameter growth may not have been optimal since a low feed rate also appeared to result in a higher output diameter, and additional trials could be designed to include a full Design of Experiments to fully understand the interactions between feed rate and spindle speed.

Through the experiments conducted during these trials, it is clear that the geometrical features follow trends with respect to both the feed rate and spindle speed. Furthermore, it can be surmised that fixing the parameter set for a particular component will help to achieve fixed tolerances and from the data collected during this experiment, an optimal set of parameters can be deduced for a specific set of component requirements.

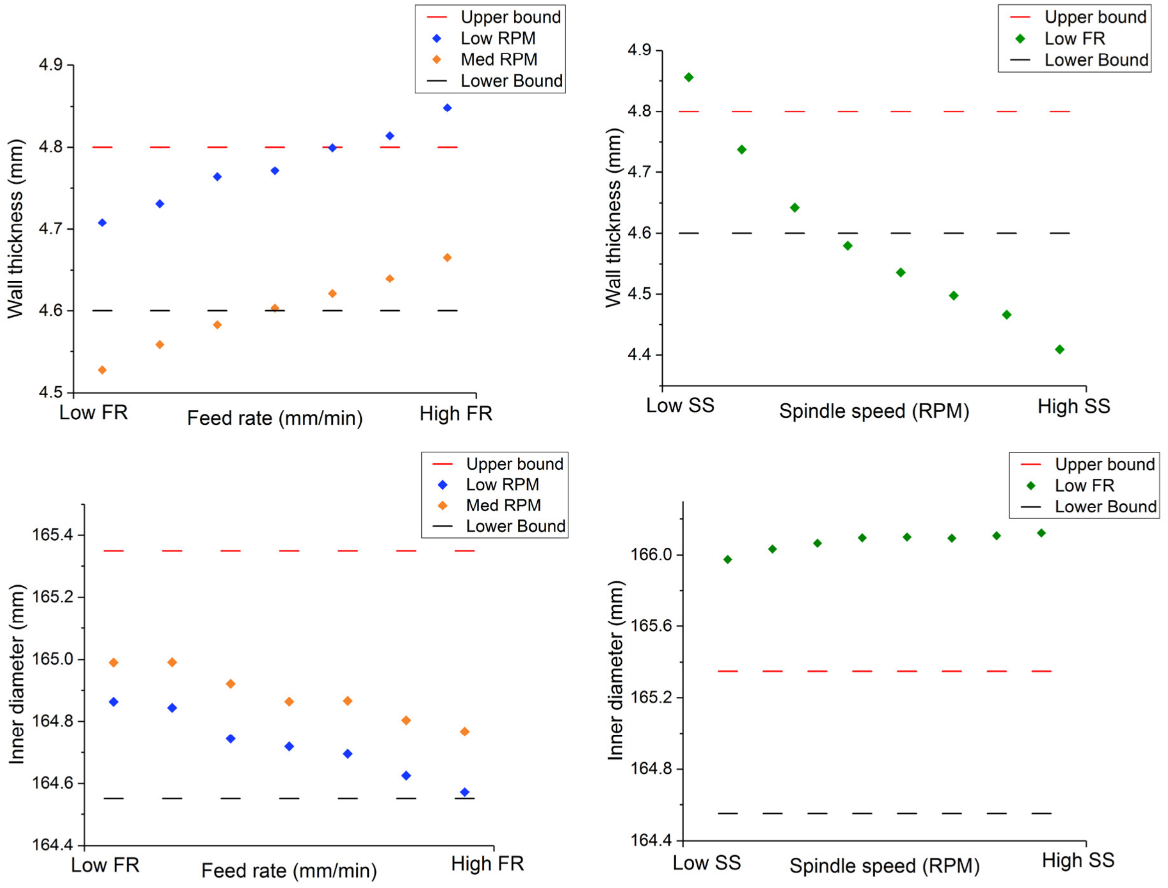

Fig. 3. Measured wall thickness (top) for variable feed rate (left) and variable spindle speed (right), and measured inner diameter (bottom) for variable feed rate (left) and variable spindle speed (right).

3.2. Material hardness

After the parts were formed, hardness values were recorded on the surface at 5 different lateral positions. Position 0 represents the non-flow formed section closest to the flange; positions 2, 3, and 4 represent formed sections with low, intermediate, and high percentage of material reduction, respectively; and position 4 represents the non-flow formed section at the end of the component.

The typical spread of hardness values for the annealed parts is shown in Fig. 4. It can be seen that the hardness recorded in the each section was proportional to the percentage reduction in the material, with the thinnest section producing the highest hardness value. This is expected since an increase in material reduction leads to more localized plastic deformation in thinner sections. The same hardening behaviour was not observable in the hardened parts, and the final hardness values were closer to those of the parent material, which may be due in part to the variation in hardness of the input material.

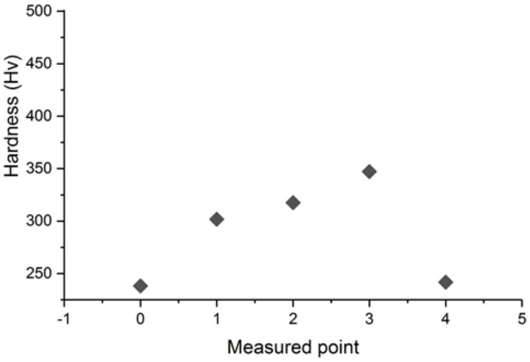

Fig. 4. Typical hardness values for parts flow formed in annealed condition.

3.3. Force evolution

Roller forces give important information regarding the resistance of the material during the flow forming process. Such information can be related to studies on tool life, machine requirements and the forming operation. Previous papers have considered the forces required to deform material during the spinning process [8], but very little information is available on the forming loads required for flow forming. For the annealed preforms, the geometry was formed in a single pass and so the force traces consist of a single cycle of data, as represented in Fig. 5.

For the hardened preforms, the forces recorded were close to the machine limits so it was decided to form the geometry in two passes which gave two distinct regions on the force trace. Typical force traces of the third and final forming roller for the annealed and hardened parts are shown in Fig. 5 and Fig. 6, respectively. Approximately 10 seconds into the force trace, the rollers contact the parts and the load increases until a peak is reached. This increase in load corresponds to the rollers compressing the material from the initial wall thickness to a 30% reduction. Once this reduction is reached the rollers are programmed to form a straight wall section of constant thickness and the force remains relatively constant with a slight reduction over time. The next peak is recorded as the rollers reduce thickness to 55% reduction from the original wall thickness. The peak force drops off again as the rollers form a straight wall section, then the highest peak is recorded as the material is deformed to 65% reduction. The peaks on the graphs are always recorded during the transitions between sections of different thicknesses, with higher material reductions creating higher peak forces.

The maximum force recorded during the total cycle for the annealed parts was 83% of that for the hardened parts. For the annealed parts the peak force was recorded during the transition to 65% reduction whereas for the hardened parts the peak force was recorded during the first pass during the transition to 30% reduction. A fairer comparison of maximum peak forces can be made by looking at the transition to 30% reduction on the first pass and which shows that the force required to deform the annealed parts is approximately 52% of that required for the hardened parts. All forces graphs shown in this section have been set to the same scale for comparison, with a normalized force of 100% shown which represents as the peak force reached during the trials.

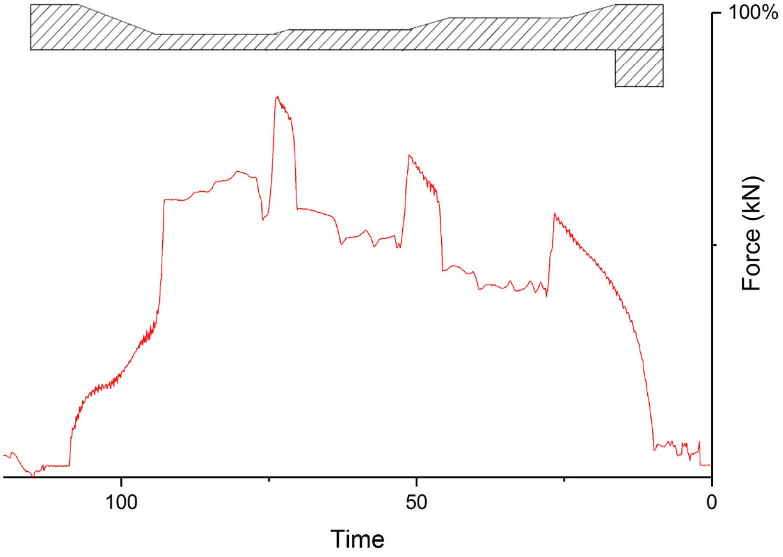

Fig. 5. Typical force trace for annealed part with schematic of formed part overlaid to show relationship between wall thickness reduction and peak force.

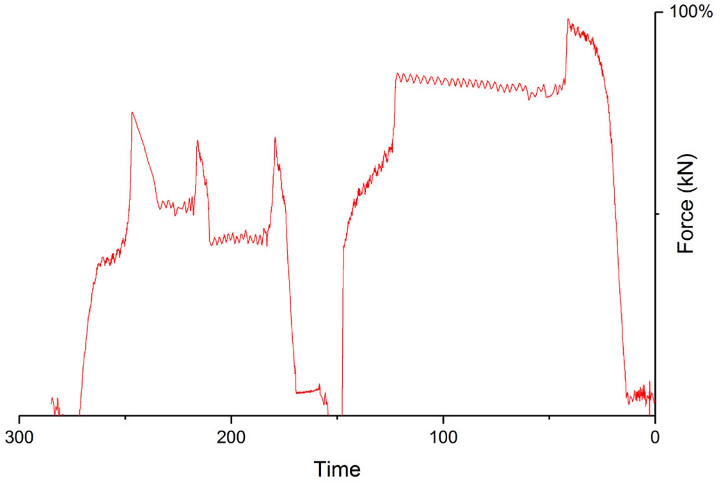

Fig. 6. Typical force trace for hardened part, with maximum force for annealed parts recorded at 83% of maximum force for hardened parts.

Fig. 7 shows the effect of feed rate and spindle speed on the forces generated during the forming operation, with the force trace for the final forming roller shown. As the feed rate increased, the maximum force generated during forming also increased. In the experimental set-up of these trials, the ‘low’ level of feed rate resulted in a peak force approximately 91% of the peak force generated for the ‘high’ level. In the case of spindle speed, an increase in RPM resulted in a dramatic decrease in the peak force recorded. The ‘high’ level of RPM resulted in a peak force which was 70% of the peak force for the ‘low’ RPM. Although faster spindle speeds resulted in lower peak forces, the use of higher spindle speeds must be weighed against the heat generated in the part and the potential resultant microstructural effects, and the wear and potential damage to forming rollers.

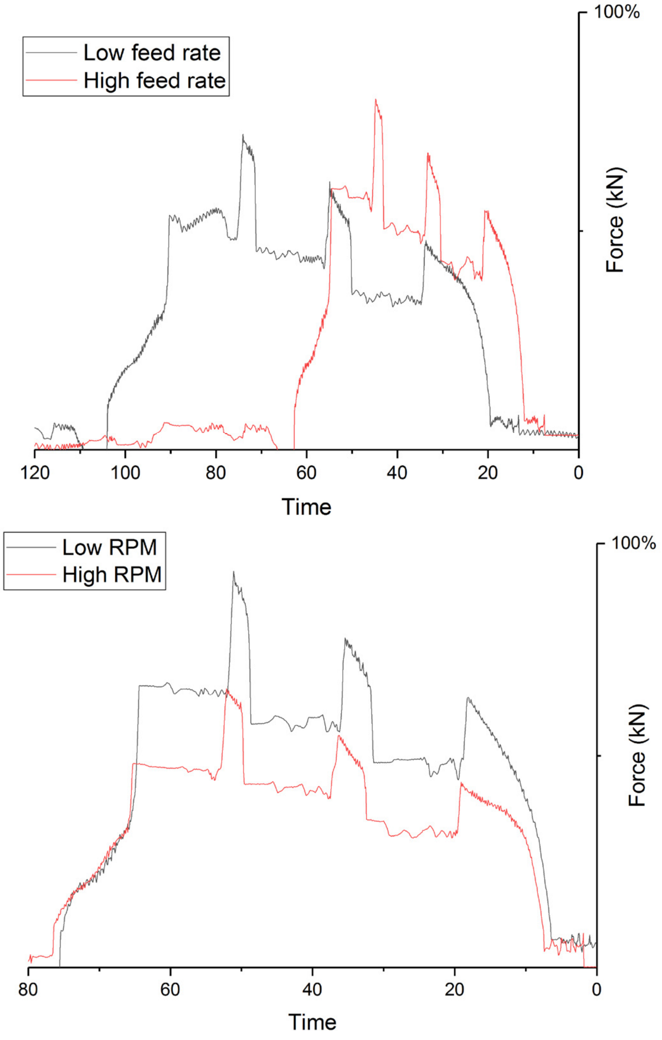

Fig. 7. Effect of feed rate (top) and spindle speed (bottom) on forces generated during forming.

4. Conclusions

The formability of Cr-Mo-V steel was proven for both annealed and hardened parts through a series of forming trials. The effect of feed rate and spindle speed on wall thickness, inner diameter and load requirements were studied. Table 3 provides a high level summary of the trends discussed in this paper.

Table 3. Summary of high level trends.

Variable	Low Value	High Value
Feed rate	Thinner wall section Larger inner diameter growth Lower forces generated	Thicker wall section Smaller inner diameter growth Higher forces generated
Spindle speed	Thicker wall section Smaller inner diameter growth Higher forces generated	Thinner wall section Larger inner diameter growth Lower forces generated

The feed rate and spindle speed have a clear effect on inner diameter, wall thickness, and load requirements. Wall thickness is the simplest of these features to control and can be readily adjusted by altering the final roller input depth. Optimising the parameter set, for example minimising inner diameter growth whilst maintaining wall thickness, for a particular material can be achieved by understanding the interaction between variables through experiments such as those presented in this paper. Overall it was observed that varying parameters in flow forming produced clear trends in the outputs, which can be used to confidently predict tolerances for near net shape component design.

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