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REVIEW

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Strategies for residual stress adjustment in bulk metal forming

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Abstract The family of bulk forming technologies comprises processes characterised by a complex three-dimensional stress and strain state. Besides shape and material properties, also residual stresses are modified during a bulk metal forming process. The state of residual stresses affects important properties, like fatigue behaviour and corrosion resistance. An adjustment of the residual stresses is possible through subsequent process steps such as heat treatments or mechanical surface modification technologies, like shot peening and deep rolling. However, these additional manufacturing steps involve supplementary costs, longer manufacturing times and harmful effects on the product quality. Therefore, an optimized strategy consists in a targeted introduction of residual stresses during the forming processes. To enable this approach, a fundamental understanding of the underlying mechanisms of residual stress generation in dependence of the forming parameters is necessary. The current state of the art is reviewed in this paper. Strategies for the manipulation of the residual stresses in different bulk forming processes are classified according to the underlying principles of process modification.

Keywords Residual stress · Bulk forming · Cold forming · Hot forming · Manufacturing

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1 Introduction

1.1 Definition of bulk forming processes

Metal forming processes are usually classified into two main groups: bulk and sheet metal forming. Although these terminologies are widely used, their denominations may misleadingly induce to think of a distinction between the two categories purely based on the initial geometry of the material. However, bulk forming can also be done with sheet metals [1] and some micro-processes are also part of this category [2]. The differentiation is instead based on the kind of plastic deformation occurring during the process. Whereas in sheet forming operations, the stresses are fundamentally in the plane of the sheet metal, bulk forming processes are characterized by a three-dimensional stress and strain state [3]. Compared to other manufacturing technologies, bulk metal forming processes are characterized by distinctive advantages for the industries utilizing it: low piece production costs, high production rates and favourable product properties [4]. From an environmental point of view, the bulk forming processes also show significantly higher resource and energy efficiency than subtractive and additive processes [5]. The high material usage in forming processes leads to a decreased influence of the raw material production costs on the costs of the finished parts in comparison with machining processes [6]. On the other side, bulk forming is characterised by very high process forces that require high investment costs for the machines and working tools. Moreover, these processes are generally characterised by lower flexibility in comparison with machining.

1.2 Classification

The topic of bulk forming processes incorporates numerous different manufacturing technologies. Apart from the characteristic three-dimensional stress and strain states during forming, different categories can be distinguished regarding the process properties. First of all, bulk forming can be divided into cold, warm and hot forming. Hot forming is defined as forming with part temperatures above the recrystallization temperature. Accordingly, the forming temperature typically used for steels is in the range of 900 to 1250 °C [7]. Above recrystallization temperature, the forces required for forming are reduced due to a decreased material strength and dynamic recrystallization, i.e. the instant compensation of work hardening. The additional increase in the elongation at fracture enables higher degrees of deformation and the production of more complex geometries. In addition, a very fine-grained microstructure can be achieved based on dynamic recrystallization effects through an adjustment of the process parameters such as forming temperature and forming speed. These effects are used to increase the strength of the components [8].There are numerous types of hot forming processes. For example, open-die forging, where a workpiece is upset between two flat dies, closed-die forging, where the workpiece is partially or completely enclosed in the die, or rolling and roll forging, where billets are reduced in the cross section by passing through two rotating rolls. On the other side, if the machines and the geometry of the workpiece allow for it, cold and warm forming show some advantages: better surface finishing, smaller tolerances and work hardening.

A second distinction is made between die-defined and incremental bulk processes [9]. Die-defined forming technologies are processes, where the desired part geometry is reached in one uninterrupted stroke and is largely defined by the geometry of the die. Examples of die-defined forming technologies are wire drawing, extrusion and closed die forging. In contrast, in an incremental bulk forming process the final shape of a component is largely dependent on the tool kinematics. In these processes, the deformation is confined within areas of the workpiece at any instance in time and the formed region undergoes more than one loading and unloading cycle during the forming process. The incremental plastic deformation influences not only the geometry, but also the static and dynamic strengths through work hardening and the generation of residual stresses [10]. Examples of incremental bulk forming are rotary swaging and thread rolling, which are industrially established incremental cold forming manufacturing processes for axisymmetric workpieces[11].

Finally, not only bars and billets but also sheet metal is used in some bulk forming processes [12]. A typical example is the sheet metal extrusion process, where a punch and a die are used to displace a part of the sheet metal relatively to the rest of it [13]. Thus, this process is closely related to the blanking process with the exception that the sheet metal is separated in the latter. Fracture in a blanking process can be minimized by fine blanking. Here, high compressive stresses are used to achieve cutting edges without a fractured surface. Contrary to conventional stamping, entirely smooth surfaces can be achieved [14]. Typical design parameters of fine blanking systems are the die clearance, the active element edge preparation and the V-ring geometry

[15]. The effects of these design parameters on the resulting cutting edges have been analysed for example in [16].

1.3 Residual stresses in bulk formed parts

Residual stresses are stresses that are present in a component even without external loads. They are in an equilibrium state over the entire component, but may be distributed inhomogeneously over individual areas. Every bulk formed component is characterized by a distinctive residual stress state due to its conditions during manufacturing. In bulk forming, they are generated by three basic mechanisms. First of all, inhomogeneous stress states during forming lead to uneven work hardening in the material, which causes stresses to remain within the produced components [17]. This mechanism is particularly relevant for cold forming, as the high strength and work hardening of the material lead to large possible residual stresses. During hot forming, however, mechanically induced residual stresses are able to dissolve due to a thermally induced dislocation movement and the reduced material strength at elevated temperatures. The second mechanism for the generation of residual stresses in forming operations is the presence of thermal gradients during cooling, which is particularly significant for hot forming. Faster cooling areas reduce their volume, leading to tensile stresses within themselves. In areas that are still hot, compressive stresses are induced and dissolved due to the reduced material strength at elevated temperatures. Component areas that cool down last induce compressive stresses in formerly cooled areas, which cannot dissolve. Therefore, earlier cooled-down areas show compressive residual stresses, while later cooled areas show tensile stresses[18]. The third mechanism for the residual stress formation in forming processes is represented by phase transformations in the material, which lead to a change of volume in the affected areas. If component distortion is restricted during cooling, residual stresses are induced.

These residual stresses are affecting the properties of the formed products in different ways. In component operation, they are superposed to load stresses, leading to an increase or a reduction in the effective stress. Therefore, residual stresses have the potential to either improve or deteriorate the operating behaviour of bulk formed components. Furthermore, residual stresses are necessary to create force-fit joints by plastic deformation[19]. The decrease or increase in these residual stresses during the usage of the components can be captured by sensors joined during bulk metal forming processes like rolling, cold forging, drawing, recess or infeed rotary swaging [20].

Numerous studies have assessed the influence of near-surface residual stresses on the fatigue life of cyclically loaded components. Tensile residual stresses in this area are undesired, as they facilitate the formation and propagation of cracks, decreasing the fatigue life [21]. Moreover, these parts also show a higher corrosion tendency [22]. Additionally, residual stresses may lead to undesired distortion of workpieces along the process chain, if certain component areas are removed [23].

Additional heat treatment operations are therefore often applied after conventional forming processes to reduce tensile residual stresses and to avoid distortion problems in subsequent process steps. In this case, an adjustment of the process parameters is focused on the minimisation of the negative effects of the residual stresses on these parts. In addition, mechanical processes such as deep rolling and shot peening can be performed on the final products' surface to reduce tensile stresses or to even induce compressive stresses. However, all supplementary processes are elongating the process chain and are therefore reducing the economic efficiency. Intelligent process design and control should be directed at manipulating the residual stress state already during the forming processes. Assuming that a favourable residual stress profile can be generated by a precise control of the process parameters, intermediate and subsequent steps to adjust the stress state could be economized. Such a shortening of the process chain will result in a gain of time, reduced manufacturing costs and increased resource efficiency.

Cold extruded parts can serve as exemplary cases for disadvantageous residual stress generation which demands post-processing operations. In Fig. 1a, a typical residual stress state of an extruded component is shown. In this process, an inhomogeneous material flow occurs, since the material on the surface has a longer flow path than the material in the centre. Therefore, a distinct state of residual stresses is induced in the material. High tensile residual stresses typically occur near the surface of the component in axial and tangential direction, while compressive residual stresses are confined in the core of the workpiece. This configuration is strongly undesirable for these parts that are often subject to cyclic loads in their applications due to their axial symmetric geometry, as it facilitates the formation and propagation of near-surface cracks [21]. Moreover, it is unfavourable for subsequent processes, such as bending operations, and usually limits the further processing of the material. The comparison of FEM and experimental results (X-ray measurements) in Fig. 1a displays

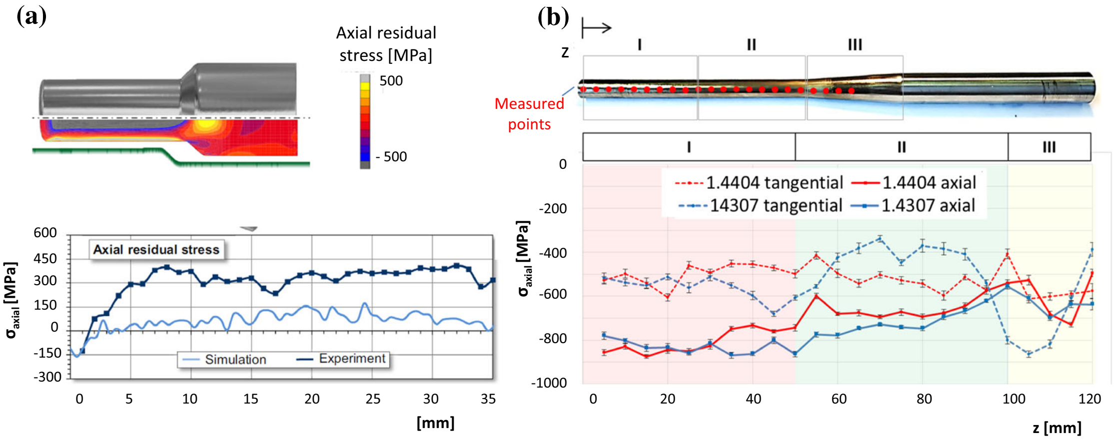


Fig. 1 Typical superficial axial residual stress distribution in extruded parts of material 1.4016 from [25] (**a**) and in rotary swaged samples of stainless steel 1.4307 and 1.4404 from [26] (**b**). In extrusion, high tensile residual stresses are occurring on the surface, while the core shows compressive stresses. In rotary swaging, the compressive residual stresses are on the surface

how for the numerical computation of residual stresses at the surface, challenges are still present. Numerous variables, such as mesh sizes and the used material and hardening model, are influencing the result of the simulation. On the other side, diameter reductions of solid material can be obtained also through incremental forming by infeed rotary swaging. Although the final geometry is very similar, the formed workpieces are in this case characterised by a completely different residual stress formation, as rotary swaging of solid material is usually characterised by compressive residual stresses on the surface. An example on stainless steels 1.4307 and 1.4404 measured through X-ray diffraction is shown in Fig. 1b. As previously explained, this stress configuration is particularly advantageous during the fatigue life and the formed parts do not require post-treatments for the adjustment of the residual stresses. It can then be observed that the formation of the residual stresses in these cold forming processes differs strongly due to the completely different material flow that characterises the two processes. In particular, the high-frequency movement of the working tools in rotary swaging plastically deforms the material in the near-surface region during all the forming process. As it can be seen in FE simulations [24], the flow of the material is overall faster on the surface then in the centre of the workpiece in opposition to cold extrusion.

Residual stresses also have influence on the operating properties of hot formed components. For example, distortion and stresses of steel rails are important with respect to safety and comfort in railway traffic. Accidents and derailments due to buckling of the rails in the context of uncontrolled residual stresses have already been observed [27]. In order to improve the crack growth resistance, low tensile residual stresses, or even better, compressive stresses in the rail head and foot are aimed for. Figure 2a shows a typical profile of the axial residual stresses in the rail after the hot forming process [28]. It is evident that, although advantageous compressive residual stresses occur on top of the rail head, undesired tensile stresses prevail in the lower part of the head and in the foot of the rail.

A targeted modification of the residual stress profile in a component can be achieved by a suitable process control in hot-forming. During closed-die forging of gears, compressive residual stresses develop in the component surfaces while cooling-down and prevent premature material fatigue during the life cycle. Figure 2b shows the measured residual stress-depth curves for two components made of 1.5919 [29]. After hot forming, tensile residual stresses are present on the surface. The depth curve of gear A represents the residual stresses at the tooth root after hot-forming and an additional shot peening operation. Due to the additional treatment step in the process chain, a favourable residual stress profile could be generated on the surface. In contrast, a favourable residual stress profile was also found at the tooth root of gear B immediately after hot forming and quenching without an additional shot peening step. These differences occur due to the varying process conditions [30] and illustrate both the challenges as well as the potentials of intelligent process design and control.

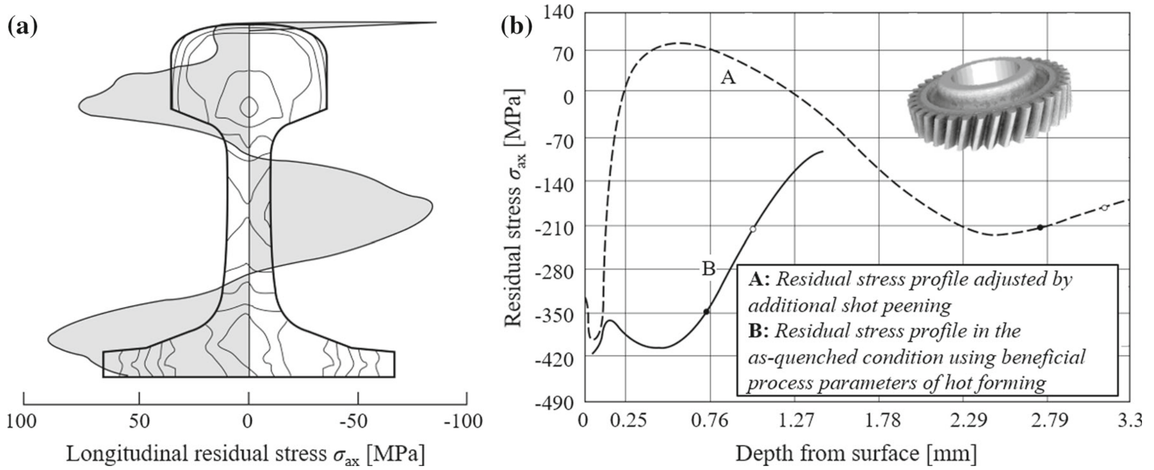


Fig. 2 Typical profile of axial residual stresses in a rail´s middle axial position[28] (**a**) as well as the extremes in residual stress distributions on tooth roots found among 40 hot formed gears using the steel 1.5919 [29] (**b**)

1.4 Difficulties related to the analysis of the formation of residual stresses

Although the investigation and understanding of the formation of residual stresses is of paramount importance for the application of formed workpieces, the literature only provides scarce information about this topic. This is due to the fact that several challenges for the investigation of the residual stresses in the production of components have to be overcome.

First of all, residual stresses are not trivially identifiable parameters. Their quantitative determination requires considerable efforts. Although numerous methods have been developed for the measurement of the residual stresses, the existing measuring techniques are associated with a difficult and time-consuming implementation and generally provide measurements with high error scattering. Residual stresses cannot be measured directly, but rather are derived from the material's deformation either on a macroscopic scale (destructive methods) or by the modification of the lattice spacing on the microscopic scale (non-destructive methods). In comparison with destructive techniques, where one sample can be used for the measurement of one single point of the workpiece, non-destructive technologies allow the determination of the stress profile in different positions of the workpieces. However, they only allow the measurement of near-surface residual stresses. Since they are generally less time-consuming when many measurements are needed, they are usually the favoured choice when a quantitative analysis of the formation of the residual stresses in response to different process parameters is needed. Although recent developments show promising results, many problems remain in the measurement of residual stresses by destructive and non-destructive approaches [31].

Also, the development of numerical models for the study of the formation of the residual stresses entails many challenges. The complex 3D material flow that occurs during bulk forming processes requires very accurate FE models for its prediction. Especially, the prediction of the residual stress state of the final part requires an accurate material model that should be able to take into account all relevant phenomena [32]. The cost for the parameter identification for these models is often very high [32]. For many processes, the modelling of the kinematic hardening behaviour is required for an accurate residual stress prediction. Consequently, for these processes, the employment of combined isotropic and kinematic hardening models in the simulations is strongly suggested. For example, studies in autofrettage of thick tubes show that the correct material modelling significantly affects the in-depth stress distribution [33]. The kinematic hardening behaviour also strongly affects bent parts, for which several studies are available (e.g. [34]). Apart from the prediction of the evolution of the back-stresses, also the effects of temperature and phase changes are for many processes fundamental. Therefore, coupled multi-physics models are often needed to take into account the different aspects of the process.

The use of different materials may also result in challenges regarding the determination of guidelines and strategies for the manipulation of the residual stresses in forming processes. A change of the material strength may lead to different mechanisms in residual stress generation. Therefore, the transferability of the results should be checked carefully, if a transfer of findings from one material to another is sought. An example related to the extrusion process is presented in [35]. Figure 3 shows the residual stresses after cold forward rod

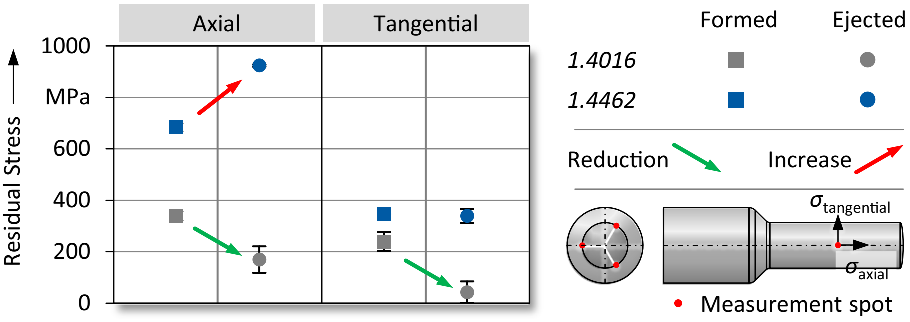


Fig. 3 Material-dependent influence of ejection after cold forward extrusion on residual stresses [35]

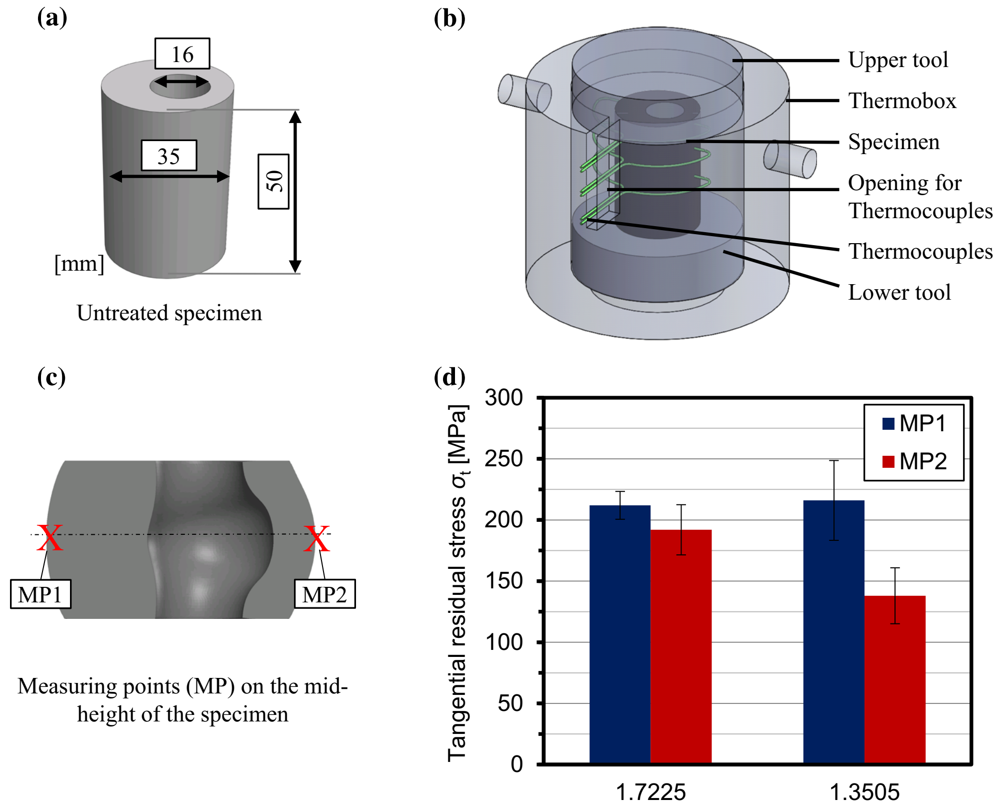
extrusion for two stainless steels, measured through X-ray diffraction. For mild ferritic stainless steel 1.4016, the ejection of the part leads to a decrease in the tensile residual stresses in axial and tangential direction. In ferritic-austenitic duplex stainless steel 1.4462 with a higher strength, the axial stresses are increased after ejection, while tangential stresses are not affected. The reason for this phenomenon can be found in the die springback, which causes a three-dimensional plastic deformation in 1.4016 during ejection, resulting in lowered residual stresses. When using 1.4462 as part material, the die springback is not sufficient to plastically deform the part and the residual stresses are only changed in axial direction by shear stresses during ejection. This shows that both the part material and the particular process setup are influencing the residual stresses generation during extrusion [35].

An interesting material-dependent behaviour is also observed in hot forging. In[36], the bearing steel 1.3505 was investigated in comparison with the tempering steel 1.7225. The geometry of the work piece analysed in this study is shown in Fig. 4a. This geometry is intended to provoke an inhomogeneous stress profile on the specimen surface, as it may occur in industrial hot forming. The work pieces are equipped with thermocouples to control the experimental temperature boundary conditions, see Fig. 4b. In case of the reference process, a specimen is formed from the initial height of 50 mm to 28 mm at the temperature of 1000 °C with the speed of 200 mm/s and subsequently quenched in water. To investigate the influences of the respective process parameters, only one of the parameters of the reference process was varied in each test series. For this purpose, the residual stresses on the thick-walled side (measuring point MP1) and on the thin-walled side (MP2) are determined by X-ray diffraction, as shown in Fig. 4c.

As shown in Fig. 4d at MP1, almost the same residual stress states of about 212 MPa have been observed in both materials with X-ray measurements. At MP2, in contrast, significantly different residual stresses of 192 MPa in the material 1.7225 and 138 MPa in the material 1.3505 were determined. The comprehensive material characterisation of the authors in [37] has shown that the plastic behaviour, the transformation-related and the transformation-plastic parameters of the two materials are different. Of particular importance is the material-specific martensitic transformation behaviour, which starts much later in 1.3505 with Ms = 184 °C compared to 1.7225 with Ms = 334 °C. This phase transformation is superimposed by the differing transformation plastic behaviour of 1.3505. As stated in Sect. 2.1, the phase transformation effects in turn are subject to the flow behaviour and the kinematics of grain growth as a result of dynamic and static recrystallization. However, these effects are prevailing at MP2. At MP1, other interrelating material phenomena compensate for this so that similar stress states arise as in material 1.7225. This means that the sensitivity of the material influences depends on the component geometry.

2 Strategies for the manipulation of residual stresses

Since the residual stresses can be considerably affected through the control of the forming and material parameters, the knowledge and understanding of the underlying mechanisms that determine the residual stress state of formed components are essential for an optimised and reliable process and manufacturing system design. This aspect is, however, not yet exploited in many industrial process chains. Instead, additional processing operations are usually performed to minimize the effects of unfavourable residual stress states and allow for subsequent manufacturing steps. The main reason for this practise is a lack of knowledge about the relationship between manufacturing conditions and the residual stress state induced through the forming process. This is to be related to the many challenges that nowadays still characterise the investigation of the formation of residual



Untreated specimen

Measuring points (MP) on the mid-height of the specimen

Fig. 4 Shape of the investigated specimen for the reference hot forming process with dimensions in mm (**a**), schematic representation of the specimen prepared with thermocouples in a thermobox (**b**) as well as illustration of the hot-formed specimen with the measuring points MP1 and MP2 at the mid height (**c**); Comparison of the resulting residual stresses in the reference process of hot forming at varying materials [33]

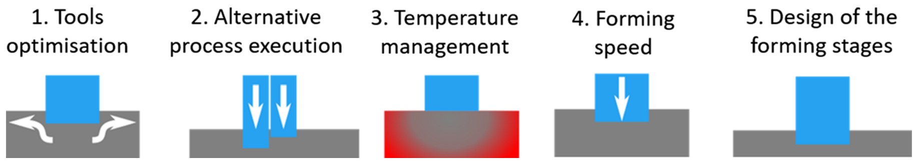


Fig. 5 Strategies to control residual stresses in bulk metal forming

stresses in bulk metal forming. In particular, these issues are connected with a reliable numerical prediction of the resulting residual stresses as well as of a repeatable and easily implementable measuring technique, as described in Sect. 1.4 [31].

Consequently, nowadays the opportunity to achieve a targeted introduction of residual stresses has not been investigated for many forming processes. Residual stress formation is strongly dependent on the process, and in the literature it is difficult to determine common strategies that may be used as general guidelines for bulk forming processes. Some process specific aspects can be observed in different technologies and rules for the beneficial manipulation of the residual stresses can, however, be found. In this chapter, these strategies are collected in subsections referring to the different modified state variables of the process. The aim of the present paper is the identification of exploitable relationships between adjustable process parameters and residual stresses that are formed during the bulk forming processes. These strategies are divided into five categories, as schematically represented in Fig. 5.

In general, these strategies affect the three main phenomena that are responsible for residual stress generation in forming processes: inhomogeneous deformations, temperature gradients and phase changes. The relevance of each category of strategies is strictly related to the characteristics of the studied process. For example, inhomogeneous plastic deformations are the governing mechanism of residual stress generation in

Table 1 Overview of the literature that describes the strategies for the residual stress control in bulk forming

		Categories				
		Tools optimisation	Alternative process execution	Temperature management	Forming speed	Design of the forming stages
Technologies	Extrusion	[38–43]	[44–47]		[48]	[47, 49]
	Hot forming			[36, 50–54]	[51, 51]	[51]
	Rotary swaging	[55–59]			[55]	
	Fine blanking	[60, 60]				

cold forming processes. Therefore, the study of the material flow in relation to the formation of residual stresses is particularly important in these technologies. Strain-induced phase changes in some materials (e.g. strain-induced martensite formation) also play a role and may be related to the material flow during the forming process. Consequently, modifications to the geometry of the working tools or introduction of active elements that allow a targeted control of the material flow are particularly indicated for cold forming processes. Temperature gradients are instead a secondary aspect for these technologies. Heating is developed only through the dissipation of the forming and friction energy, and the temperature is affected in a limited range that normally does not cause a phase change. As the temperature in the workpiece increases not uniformly and different areas of the workpiece may be characterized by slightly dissimilar material behaviour (e.g. Young modulus or yield strength), this may generate inhomogeneous material flow and, consequently, affect the residual stresses. However, this effect is very moderate and such an influence was not reported in the present state of the art. Also, the FE models employed in the literature for the prediction of the residual stresses in cold forming usually neglect the temperature effects, e.g. [25]. As a result, the control of the process temperature is not a promising strategy to follow during cold forming. On the other side, in hot forming processes the residual stress generation is mainly affected by the temperature gradients and phase changes related to heat generation and flow during the forming and cooling phase. Therefore, an attentive study of the process temperature is a valid technique to beneficially affect the final stress state of the workpieces, while the study of the inhomogeneous material deformations is a secondary aspect. Also, forming speed and deformation degree are connected with the phenomena of recrystallization and temperature gradients and play an important role in hot forming. It is important to notice that the implementation of these strategies is always strongly material-related and therefore requires an appropriate process design and control for the material involved.

Table 1 provides an overview about the literature on the topic of targeted manipulation of the residual stresses during bulk forming processes, divided into the five categories.

2.1 Tools optimisation

In some technologies, it has been seen that the geometry of the working tools can be modified to affect the material flow and, consequently, the final residual stress state of the workpiece. The influence of an inhomogeneous material flow is particularly visible in cold forming, where the high residual stresses are due to different material flow conditions acting in different parts of the workpiece. In this context, some possible strategies are identified to modify the residual stress state during the process with a control of the material flow. In general, a possible strategy could aim at avoiding high stress gradients in the component, which may lead to undesired distortions along the process chain. For this purpose, a valid approach for modifying residual stress states in cold forming technologies is to minimize the inhomogeneities in stresses and strains throughout the formed component. For example, by means of a suitable design of the die, the final stress state in extrusion can be beneficially affected. It was seen that the opening angle of the die influences the residual stresses: smaller opening angles lead to a more uniform velocity field in the cross section of the extruded material, decreasing the final residual stresses [39]. In this case, it is not possible to change the orientation of the stress state significantly, but the tensile residual stresses on the surface of the workpiece can be reduced[38]. The same phenomenon was observed for radial cold forging [59], where an optimization of the residual stresses is achieved with a decrease in the inlet angle. Alternatively, new concepts are developed for a targeted introduction of compressive residual stresses on the surface of the workpieces. In gradation extrusion, this goal can be accomplished with a modification of the tool geometry. In Fig. 6, this new technique for a local modification of residual stresses is displayed. Here, a modified extrusion die geometry is employed, which produces the same final component

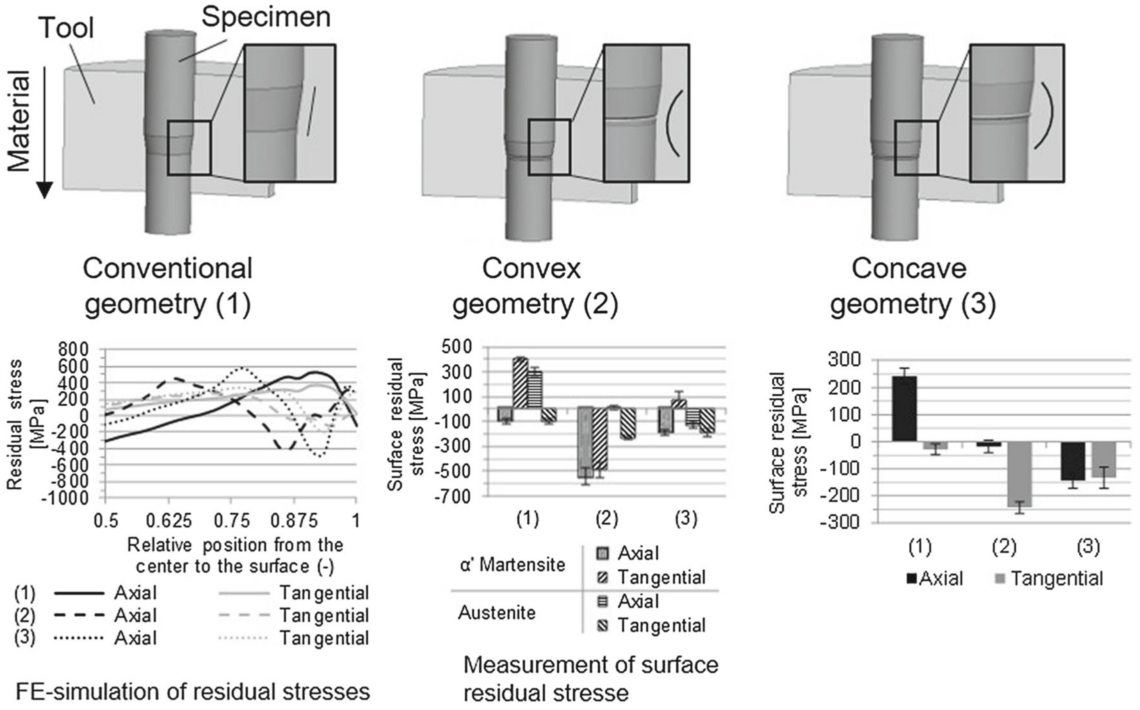


Fig. 6 Gradation extrusion: Geometry variants of the dies with special geometric elements; and simulation of the final stress state distribution; measurement of surface residual stresses

geometry as the conventional extrusion process, but with a different residual stress distribution inside the component. A basic investigation of this strategy was carried out in [43], see also [41, 42]. A conventional tool is combined with two dies characterized by special features in their geometry, which consist of additional small elements incorporated in the forming zone. One die includes a convex forming element, the other die a concave forming element, as shown in the top of Fig. 6. These elements cause a modified material flow and a high degree of plastic deformation during the forming process near the specimen surface, resulting in a change of the residual stress distribution in the material. Based on FE simulations and experiments performed, it was demonstrated that the dies with the specific geometric elements in the forming zone have an influence on the residual stress state and deformation-induced phase transformation in the specimen. The FE simulations illustrate that the influence of the geometric elements is in the near surface layer of the specimen. The curves for the axial (black) and the tangential (grey) residual stresses over the cross section measured per X-ray diffraction are depicted in Fig. 6. The most significant influence on the residual stress states of the material is achieved using a die with a convex geometric element in the forming zone. The experimental results confirm a shift from tensile residual stress states to compressive stress states due to the geometric elements in the dies. These compressive stress states near the surface are favourable for subsequent processing and final product properties. The evaluation for the conventional geometry shows an increase in axial residual compressive stresses in the near surface zone. Towards the centre, they change into tensile residual stresses. Measurements with X-ray diffraction methods were carried out on samples of austenitic stainless steel 1.4301 in order to study the influence on the residual stress state of the different tool geometries and are displayed in Fig. 6. XRD allows a phase-specific analysis of residual stresses, as the differences in the crystal lattices of the austenite and martensite phases result from different Bragg angles, and each phase can be analysed by their reflections. The evaluation of the samples shows that deformation-induced martensite is formed in the peripheral zone. The residual stress states determined for the martensite and austenite phases differ depending on the individual dies. For example, the martensite phase in the tangential direction shows significant residual compressive stresses when using the convex die with up to − 490 MPa, whereas for the martensite phase significant residual tensile stresses were determined when using the conventional die in the tangential direction with + 400 MPa. It can be observed that there are significant variations in the values of the residual stresses on the selected measuring location. The highest residual compressive stresses in the martensite phase are generated by the convex die. In general, however, it can be shown that the use of the modified tools mostly results in surface stresses as

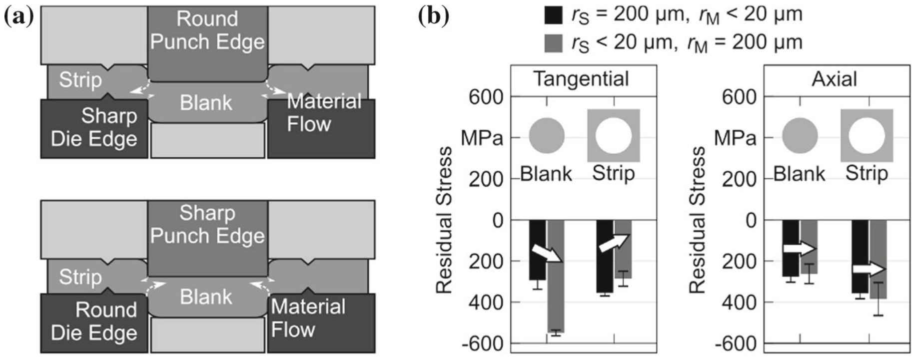


Fig. 7 **a** Illustration of the material flow when cutting with a round punch edge and a sharp die edge (top) and when cutting with a sharp punch edge and a round die edge (bottom) together with a comparison of the surface residual stresses of blanks and sheet metal strips manufactured by fine blanking (**b**) with a die clearance of 0.5% in tangential (left) and axial (right) direction for the two different active element edge preparations

compressive stresses. In the example, only one small convex or concave element was inserted into the modified tool. The combination of these elements in a modified forming process is seen as a promising research approach for influencing the residual stress within the forming process.

Interesting effects of the material flow control through attentive tool geometry design on the residual stresses have been lately described also for fine blanking [60]. By using different cutting edge preparations, the material flow can be guided. A round punch edge pushes the material towards the sheet metal strip, especially as material flow over the sharp die edge is restricted, as illustrated in Fig. 7 a. A round die edge on the other punch favours material flow towards the blank. This results in different residual stress states, as explained in [61]. As shown in the results of X-ray measurements in Fig. 7 b, this pressure caused by the changed material flow mainly affects the residual stresses in tangential direction. Here, the sheet metal strip formed with a round punch edge ($r_S = 200\ \mu\text{m}$) shows higher compressive residual stresses compared to the one manufactured with the sharp punch edge ($r_S < 20\ \mu\text{m}$). For the blank, it is the other way around. Here, the variant with the round die edge ($r_M = 200\ \mu\text{m}$) shows higher compressive residual stresses in tangential direction than the variant with the sharp die edge ($r_M < 20\ \mu\text{m}$). Again, the same behaviour is responsible for this. The round die edge guides material towards the blank. This causes a high pressure in tangential direction which remains after springback as a higher compressive residual stress. Thus, the material flow is guided by the targeted element edge preparation which is used to influence the part's residual stress state.

Studies on residual stress formation in rotary swaging showed instead a dependence of the stress state from the process parameters. In this technology, the formation of the intrinsic material properties is strictly correlated with the extremely complex material flow that characterizes this process [56]. The incremental plastic forming influences not only the geometry but also the static and dynamic strengths through work hardening and the introduction of residual stresses [57]. In this context, inhomogeneous conditions may affect the different regions of the surface of the workpiece. The analysis at the surface of the round parts (E355 tubes) swaged by curved-shaped dies with a difference between the rotation angle of the workpiece and the rotation angle of the dies between consecutive strokes $\Delta\varphi$ reveals strong fluctuations of axial residual stresses both in the positive and negative region, see Fig. 8a. Additionally, finite element simulations with the code Abaqus™ show the influence of the variation in the swaging process on the intrinsic process fluctuations. It was demonstrated that the axial stress component stress depends on the stroke amplitudes of the individual tools, which in turn correlate with the tolerance of the cylinder roller diameter of the rotary swaging machine [55]. Consequently, the technical tolerances of the machine components can cause the fluctuations in residual stresses inside the swaged component. The fluctuations of residual stresses shown in Fig. 8a can be significantly reduced by the use of flat dies in the reduction as well as in the calibration zone. Studies from [58] displayed also the influence of the forming dies' geometry on the residual stresses of the swaged parts. The use of flat shaped dies with a stroke following angle of $\Delta\varphi = 0°$ (the workpiece rotates with the same angular velocity as the dies) leads to homogeneous and reproducible residual stresses at the surface of the square parts, Fig. 8b. By using angles $\Delta\varphi$ near to zero and rotary swaging dies with a curved surface in the calibration and reduction zones, a significant reduction in the fluctuation of the residual stresses is observed in conventional rotary swaging of solid materials (S355, 1.0580), see Fig. 8c. The angles $\Delta\varphi$ near to zero could be achieved by a free rotation of the workpiece with the dies. Although the semi-finished parts were not normalized prior to the swaging process homogeneous

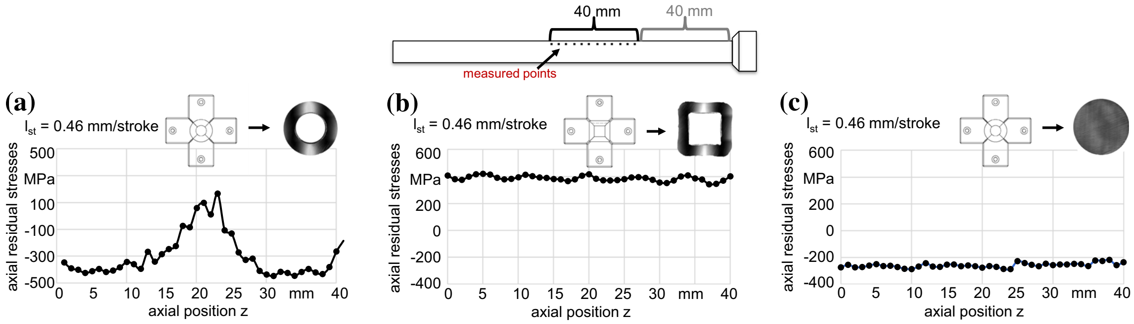


Fig. 8 Axial residual stress measured through X-Ray diffraction along the outer surface for the tubes swaged with round (**a**) and flat (**b**) shaped dies and full bars swaged with round-shaped dies (**c**)

compressive axial residual stresses and nearly no tangential residual stresses could be detected. The difference in residual stresses indicates a dependence of the material flow and thus of the intrinsic material properties of the swaged parts on the process kinematics, the material condition and the die geometry.

2.2 Alternative process execution

In order to achieve a desired residual stress state, the actual process execution could be altered by stress superposition during the forming process through the employment of active elements. Two examples of this approach with respect to cold extrusion are depicted in the present section. Franceschi et al. demonstrated that an active counter-punch can significantly reduce the axial and tangential residual stresses in the extruded components and potentially avoid the need of post-heat treatments[46]. The process is displayed in Fig. 9a. Here, the ejector, which is usually only activated after the completion of the forming process, is actively controlled to apply an axial force on the workpiece during extrusion. Similarly to the modification of the opening angle, the difference in material flow between centre and surface of the workpiece is influenced. A control of the stresses can be achieved through the application of the counter-force during the process, thereby decreasing stress gradients in the section of calibration. In this way, lower tensile residual stresses result on the surface of the final cold extruded parts. In detail, Fig. 9b displays the numerical results as to the axial residual stresses in the austenitic stainless steel 1.4301 in the depth of the samples [46]. Here, the tensile residual stresses on the surface in the steady-state region are reduced from about 750 to about 200 MPa with a constant counter-force of 80 kN. These results were validated by X-Ray diffraction measurements and similar results were obtained for the material 1.4404 [45]. Looking at Fig. 9b, it can be noticed that the absolute value of the residual stresses is reduced in all the section of the components, beyond the near-surface region. This results in a lower tendency of these parts to distortions. For demonstration purposes, some samples were axially cut in the middle and the experimental and numerical results are displayed in Fig. 9c. As it can be observed, the distortion that occurs in the conventionally extruded parts is completely avoided with the use of the counter-punch. As a result of numerical investigations, it was also displayed that the distortion of extruded parts of carbon steel C15 during heat treatments could be avoided using this technology [44].

In [47], another strategy consisting in the employment of active elements was studied for the cold extrusion process. Unlike the previous strategies, in this case the residual stress state is not directly adjusted during the forming process, but during the following ejection of the workpiece from the die. From the literature, it is well known how the extruded component, being pushed a second time through the calibration zone, undergoes a second plastic deformation. After this step, the tensile residual stresses on the surface of the specimen in axial and tangential direction are typically significantly reduced [49]. The reason is the reduced deformation degree that the sample undergoes during this stage and was explained by Tekkaya with the theory of the "extreme layer"[49]. This aspect will be better explained in Sect. 2.5 "Design of the forming stages". These positive phenomena typically occurring during ejection can be further exploited by the application of the tool technology displayed in Fig. 10a. The system is based on a segmented sleeve, whose radial motion is controlled through a separate drive system. The segmented sleeve is in contact with the external wall of the die. By activating the additional drive, it is possible to affect the internal diameter of the calibration zone and, consequently, the deformation during the ejection. An experimental and numerical analysis displayed that through this system not only a reduction in the undesired tensile residual stresses is possible, but also an introduction of desired

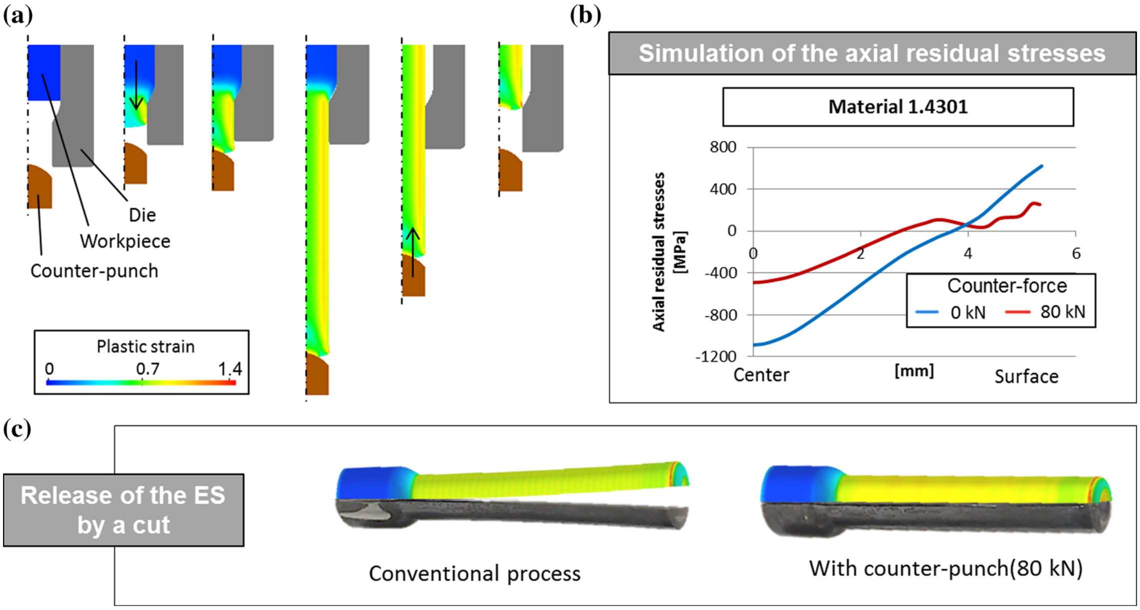


Fig. 9 Use of active elements during full-forward extrusion to control the residual stresses: schematic explanation of the process (**a**), simulation of the axial residual stresses in the cross section (**b**) and validation of the simulations through an axial cut and analysis of the distortion of the workpieces (**c**)

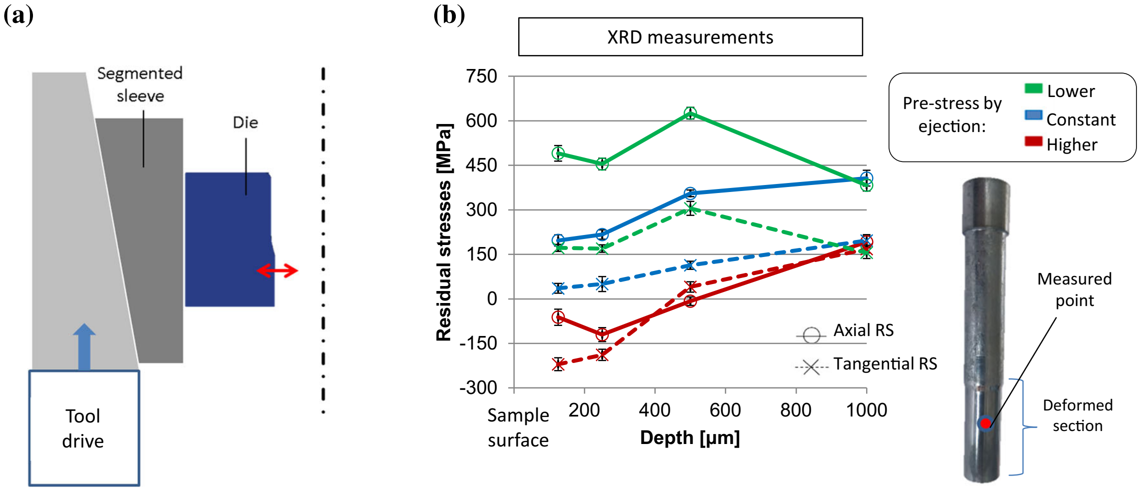


Fig. 10 Use of active elements during full-forward extrusion to affect the residual stresses: schematic representation of the system that activates the active die (**a**) and results of the measurement with X-Ray diffraction (**b**) [47]

compressive residual stresses can be achieved. Three elementary cases were investigated in [47]. After the forming with a certain value of pre-stress, the pre-stress during ejection was either kept constant (as in the conventional process), decreased or increased. The change of pre-stress causes a modification of the internal diameter of the die in the order of 25 µm. In Fig. 10b, the results of XRD measurements on the extruded samples are displayed. It was clearly shown that the residual stresses are improved by an increase in the pre-stress during ejection and that compressive residual stresses can be obtained on the surface of the workpieces. Also, the limit for this process was determined. It was proven that the positive effect of the ejection phase is bound to the condition that the plastic deformation is limited to the surface of the workpiece. When an excessive pre-stress is applied during ejection and the plastic limit is reached in the entire section of the workpiece, the effects on the residual stresses become similar to a second extrusion and are detrimental for the part.

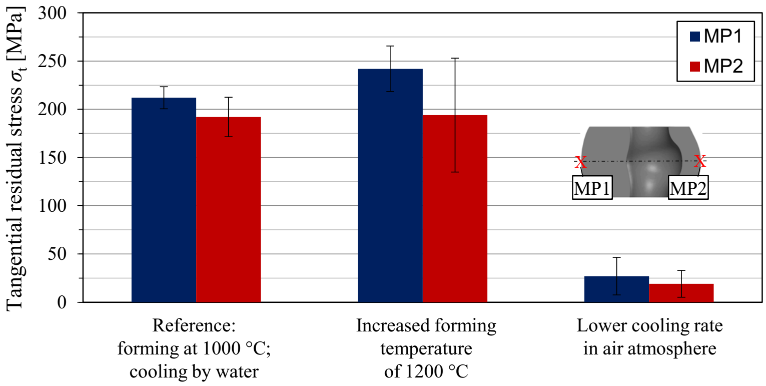


Fig. 11 Resulting residual stresses on the material 1.7225 at MP1 and MP2 after hot forming of the specimen from 50 to 28 mm height at a temperature of 1000 °C, forming speed of 200 mm/s and subsequent cooling by water as well as changes in residual stresses following a changed forming temperature and lower cooling rate [49]

2.3 Temperature management

Regarding residual stresses, hot forming as a thermo-mechanically coupled process principally offers the potential for several control parameters. However, a targeted adjustment of residual stresses to improve component properties by combining defined forming parameters with a tailored cooling strategy from the forging heat has not been researched to date. Instead, the focus was on minimizing residual stresses in order to eliminate undesirable effects. From an engineering point of view, heating the workpiece prior to the forming process offers an important advantage: all previously prevailing stresses in the material are substantially relieved as a result of the recrystallization and a new residual stress profile can be generated in the process. In addition to the process parameters such as forming speed and degree of deformation, the forming temperature and the cooling route also has an influence on the arising residual stresses [36].

In [51], the results of the residual stresses were analysed for two different forming temperatures: 1000 °C and 1200 °C. Figure 11 reflects the residual stresses at the measuring points MP1 and MP2 after cooling of the specimen in water. Further information on the process conditions and the measuring points is given in chapter 1.4.

It was found that a higher forming temperature of 1200 °C compared to the lower forming temperature of 1000 °C leads to higher tensile residual stress values at MP1, while constant stresses were measured at MP2. The higher stresses at MP1 as a result of an increase in the forming temperature can primarily be attributed to a change in the austenite grain size. Due to the higher austenitising temperature, increased grain growth occurs in the material, resulting in larger austenite grains [62]. The increased grain size in turn leads to several effects. The enlarged grains cause an increase in the martensite start temperature Ms and in the martensite finish temperature Mf[52]. Due to the coarser structure of the austenite grains, diffusion of the interstitial atoms at the long grain boundaries of the austenitic crystal lattice is hindered and diffusion-free, martensitic phase transformation is facilitated. Since martensite transformation is favoured in the process with 1200 °C forming temperature, in this case less retained austenite is present in the material[63]. Accordingly, in X-ray diffractometric measurements at MP1, for example, an average retained austenite content of 15.9% was determined for the specimen formed at 1000 °C and an average retained austenite content of 8.4% for the specimen formed at 1200 °C. As a result of a higher martensitic phase fraction in the core of the specimen, the volume shift increases due to the phase transformation in these areas. Consequently, higher strain gradients between the sheath and the core and thus higher residual stresses occur on the surface of the specimen. Furthermore, it is assumed that the larger grains prevent stress relief during the cooling process and thus accumulate more stress inside the material. The increased number of grain surfaces in the material within the process at 1000 °C forming temperature causes a better transfer of distortions, which leads to lower residual stresses (cf. [53]). In addition, since the maximum possible residual stresses are limited by the yield stress, increasing the proportion of the harder martensitic phase and reducing the softer austenitic phase can lead to an increase in residual stresses. These effects obviously conceal the fundamental reduction in yield stress that occurs according to the Hall–Petch law [64, 65] as a result of grain enlargement.

In another investigation, the influences of the two different cooling media, water and air, for cooling after hot forming at 1000 °C on the arising residual stresses were investigated [36]. Using water cooling, a diffusion-free phase transformation of the austenitic into the martensitic phase takes place, which leads to severe stresses ranging from 192 MPa at MP2 to 212 MPa at MP1 (cf. Figure 11). During diffusion-controlled phase transformation, which occurs during air cooling, comparatively lower residual stresses around zero can be observed. Due to the different cooling media water and air, different temperature–time profiles and different transformation kinematics arise in the steel alloy. During rapid cooling in water, a diffusionless transformation occurs, where austenite is transformed to the martensitic body-centred tetragonal (bct) lattice structure. When cooled by air, a body-centred cubic (bcc) lattice with a bainitic microstructure is formed for steel 1.7225, because of diffusion-controlled transformation. On the one hand, the phase transformation from austenite to martensite is accompanied by significant volumetric expansion, which leads to a strain gradient in the material. This effect is further enhanced by the highly pronounced transformation plasticity of martensitic transformation. On the other hand, the growth of the harder martensitic phase in the softer austenitic phase leads to stresses in the crystal lattice structure. The relatively high yield stress of the martensitic phase compared to the phases resulting from diffusion-controlled transformation thus determines the maximum achievable residual stress in the material. In summary, Fig. 11 shows that the cooling strategy has a more significant influence on the resulting residual stresses than the forming temperature.

2.4 Forming speed

For cold forming processes like extrusion, the literature does not provide clear evidence for the possibility to affect the residual stresses of the final products through adjustments of the forming speed. In [66], it was shown that forming and ejection speed are influencing the temperature of the cold extruded parts. However, no correlation between the forming speed and the near-surface residual stresses was found, since the deviations are within the range of the measuring uncertainty. Apart from the temperature, the modification of the forming speed also has an effect on the conditions at the contact region between workpiece and die. In particular, the sliding speed between two surfaces affects the friction coefficient. It was shown for most materials that the friction coefficient decreases with increasing speed [48]. For finite element modelling, a model with exponential attenuation is often employed[67]:

$$\mu = \mu_k + (\mu_s - \mu_k)e^{-d\dot{\gamma}} \tag{1}$$

where μ_k is a coefficient of kinetic friction, μ_s is a coefficient of static friction and d is a coefficient of attenuation. The behaviour of the friction coefficient versus sliding speed depicted by this formula is shown in Fig. 11.

Considering the case of cold forming where the residual stress formation is mainly due to inhomogeneous material deformations within the workpiece, an increase in the friction should contribute to this phenomenon. Especially in the near-surface region, inhomogeneous deformations that lead to tensile residual stresses should be avoided. Taking into account the exponential law in Eq. 1, the effect of the forming speed on the friction conditions is particularly significant for very small forming speeds.

To prove this aspect, a test was done with cold extrusion on samples of carbon steel S355. The raw material was quenched at 800 °C for 60 min and milled to the initial geometry. Samples with an initial diameter of 14.5 mm were reduced to 10.78 mm with two different die geometries. With the first die, the sample was formed to the final shape in one stage with an opening angle of 60°. The second die has the same angle and geometrical characteristics of the first one, but is composed of two forming stages. The final geometries of the samples are represented in Fig. 12. Three different forming velocities were tested (2.7, 8 and 13.3 mm/s), and three samples per test parameter were produced and analysed. Residual stresses were then measured on the surface in the steady-state region of the workpieces with X-Ray diffractometry, and the results are represented in Fig. 12. In general, it can be noticed that an increase in the forming speed leads to a decrease in the residual stresses, as expected from the previous considerations. Therefore, as a general rule for cold processes, the forming at extremely low speeds should be avoided.

In hot forming, the forming speed affects the final stress state through different phenomena and can lead to considerable variability in the residual stresses in the specimens [51]. However, as shown in Fig. 13, no universal tendencies can be derived from the relationship between forming speed and resulting residual stresses measured through X-ray diffraction. It is rather necessary to consider each parameter combination individually, as the dynamic recrystallization occurs in different forms for each case study. Dynamic recrystallization means that starting at a certain level of critical deformation, the dislocations and lattice defects caused by forming are absorbed by grain formation and grain growth. This leads to a decrease in the yield stress, reducing the required

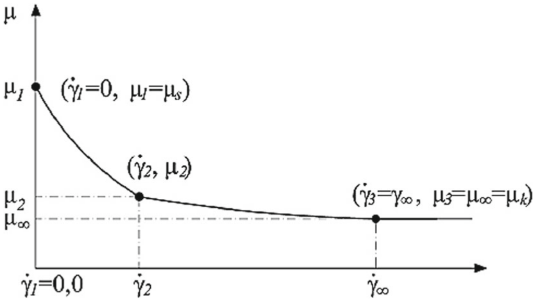


Fig. 12 Exponential model describing dependence between friction coefficient and sliding speed [48]

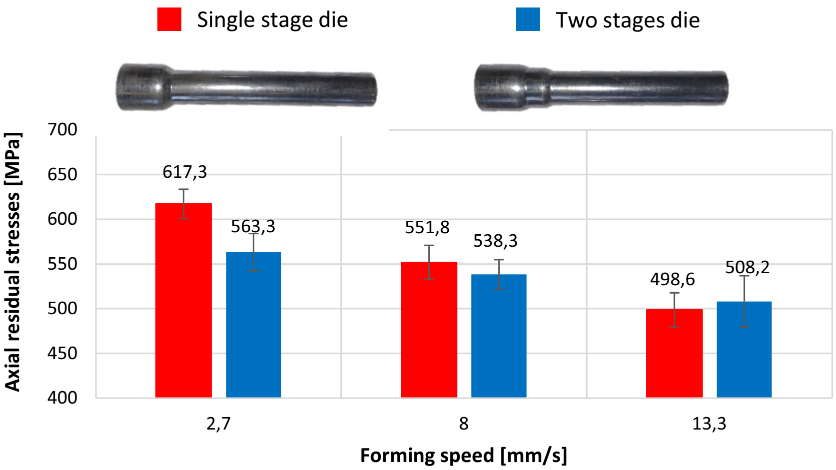


Fig. 13 Geometry of the formed workpieces with single and double stage and measurement of the axial residual stresses through X-ray diffraction

process forces and increasing the maximum plasticity of the material [8]. Depending on the relationship between the temperature-dependent diffusion rate and the forming speed, an austenitic microstructure is formed, which results in different amounts of residual stress.

In incremental bulk forming processes, some papers describe the effects of different forming speeds. In rotary swaging, a comparison of the axial residual stresses of the workpieces formed with curved-shaped dies as well as with flat-shaped dies reveals a strong influence of the process parameters such as feed per stroke l_{st} on the surface residual stress distribution [55], see Fig. 14. The workpieces swaged with curved-shaped dies predominantly showed compressive axial residual stresses and a high scattering for each feed per stroke value. Workpieces formed with flat-shaped dies revealed stable positive tensile axial residual stresses at the surface. Indeed, the evolution in depth (300 μm) was mostly independent for all investigated process variations and showed also positive values of residual stresses. In particular, this typical effect for hollow parts is seen in Fig. 14b. The residual stresses depth profile illustrates that at the surface the workpieces swaged with round shaped dies have positive values and swaged with flat-shaped dies workpieces have negative axial residual stresses. In the depth of 30 μm, the residual stresses change significantly and stabilize for deeper positions for both variants of swaging dies and feed per stroke l_{st}.

2.5 Design of the forming stages

The forming of a metal component could be performed in one or more stages. If the process is completed in more steps, the final stress state will be the result of the superimposing of the stresses of all these stages. Therefore, different strategies could be studied to design the forming steps in function of the load history that the workpiece undergoes. In particular, it is possible to exploit the different stress formation offered by the variation of the forming degree to optimise the stress state after the final forming step. Substantial differences characterise the response of residual stresses to an increase in the deformation degree in cold and hot forming

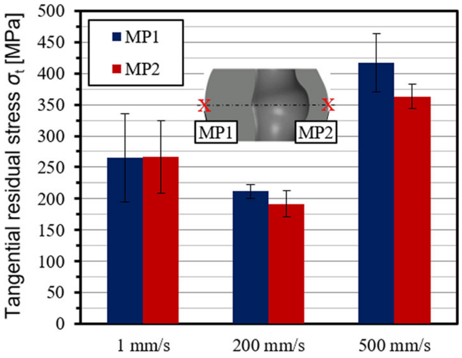


Fig. 14 Comparison of the resulting residual stresses in a reference process of hot forming at varying forming rates for forming a specimen from 50 to 28 mm height at the temperature 1000 °C and subsequent cooling in water [51]

processes. For the first ones, the degree of deformation is strictly connected to the two steps that characterise the residual stress formation: forming and unloading. The amount of residual stress on the final part depends both on the magnitude of the stress introduced in forming and on the constraints that influence the spring-back during unloading. Both these aspects are affected by the deformation degree. Therefore, the steps of loading and unloading must be studied for processes of interest. In particular, the connection to inhomogeneous deformations is determinant. Considering for example an ideal compression test, an increasing deformation degree has no influence on the residual stresses. The reason is that a complete elastic recovery is always possible in this forming process, independently from the magnitude of the deformation degree. However, higher forming degrees in many manufacturing technologies are connected with increasingly high inhomogeneities inside the workpiece. A clear example for this behaviour is bending, where very different strains affect the section of the workpiece for increasingly high forming angles. For these processes, it could be expected that higher forming degrees lead to higher residual stresses in the material.

An example of a conventional two-step process is full forward extrusion, where the deformation degree is a key parameter. The conventional process is typically characterised by two steps: forming and ejection. Being pushed a second time through the calibration zone, the extruded component undergoes a second plastic deformation characterised by a very small deformation degree. Typically, the final stress state is improved after the ejection of the workpiece. Tekkaya in [49] described the effects that this second deformation step has on the residual stresses with the use of a conceptual experiment. The extruded sample during ejection can be modelled as a tensile test, as represented in Fig. 15. The core of the part consists of a solid body with residual compressive stresses, while the surface is a hollow body with tensile residual stresses. The profile of the stress–strain curve during the various steps of the tensile test is shown in Fig. 15b. Due to the initial stress state, the surface reaches the plastic region (from Point A) much earlier than the core of the sample, which is plastically deformed only from Point B. The deformation follows until point C, where the sample is then unloaded. At this point, the strain range of the core is lower than the one of the surface, which should be then compensated when the external force is removed. However, the constraints in this system oblige the core and the surface to have the same length at the end of the unloading phase. As it can be seen in the diagram, this leads to a significant reduction in the residual stresses, which is often desired for the subsequent use of the part.

The principle described by Tekkaya was further exploited in the system with an active die described in Sect. 2.2 [47], where the deformation degree during the second plastic deformation is actively modified during ejection to optimise the final residual stress state. As shown in Fig. 10, increasing slightly the deformation degree during ejection compressive residual stresses on the surface of the extruded workpieces can be induced. However, [47] also shows that above a certain value of the deformation degree, the second plastic deformation has detrimental effects on the residual stresses. In fact, drastically different phenomena are noticed in the material deformation based on the reduction in cross section. In the case of large cross-sectional reductions, the material in the core of the workpiece is axially stretched to a greater extent than in the surface area, while the opposite happens with small reductions. Therefore, the resulting residual stress state in a conventionally extruded part is the result of the interaction of the two different deformation characteristics, the forming with a large cross-sectional reduction and the ejection process with a small cross-sectional reduction. By controlling the deformation degree in the second forming step, the properties can be adjusted to the desired level. Tekkaya in [49] describes this phenomenon through the definition of an "extreme layer ", which is the region of the

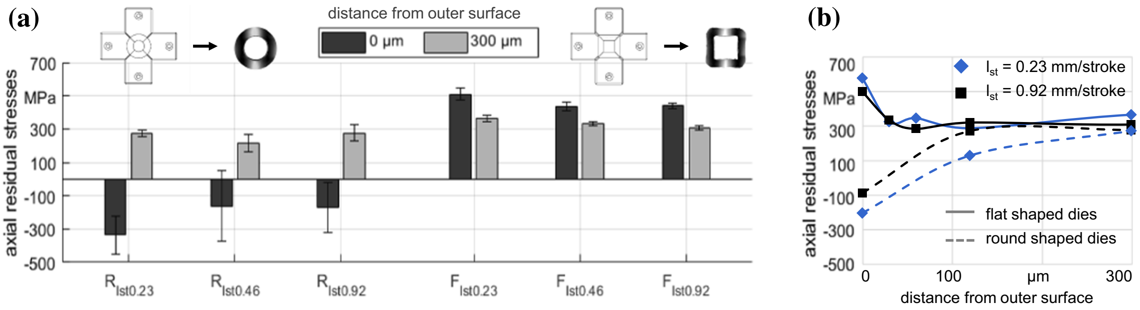


Fig. 15 Average axial residual stress values at the surface and 300 µm below for the workpieces swaged with curved shaped dies (R) and flat shaped dies (F), cf. [55]. Measurements through X-ray diffraction

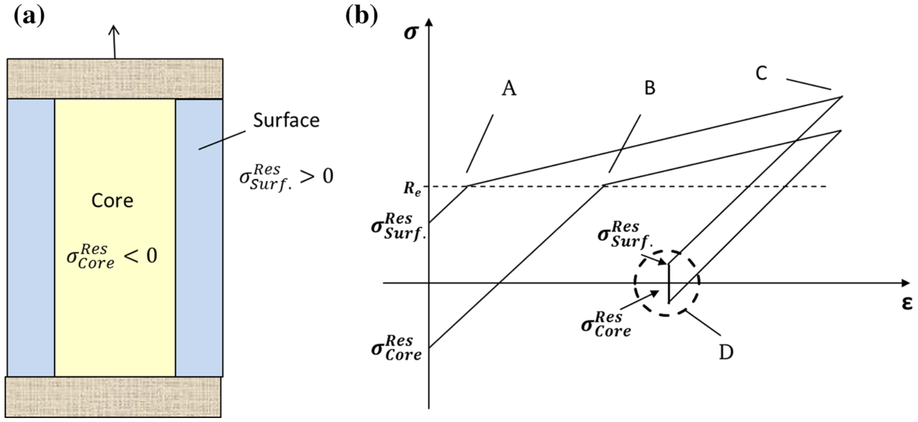


Fig. 16 Conceptual experiment to represent the mechanisms during the ejection phase of full-forward extrusion from [49]: set up of the experiment (**a**) and stress–strain diagram (**b**)

sample where plastic deformation occurs. A bigger reduction in the specimen cross section leads to a further movement of the extreme layer towards the specimen core. Finally, the plastic deformation reaches the core and a negative stress state is induced in the extruded part [47]. The example of extrusion displays how the superposition of successive forming steps can be a winning strategy for the manipulation of the residual stresses in cold forming processes. In particular, it could be convenient to perform smaller deformation degrees in the last forming operation. This could be particularly interesting in incremental processes, where a higher compressive deformation degree is always reached through the application of more steps of loading and unloading. In these processes, it would be easier to adapt the deformation degree of the last step of the process to calibrate the residual stresses without negative effects on the production times. However, such a strategy has not yet been described in the literature for these processes.

Also, in hot forming, the effects of the deformation degree are significant. The influence of this parameter on the residual stresses in the hot forming processes was investigated in [51]. Specimens were upset to two different final heights. An increase in upsetting distance led to a reduction in residual stresses. As presented in Figs. 16, 17, average stresses between 291 and 306 MPa were measured on the specimens without deformation, 192 to 212 MPa on the specimens upset by 22 mm and 84 to 165 MPa on the specimens upset by 30 mm. As the final height of the specimen decreases, the degree of deformation in the material increases and thus also the number of dislocations. As mentioned in Sect. 2.2, at a critical degree of deformation dynamic recrystallization occurs. Nucleation forms in the deformed areas, resulting in the growth of new austenite grains. The higher the deformation, the higher the number of dislocations and the finer the newly formed grain. In the non-deformed specimen, grain growth can proceed unhindered by static recrystallization during the holding time at 1000 °C. Accordingly, depending on the resulting grain size, the same effects were found with a decrease in the forming parameter "deformation degree" as with an increase in the forming temperature discussed above.

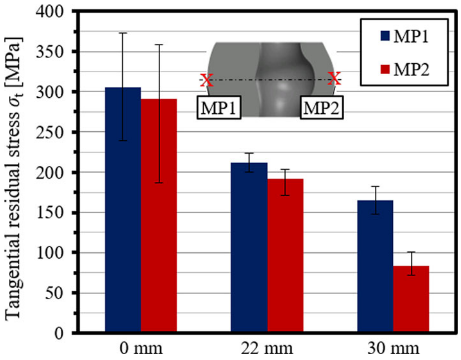


Fig. 17 Comparison of the resulting residual stresses in a reference process of hot forming at varying degree of deformation for forming a specimen at the temperature 1000 °C with a forming speed of 200 mm/s and subsequent cooling in water [46]

3 Conclusions

Different strategies to affect the final stress state in bulk formed parts and related processes were reviewed and summarized in the present paper. These techniques were collected according to five categories: tools optimisation, alternative process execution, temperature management, forming speed and design of the forming stages. From the paper, it appears clear that the topic of conscious stress introduction has not been deeply investigated for many bulk forming processes. Despite this deficit of knowledge, some interesting strategies have been developed for some technologies. In general, hot forming processes allow an easier manipulation of the stress state in the final products thanks to the possibility of controlling the thermal cycle. In particular, the control of the forming temperature and of the cooling path allows the control of the residual stresses through appropriate temperature gradients and phase changes. However, the material properties should be accurately studied in order to achieve a targeted formation of residual stresses. In cold forming processes, other strategies must be investigated, as no significant influence comes from the process temperature according to the published studies. In this context, particular attention should be paid to the study of the material flow. Through the control of the material flow and study of particular strategies for its control, a drastic improvement of the stress state can be obtained directly during the forming process. It was especially shown for cold extrusion that a reversal of the stress sign on the surface can be obtained. Other parameters, like deformation degree and forming speed, also influence the final stress state. Through their adjustment, the absolute value of the residual stresses can be decreased through the achievement of more homogeneous deformations. However, these parameters do not generally allow the possibility to invert the stress sign, in particular to turn tensile into compressive residual stresses on the surface. Incremental bulk forming processes seem to be more instable than continuous processes due to their dynamic nature. In these processes, the reproducibility of the residual stresses is an issue and should be carefully investigated. As seen for rotary swaging, the residual stresses in these processes can oscillate significantly from tensile to compressive. Moreover, it was observed that the residual stress strategies should always be considered in relation to the material employed, as different phenomena could take place. Consequently, the transferability of the results should be checked each time a different material is employed.

Although significantly different processes were discussed in this paper, similarities were observed. Still, research is necessary to transfer the mechanisms from one process to another. This deep understanding is necessary to adjust the part's residual stress state to fully use the materials potential for the relevant load case, i.e. to improve its properties and thus reduce cost and energy consumption.

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Data Availability The authors guarantee no restrictions on availability of data and material.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Code availability The authors guarantee no restrictions on availability of codes.

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