Increasing the formability of ferritic stainless steel tube by granular medium-based hot forming

H Chen, D Staupendahl, L Hiegemann and A E Tekkaya

Institute of Forming Technology and Lightweight Components
TU Dortmund University, Baroper Str. 303, Dortmund, 44227 Germany

E-mail: Hui.Chen@iul.tu-dortmund.de

Abstract. Ferritic stainless steel without the alloy constituent nickel is an economical substitution for austenitic stainless steel in the automotive industry. Its lower formability, however, oftentimes prevents the direct material substitution in forming processes such as hydroforming, necessitating new forming strategies. To extend the forming capacity of ferritic stainless steel tube, the approach of forming at elevated temperatures is proposed. Utilizing granular material as forming medium, high forming temperatures up to 900 °C are realized. The forming process works by moving punches axially into the granular medium, thereby, compressing it and causing axial as well as radial pressure. In experimental and numerical investigations it is shown that interfacial friction between the granular medium and the tube inherently causes tube feed, resulting in strain states in the tension-compression region of the FLD. Formability data for this region are gained by notched tensile tests, which are performed at room temperature as well as at elevated temperatures. The measured data show that the formability is improved at forming temperatures higher than 700 °C. This observed formability increase is experimentally validated using a demonstrator geometry, which reaches expansion ratios that show fracture in specimens formed at room temperature.

Keywords: Formability; Ferritic stainless steel; Granular medium; Hot forming; Tube forming

1. Introduction
Efforts to reduce greenhouse gases are one of the most important environmental issues and occupy a broad area of public perception and legislation. Lightweight construction is the key factor in reducing the CO₂ emissions of vehicles. However, the vehicle weights continue to rise as a result of increased passenger safety regulations and the electrification of internal systems. In the automobile, a significant weight is found in the so-called "hot end", which is the part of the exhaust system directly connected to the internal combustion engine. Conventionally, exhaust manifolds are steel or stainless steel castings. Alternatively, bent pipes or shells can be used, so that a heavy cast design can be dispensed with and the fuel efficiency can be significantly improved. The use of these lightweight designs is widespread and is now part of the state of the art. In the exhaust system of an automobile, the steels used are subjected to extreme conditions such as corrosion, vibration and heat [1]. The high temperature loading of the manifold elbow results in increased oxidation processes or thermomechanical fatigue. This has a direct effect on the service life and, thus, also on the cost of the exhaust system.
Typically, austenitic and ferritic stainless steels are used for exhaust manifolds. These stainless steels offer resistance to high-temperature oxidation as well as atmospheric corrosion and fatigue properties at high temperatures [2]. In terms of their high-temperature strength and thermal fatigue properties, austenitic stainless steels are more suitable than ferritic grades, but they are also more cost-intensive. Ferritic stainless steel are low-cost, price-stable, corrosion-resistant steels. In contrast to austenitic grades, ferritic grades have a low coefficient of thermal expansion, high thermal conductivity and they are immune for chloride-induced stress-corrosion cracking (SCC) [3]. The challenge to the wide use of ferritic stainless steels is that their forming capacity is poorer than that of austenitic stainless steels. The ductility of ferritic stainless steel usually decreases in the temperature range of warm forming (0.35T_m>T>0.55T_m), where T_m represents the melting point [4]. Manninen and Säynäjäkangas [3] indicated that the elongation rate of ferritic stainless steel decreases at warm temperature up to 700 °C and then increases at elevated temperature above 700 °C, which suggests a promising strategy of forming at high temperature. According to the uniaxial hot tensile test an increase of the ultimate elongation rate can be expected at elevated temperature of around 800 °C [5]. Unfortunately, the formability of ferritic stainless steel 1.4509 under different stain states besides uniaxial tension is unknown above the recrystallization temperature. Exhaust manifolds made of stainless steel tube are conventionally produced by hydroforming. To realize the forming temperatures up to 700 °C, adequate forming media such as gas or shapeless solid should be used. However, compared to hot and pressurized gas, which escapes quickly through leakages and, thus, poses a potential safety hazard, granular material (e.g. quartz sand and zirconia beads) is convenient and safe. There is no need for a special pressure generator and sealing and in the case of leakage, sand solely trickles out of the defect [6]. In addition, the interfacial friction between the granular medium and the tube inherently generates axial feeding, which drastically reduces the thinning of the tube. The tube material is loaded under the generated internal pressure and axial friction force [7].

In this paper, the formability of ferritic stainless steel tube is characterized by hot notched tensile tests under different temperatures. The derived left-side of the forming limit curve is used to determine the temperature process window. The data is used to setup simulations and experiments of a granular medium-based tube hot forming process to investigate the influence of the formability of ferritic stainless steel on the expansion ratio.

2. Material and method

2.1. Material

The material type used for this research is X2CrTiNb18 (or EN 1.4509, AISI 441) stainless steel, which is a titanium and niobium dual-stabilized ferritic grade with improved weldability. It is mainly applied in the automotive industry and process equipment, e.g. tubular products and heat exchangers. The high chromium content makes this grade well suited for replacing standard austenitic grades, e.g. 1.4301, in selected applications. The chemical composition of the steel is given in Table 1. The physical properties including mechanical and thermal parameters are shown in Table 2.

| Chemical composition | C     | Cr       | Mn | Ni | Ti+Nb | Fe |
|----------------------|-------|----------|----|----|-------|----|
| Amount (wt-%)        | 0.02  | 18       | -  | -  | 0.6   | Bal.|

| Table 2. Physical properties of 1.4509 (X2CrTiNb18) |
|-----------------------------------------------|
| Density (g/cm³)                              | 7.7  |
| Young’s modulus (GPa)                        | 220  |
| Heat capacity (J/kg·K)                       | 460  |
| Coefficient of thermal expansion (/K)        | 10x10⁶ |
| Thermal conductivity at 20 °C (W/m·K)        | 25   |
Two types of granular materials are selected as forming media: zirconia beads with a granule diameter of 0.4 mm and steel balls with diameter of 1 mm (Table 3). The zirconia beads are cerium-stabilized zirconium oxide grinding beads of a high density and hardness that have a much lower coefficient of thermal conductivity and heat capacity compared to steel balls. The steel balls used in the experiments are made of 100Cr6 (EN 1.3505, AISI 521000). Both of these materials have a high microhardness at room temperature. The zirconia beads have a melting point of 2715 °C. They maintain a high microhardness at elevated temperatures. However, the hardness and strength of the steel balls drastically decreases under elevated temperatures. Their maximum operating temperature is 468 °C.

Table 3. Physical properties of granular materials

| Granular material | Particle size (mm) | Hardness | Melting point (°C) |
|-------------------|--------------------|----------|-------------------|
| Zirconia beads    | 0.4-0.6            | >1180 HV | 2715              |
| Steel balls       | 1.0                | 60-66 HRC| 1505              |

2.2. Tensile tests at elevated temperatures

The system for tensile tests at elevated temperatures is built up on a universal testing machine as shown in [6]. Digital image correlation (DIC) is used to measure the stain state during the test. To enable strain measurement during heating, an open heating system (i.e. induction heating) instead of ambiance heating (i.e. furnace heating) is used. DIC is a non-contact method capable of measuring strain distributions and resultant material properties by comparing image recordings of a stochastic speckle pattern on the deforming sample surface [8]. Therefore, the stochastic speckle pattern is of paramount importance for strain measurement. A typical speckle pattern consists of random black speckles on a white background. The challenges of speckle patterns for high temperature DIC measurement are:

1) The spray paint must retain its colour at elevated temperature.
2) The spray paint must adhere to the surface of the specimen and deform simultaneously with the specimen without peeling off or generating cracks.

Therefore, the spray paint must contain ingredients that can withstand high temperatures and offers similar formability as the specimen [9]. In this paper, a VHT™ FlameProof Flat White background coating with VHT™ FlameProof Flat Black speckles are applied on the specimen surface to generate a stochastic speckle pattern. This type of coating consists of amorphous precipitated silica and titanium dioxide, which fulfills the above-mentioned properties [10].

2.3. Granular medium-based tube forming

The experimental procedure is illustrated in Figure 1. The ferritic stainless steel is heated in an oven to an elevated temperature and then transferred into the die cavity. Granular medium is filled into the tube manually. The upper punch moves down to compress the granular medium, which produces internal pressure to form the tube into the die cavity.

![Figure 1](image-url)
The experimental setup to enable granular medium-based tube forming is implemented on a universal press by Schuler Hydrap that has a maximum loading force of 1000 kN. The two half shells of the die are mounted on a die-plate, which is supported by a spring (Figure 2(a)). Thus, although only the movement of the upper punch plate is controlled by the main cylinder of the press, asymmetric loading from both the upper and lower side is realized. The internal forming pressure is generated by the compaction of the filled granular medium.

The ferritic stainless steel tube has an initial thickness of 1.5 mm with an outer diameter of 50 mm. The die cavity is designed with a slightly larger diameter of 52 mm considering the thermal expansion at elevated temperatures (Figure 2(b)). The dimension of the expansion zone is designed to assure the occurrence of fracture when forming at room temperature. Based on [4], the FE model of the granular medium based tube forming process is established and used for tool design. The FLC is derived by Nakajima tests at room temperature. The strain states of the tube material are mainly on the left side of the forming limit diagram (Figure 3(a)). The fracture is forecasted based on the simulation result. The experiment performed under the same process condition also proves the insufficient formability of 1.4509 tube at room temperature (Figure 3(b)).

Figure 2. (a) Experimental setup of granular medium-based tube hot forming; (b) Geometry of tool.

Figure 3. Granular medium-based tube forming at room temperature: (a) simulation result; (b) experimental result.
3. Improved formability at elevated temperature
Owing to the inherent axial feeding, the stain states of the tube material are mainly on the left side of the forming limit diagram (Figure 3). Therefore, the left side of the FLC can sufficiently predict the forming limit of the granular medium-based tube forming process.

To evaluate the formability under different strain state, hot tensile tests with different specimens were conducted under temperatures of 600 °C, 700 °C, 800 °C and 900 °C. Figure 4(a) shows the geometries of the different specimens at pure shear, uniaxial tensile and plane strain. Each hot tensile test begins with inductively heating the specimen to the testing temperature. Tension is applied to the specimen after the specimen temperature has been maintained for 3 min. An example of the strain distribution measured by DIC for the tension-compression strain state specimen with R=10 mm is shown in Figure 4(b). At a major strain of 1.05, the sprayed on paint still adhered to the specimen and is recognizable.

![Figure 4](image)

**Figure 4.** (a) Specimen for hot tensile test; (b) Strain distribution of the notched specimen (R=10mm) at testing temperature of 800 °C

According to the standard ISO 12004-2, the forming limit curves (FLCs) under different testing temperatures are derived (Figure 5(a)). The forming limit curves increase from 600 °C to 700 °C but are still lower than the formability at room temperature. Comparing the forming limit curves to the corresponding fracture forming limit lines (FFLs), it can be seen that the FFLs are close to their respective forming limit curves (FLCs) below a temperature of 700 °C. However, large differences exist between the FFLs and the corresponding FLCs at testing temperature of 800 °C and 900 °C. This indicates that the ferritic stainless steel presents high value of postuniform elongation above 700 °C.

![Figure 5](image)

**Figure 5.** Left side of the forming limit diagram of 1.4509 steel under different temperatures: (a) Forming limit curves (FLC); (b) Fracture limit curves (FFL).
4. Experimental validation

According to Figure 5, the ferritic stainless steel 1.4509 presents much better formability above temperature of 700 °C. To realize a temperature of 700 °C during the forming step, the tube is initially heated to 950 °C. Figure 6 shows the results of the experiment using steel balls as forming medium. The steel balls are at room temperature and filled into the hot tube after it has been transferred into the die cavity. Due to the high conductive heat transfer between steel balls and ferritic stainless steel tube, the tube cools down very fast. The temperature is below 400 °C before the tube has expanded to its final diameter, which results in the occurrence of fracture.

Figure 6. Hot forming of 1.4509 tube using steel balls as forming medium

Zirconia beads are made from a thermal insulation material. However, the substitution of steel balls by zirconia beads as forming medium still leads to fast cooling of the tube (Figure 7). The cooling rate is slower than when using steel balls as forming medium. Nevertheless, the temperature of the tube is again below 400 °C before tube has expanded to its final diameter, which again results in the occurrence of fracture.

Figure 7. Hot forming of 1.4509 tube using zirconia beads as forming medium

To maintain the tube at a higher temperature with the aim of better formability, a feasible solution is to use a preheated granular medium. The maximum operating temperature of steel balls is much lower than the temperature window of 1.4509 with good formability. Therefore, sole zirconia beads are used
in the preheating tests. To save the operation time of filling the tube with granular medium after heating and thereby reducing heat loss, the zirconia beads are filled into the tube before heating the combined package in the furnace. Using this heating strategy, the temperature of the tube is still above 500 °C after forming, as can be seen in Figure 8. With this process solution, the tube was able to be fully expanded without fracture.

Figure 8. Hot forming of 1.4509 tube using the heated zirconia beads as forming medium

5. Conclusion
The relatively low formability of ferritic stainless steel hinders the substitution for austenitic stainless steel in the automotive industry. Granular medium-based tube hot forming of ferritic stainless steel can extend the forming capacity by allowing forming in the temperature range that is optimal for the material. The formability of ferritic stainless steel decreases from room temperature up to 700 °C and drastically increases above 700 °C. When using a non-heated forming medium, the heat transfer from the tube to the forming medium causes the temperature of the ferritic stainless steel tube to decrease beyond the temperature process window, thereby causing premature fracture. To minimize the heat transfer from the steel tube to the forming medium, the granular material was heated together with the steel tube. Using the heated granular medium, the experimental validation reaches expansion ratios that show fracture in specimens formed at room temperature.

6. References
[1] Santacreu, P. O., Cleizergues, O., Simon, C., & Duroux, P. (2004). Design of stainless steel automotive exhaust manifolds. Revue de Métallurgie, 101(7-8), 615-620.
[2] Alenka Kosmač, (2012). Stainless steels at high temperatures. Materials and Applications Series, V18
[3] Manninen, T., & Säynäjäkangas, J. (2012). Mechanical Properties of Ferritic Stainless Steels at Elevated Temperature. In Proceedings of the Fourth International Experts Seminar on Stainless Steel in Structures
[4] Bong, H. J., Barlat, F., Ahn, D. C., Kim, H. Y., & Lee, M. G. (2013). Formability of austenitic and ferritic stainless steels at warm forming temperature. International Journal of Mechanical Sciences, 75, 94-109.
[5] Bong, H. J., Barlat, F., Lee, M. G., & Ahn, D. C. (2012). The forming limit diagram of ferritic stainless steel sheets: Experiments and modeling. International Journal of Mechanical Sciences, 64(1), 1-10.
[6] Chen, H., Güner, A., Khalifa, N. B., & Tekkaya, A. E. (2016). Granular media-based tube press hardening. Journal of Materials Processing Technology, 228, 145-159.

[7] Chen, H., Hess, S., Haeberle, J., Pitikaris, S., Born, P., Güner, A., ... & Tekkaya, A. E. (2016). Enhanced granular medium-based tube and hollow profile press hardening. CIRP Annals-Manufacturing Technology, 65(1), 273-276.

[8] Qu, Z., Fang, X., Hou, G., Su, H., Feng, X., Li, H., ... & Fukuta, Y. (2016). Ceramic-Based Speckles and Enhanced Feature-Detecting Algorithm for Deformation Measurement at High Temperature. Experimental Mechanics, 1-10.

[9] Guo, X., Liang, J., Tang, Z., Cao, B., & Yu, M. (2014). High-temperature digital image correlation method for full-field deformation measurement captured with filters at 2600 C using spraying to form speckle patterns. Optical Engineering, 53(6), 063101-063101.

[10] Chen, X., Xu, N., Yang, L., & Xiang, D. (2012). High temperature displacement and strain measurement using a monochromatic light illuminated stereo digital image correlation system. Measurement Science and Technology, 23(12), 125603.

7. Acknowledgments
The authors thank the Research Center of Industrial Metal Processing (ReCIMP) for financially supporting the performed research.