Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 1021-1029
doi:10.4028/p-mqac87

Submitted: 2021-12-08
Revised: 2022-01-16
Accepted: 2022-02-04
Online: 2022-07-22

Experimental Investigation of Factors Influencing the Determination of the Onset of Yielding by Temperature Measurement

Simon Vitzthum[1,a*], Maximilian Gruber[1,b], Joana Rebelo-Kornmeier[2,c], Michael Hofmann[2,d], Wolfram Volk[1,e]

[1*]Chair of Metal Forming and Casting, Technical University of Munich, 85748 Garching, Germany

[2]Heinz Maier-Leibnitz Zentrum (MLZ), Technical University of Munich, Garching, Germany

[a*]simon.vitzthum@tum.de, [b]max.gruber@tum.de, [c]joana.kornmeier@frm2.tum.de, [d]michael.hofmann@frm2.tum.de, [e]wolfram.volk@tum.de

Keywords: thermoelastic effect, elastic behavior, onset of yielding, heat flow, cyclic tensile test

Abstract. The cooling of the material during elastic tensile loading is well known as the thermoelastic effect. It is already known that the temperature minimum at the elastic-plastic transition can be used for the determination of the onset of yielding. Conceivable parameters for this have already been presented and investigated. Within this study factors influencing the specimen temperature during tensile loading and unloading are experimentally analyzed to improve the determination approach and the understanding of it. Furthermore, the robustness and repeatability of the measurement and evaluation procedures are analyzed. Therefore, cyclic tensile tests with the mild steel DC06 and the high strength steel CR590Y980T (DP1000) are performed with four PT1000 sensors applied on the specimen. The temperature behavior during elastic loading, elastic-plastic elongation and elastic unloading is separately evaluated. Different strain rates are investigated to better understand the strain-dependent heat development and its influence on the temperature-dependent evaluation. In this way, correlations between strain rate and thermal conduction due to prevailing temperature differences are found and their influence on the temperature-based determination of the onset of yielding is analyzed. Therefore, the yield stress at temperature minimum YS_{Tmin} as well as an additional yield stress at zero plastic strain YS_0 are evaluated for all experiment settings. In a comprehensive experimental study, the standard deviations are compared and thus conclusions can be drawn about the robustness of the determination methods.

Introduction

Accurate modeling of elastic material behavior is becoming increasingly important as more and more high-strength materials are used in production [1]. The state of the onset of yielding represents the upper limit of elastic deformation and thus the beginning of plastic deformation. Since it is not straightforward to determine this point exactly, especially for mild steels with no pronounced yield stress and a continuous elastic-plastic transition, it is common to use an equivalent yield point, like the yield stress at 0.2 % plastic strain [2]. However, it has also been known for a long time that the temperature behavior during elastic and plastic deformation differs and that this behavior, known as thermoelastic effect [3], can be used to describe the onset of yielding [4]. This goes back to the results of Weber [5], Joule and Thomson [6], who showed a dependency between the temperature and the volume for gases, which is also valid for solid materials [7]. During elastic deformation, a volume change occurs due to Poisson's ratio [8], which leads to a measurable temperature change [9]. With the heat dissipation during plastic deformation [10,11], a temperature minimum can be detected in case of tensile loading, which is equivalent to an increase in volume. There are already many studies that deal with the subject of this temperature minimum and a summary of these can be found in [12]. The big challenge is the accuracy of the measurement, because in metallic materials there is only a very small temperature decrease before the temperature starts to rise again due to plastic deformation [13]. Mainly optical temperature measurement by means of infrared and thermistors [14,15], but also thermocouples [16] were used for measurement. There are results for a variety of materials including aluminum [17], stainless steel [18,19] and low carbon steel [20]. The effect has been demonstrated

for the materials, but a comprehensive study of the effect and its potential for material characterization is still missing. The extent to which the temperature behavior really reflects the material behavior must be investigated in detail in order to exclude the possibility that external factors such as the measurement technique or the laboratory conditions influence the result.

In [21] a clip-on device was presented, which uses a PT1000 sensor to measure the specimen temperature during cyclic tensile tests with high precision. Furthermore, an additional yield stress parameter is determined by using a temperature-dependent evaluation method. Within the present paper the robustness and reproducibility of the introduced parameters yield stress at temperature minimum YS_{Tmin} and yield stress at zero plastic strain YS_0 are investigated. Cyclic tensile tests with four PT1000 sensors at different positions on the specimen are performed to investigate the influence of the positioning of the sensors on the determination results for both materials. In this way, however, the influence of conduction is also verified. Finally, the temperature behavior is shown and compared for the two considered materials and standard deviations for several strain rates are given to get a feeling for the reproducibility of the parameters and their evaluation.

Experimental Setup and Execution

The universal test machine ZwickRoell Z150 Allround Line with a maximum load of 150 kN is used for the cyclic tensile tests. For cyclic tests, it is particularly important that the specimen grips have little clearance. Otherwise, inaccuracies will occur during loading and unloading. That is why special screw grips were developed, which clamp the specimen horizontally. Laser speckle pattern is tracked by the ZwickRoell LaserXtens to optically measure the strain with an accuracy of 0.07 µm, which is in the range of accuracy class 0.5 according to the standard [22]. Figure 1 (a) shows the experimental setup. The gauge length is set to 50 mm and the dog bone specimen geometry was chosen according to the standard form H with a parallel length of 75 mm and a width of 12.5 mm [23]. The thickness of both materials is 1.5 mm. For the temperature measurement, PT1000 sensors class B are clipped on the specimen with a common clip and are connected with HBM QuantumX amplifier. The load and strain signal is also read directly into the QuantumX, so that timing errors due to poorly synchronized triggers can be excluded. All signals are recorded with a frequency of 0.01 s^{-1}, which is important for the precise evaluation of the temperature gradient curve afterwards. For the investigations within this study no absolute temperature values are necessary. Because of this and for a better comparison of the particular temperature signals, all temperature signals are zeroed at the start of every test. Hence, all temperatures shown in this study are relative temperatures and start at 0 K.

Both steel materials used are typical steel grades for vehicle car bodies. The mild steel DC06 is a classical deep drawing steel and is characterized by its high formability. The material behaves homogeneously and shows hardly any scattering. Different behavior shows the dual-phase steel DP1000, which is commonly used for crash relevant parts in the car body [24]. The formability is significantly lower than for the DC06. The main mechanical material properties are summarized in Table 1. In the following experiments, loading and unloading cycles are done every 3 % engineering strain up to 15 % for DC06 and every 1.5 % up to 6 % for DP1000.

Table 1: Main mechanical properties of the considered materials.

Material	Yield strength ($R_{0.2\%}$)	Tensile strength (R_m)	Uniform elongation (A_g)
DC06	144 MPa	274 MPa	28 %
DP1000 (CR590Y980T)	698 MPa	1047 MPa	8 %

In a first series of tests, the measuring accuracy of the measuring system is investigated. For this purpose, all four sensors are applied as close to each other as possible in the center of the sample (Figure 1 (b)). The accuracy of the measurement system can be investigated in this way, as the curves and results should not differ from each other. To investigate the temperature behavior in the specimen and the influence of the positioning of the sensors respectively, the PT1000 sensors are applied 15 mm above the center (sensor T1), at the center (sensor T2), 15 mm below the center (sensor T3) and

35 mm below the center (sensor T4) (see Figure 1 (c)). This distribution of the sensors allows studying the symmetry of the temperature through the specimen by comparing T1 with T3 and the influence of thermal conduction by comparing the temperature signal close to the voluminous clamping grips T4 and the temperature in the center T2.

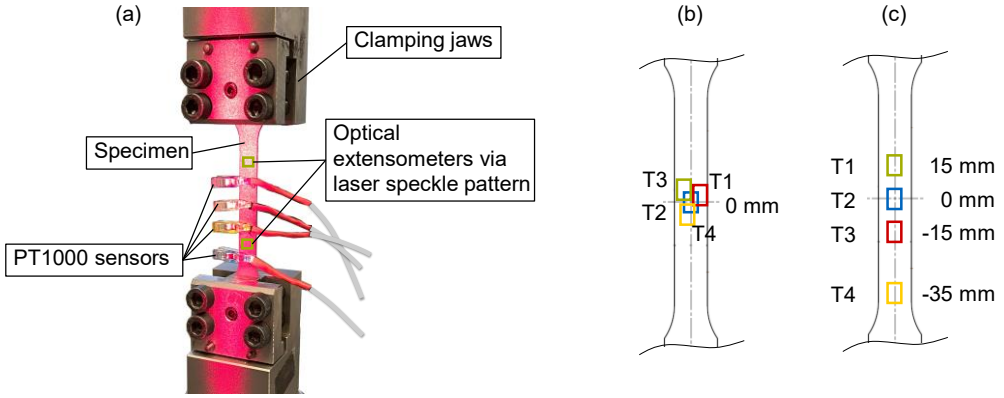

Figure 1. (a) Experimental setup for cyclic tensile tests; (b) PT1000 setup for measurement validation test; (c) general test setup;

Results

General temperature behavior and its influence on the thermoelastic effect. Figure 2 shows the result for the measurement validation test (see setting Figure 1 (b)) for the material DC06. It can be seen that the temperature signals of the four sensors differ only slightly from each other across the test. The highest temperature deviation in the last loading cycle shown is 0.2 K. The temperature minima, respectively the YS_{Tmin} of the four temperature curves were evaluated and compared. The standard deviation found is 0.9 MPa. Hence, the accuracy of the measurement system is less than 1 MPa on the determination of YS_{Tmin}.

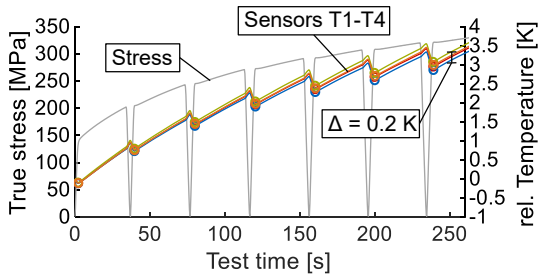

Figure 2. True stress versus time curve (strain rate 0.001 s^{-1}) and corrensponding temperature signals (T1 – T4) for validation test setting (see Figure 3) for DC06.

Figure 3 shows the corresponding temperature curves of the four PT1000 sensors to the true stress-time curves for (a) DC06 and (b) DP1000. The differences between the materials can be seen clearly. When looking at the stress curve, one can see that the high strength steel DP1000 shows a large elastic range in comparison to the DC06. As a result, the specimen temperature decreases further than with DC06 before it reaches the minimum due to the onset of plastic yielding. The temperature drops 0.5 K for DP1000 and 0.1 K for DC06 until it increases again. Further differences become apparent when comparing the temperature curves of the materials. Since the volume increase during elastic loading leads to a cooling, the volume decrease during elastic unloading leads to a warming. Both materials show this behavior. But for the dual phase steel DP1000 the temperature increase during elastic-plastic deformation is significantly higher than the increase caused by elastic unloading. For DC06 it is the other way around. Furthermore, one can see that the slope of the temperature increase during elastic unloading decreases with increasing plastic strain. Thermal convection can be an explanation for it, because the temperature difference between the laboratory temperature (constant at 20°C) and the specimen temperature is getting higher. Interesting is the comparison of the four PT1000 sensors applied at 15 mm, at the center, at -15 mm and -35 mm. It is expected that the voluminous metal specimen grips in direct contact with the specimen, will cool the specimen via thermal conduction. This behavior is shown for both materials. The temperature sensor T4, which is close to the grips and with -35 mm to the center even outside of the gauge length of 50 mm, is significantly lower than the sensors T1-T3.

For DC06 it increases up to 1 K whereas the temperature of the other three sensors in the middle and close to the middle of the specimen increase up to around 3 K. A relatively similar difference can be seen in the DP1000. With the reasoning of the thermal conduction for this effect, the temperature of the sensor T2 should be highest in the center. And this is exactly the case for both materials. Sensors T1 and T3 are symmetrically arranged and show comparable temperature behavior, so that a symmetrical temperature behavior towards the specimen grips can be assumed.

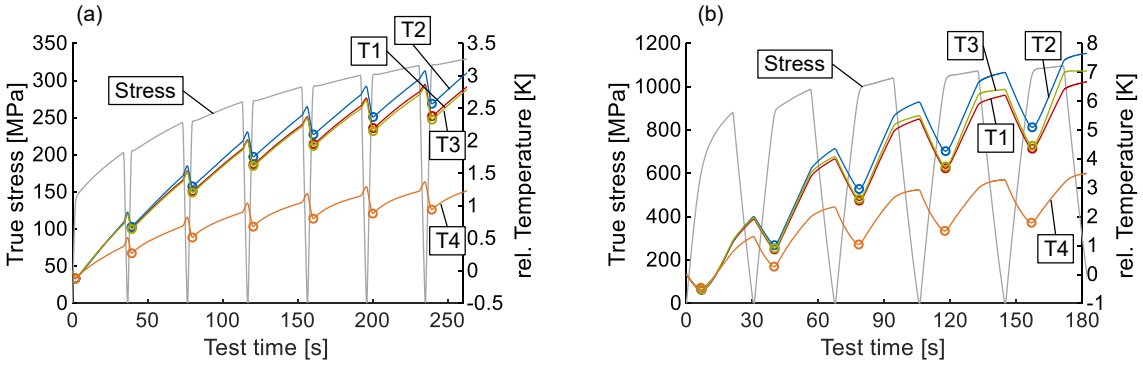

Figure 3. True stress versus time and temperature versus time curve for a cyclic tensile test (strain rate 0.001 s^{-1}) for (a) DC06 and (b) DP1000.

Now the question arises whether this has an influence on the temperature minimum and thus on the yield stress value YS_{Tmin}. To investigate this, the respective true stress values at temperature minimum (YS_{Tmin}) of the four sensors were evaluated and compared. The difference to the YS_{Tmin} of the sensor T2 in the middle was determined and the standard deviation in MPa was calculated over all cycles for the strain rates 0.004 s^{-1}, 0.001 s^{-1} and 0.0004 s^{-1}. In this way, it can be shown that the different temperature development in the specimen has no influence on the parameter YS_{Tmin} and that this is therefore linked with the yielding behavior, since homogeneous yielding can be assumed in the parallel specimen length. Table 2 shows the results for this investigation. The highest standard deviation 7.34 MPa can be seen for the strain rate 0.0004 s^{-1}, the sensors T2 and T4 and the material DP1000. However, compared to the tensile strength, this is also only 0.7 % and since this sensor is outside the gauge length, it would not be valid to use this value. But it shows how stable the determination of YS_{Tmin} is. The remaining deviations are below 5 MPa and for the material DC06 significantly lower with below 2 MPa. Thus, no real influence of the different temperature behavior on the parameter YS_{Tmin} can be detected. It is also robust for different strain rates, which can be seen in Table 2.

Table 2. Standard deviation of the difference in YS_{Tmin} determined by the sensors T1, T3 and T4 relative to T2 over all loading and unloading cycles for three different strain rates.

YS_{Tmin}	Strain rate [1/s]	T2 ↔ T1 std* [MPa]	T2 ↔ T3 std* [MPa]	T2 ↔ T4 std* [MPa]
DP1000	0.0004	1.31	1.08	7.34
	0.001	3.21	0.96	2.11
	0.004	4.60	2.22	1.58
DC06	0.0004	1.13	0.98	1.64
	0.001	0.21	0.35	0.72
	0.004	1.19	0.13	0.78

* Standard deviation over all cycles

Robustness and reproducibility of the parameters YS_0 and YS_{Tmin}. In [21], based on an assumption, an evaluation method was presented that allows the determination of another elasticity parameter. It is assumed that at the point of time of the temperature minimum, the temperature increase caused by plastic deformation is in balance with the decrease caused by elastic loading. Hence, there is already plastic deformation. With this background, it was assumed that the start of

yielding occurs at the time when the temperature curve leaves its approximate linearity. This point of time can be determined with a time-dependent line fit method, based on the findings in [25]. The newly found parameter is called yield stress at zero plastic strain YS_0. The temperature gradient is used for the determination of YS_0. Consequently, high demands are made on the quality of the temperature signal in order to be able to work sensibly with the first derivative. In [21], YS_0 was evaluated for several materials and the functionality could be shown. In this paper, the applicability of the method at different strain rates is shown and their standard deviations are given to further qualify the method. From now on, just the sensor T2 in the middle of the specimen is evaluated. Figure 4 shows the true stress versus time curve and the corresponding temperature gradient curve for the intial loading and the first unloading loading cycle for both materials. Furthermore, the curves for three different strain rates are shown for DP1000. Comparing the DC06 with the DP1000 with the same strain rate 0.001 s^{-1} (Figure 3 (a) and (c)), one can see that the temperature gradient differs for the two materials. Due to the lower yield strength, the DC06 quickly changes to elastic-plastic deformation (range between YS_{Tmin} and first unloading). During this, the temperature linearly increases, which can be seen by the horizontal gradient curve. During unloading and loading it comes to a change in slope, which is clearly visible. The elastic range of the DP1000 is known to be larger. Furthermore, the elastic-plastic transition is soft and during the first elastic-plastic deformation the stress is still increasing a lot, which probably results from the interaction of the ferritic and high strength martensitic phase. This leads to a more soft change in the temperature gradient curve. During unloading and loading, the slope again changes significantly until it finally turns into a horizontal in the elastic-plastic range. The parameter YS_0 represents the point of time of the change in slope and is determined with a vertical and horizontal fit, introduced in [21]. To analyze the applicability, but also the robustness and reproducibility of the parameter, this evaluation method was applied for the strain rates 0.0004 s^{-1}, 0.001 s^{-1} and 0.004 s^{-1} for both materials. Figure 3 (b)-(d) shows the temperature gradient curves for DP1000 for the three strain rates. It can be stated in advance that the method can be reasonably applied to all strain rates, so the parameter can be uniquely determined. The fact that the gradient curve becomes thinner with increasing strain rate, i.e. has fewer data points, is due to the constant measurement frequency of 100 Hz. This shows no effect on the evaluation method. In the stress-time curve, as well as in the gradient-time curve for the strain rate 0.004 s^{-1}, the deceleration and acceleration of the tensile machine can be seen in the changes of directions. However, the evaluation range for YS_0 is not affected, so that this also has no influence on the parameter. It is also worth noting that the evaluation is unambiguously possible at all strain rates, although the absolute values differ by a factor of 10. Thus, the gradient curve at 0.004 s^{-1} is in the range between ± 0.075 Ks^{-1} and at 0.004 s^{-1} between 0.75 Ks^{-1}. This shows again the high signal resolution and accuracy, which is achieved with the present experimental setup.

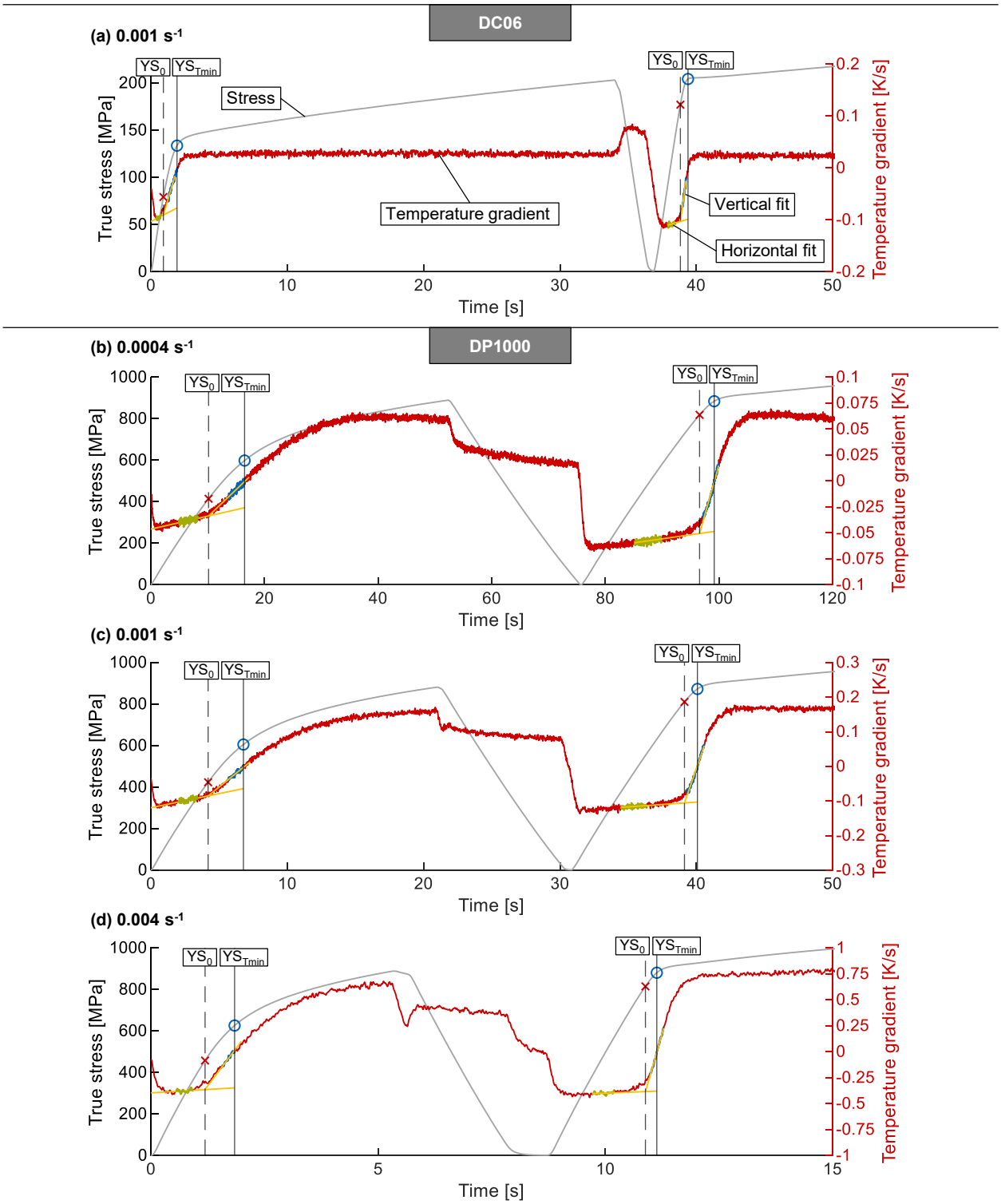

Figure 4. True stress versus time curve in comparison with the corresponding temperature gradient versus time curve for the materials (a) DC06 and (b-d) DP1000. Shown is the initial loading and the first unloading loading cycle. For DP1000 three different strain rates are shown (b-d).

Figure 5 shows the true stress true strain curves of three experiments for both materials. It can be seen that the stress strain curves of the DC06 (a) almost show no deviation. The DP1000 shows an increasing deviation with increasing strain. Looking at the parameter YS_{Tmin} small deviations can be seen, which shows the high reproducibility of the temperature minimum. The deviations for YS_0 are slightly higher. It must be said here that an evaluation method always involves a certain degree of inaccuracy.

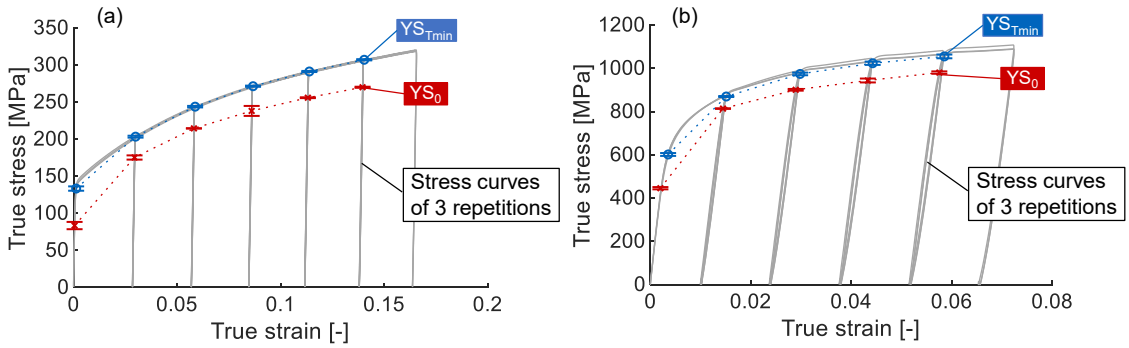

Figure 5. True stress vs. true strain curves (strain rate 0.001 s^{-1}) of three repetitions and the parameters YS_{Tmin} and YS_0 with standard deviation from temperature T2 for (a) DC06 and (b) DP1000.

The standard deviations of three repetitions were evaluated for three strain rates and are shown in Figure 6. The homogenous material DC06 (a) shows almost no deviation for the temperature minimum and hence, the YS_{Tmin}. The highest deviation of around 4 MPa is at the lowest strain rate for the initial loading. Relative to the yield stress the deviation is around 3 %. The YS_0 shows higher deviations up to 6 MPa. It must be clearly stated here that due to the additional evaluation a larger deviation occurs than with the temperature minimum, for which no evaluation is necessary. For the DP1000 (b) the overall deviation for the YS_{Tmin} and the YS_0 is at around 6 MPa, which is relative to its initial yield stress less than 1 %. There are no recognizable tendencies depending on the strain rate. The higher deviation of the stress strain curves for the DP1000 explain the higher deviations for YS_{Tmin}. The material is not as homogeneous as the DC06.

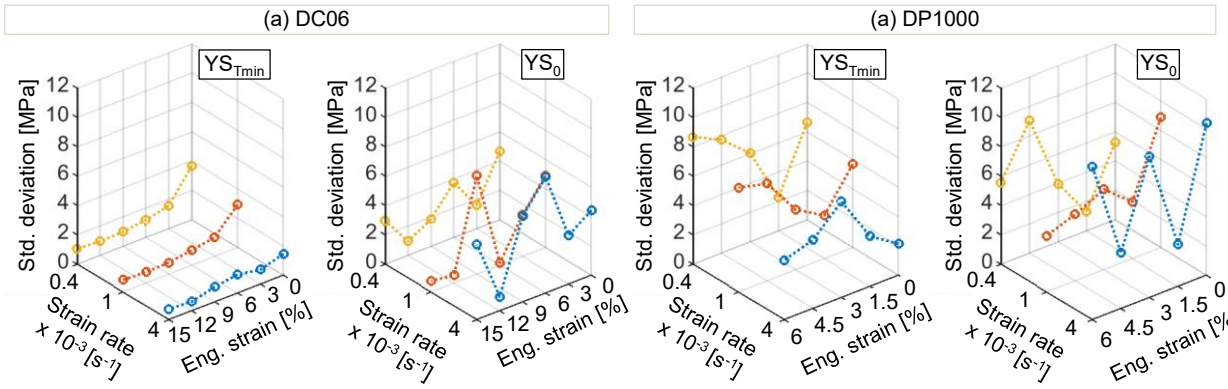

Figure 6. Standard deviations of three repetitions for three different strain rates and the two elasticity parameters YS_{Tmin} and YS_0 for the materials (a) DC06 and (b) DP1000.

Conclusion

On basis of the experimental results of this study, the following conclusions can be summarized:

- An experimental and measurement setup was further improved. It allows highly accurate and repeatable measurement of the specimen temperature. By bypassing triggers to synchronize the data, a valid measurement of the thermoelastic effect is possible even for different strain rates and materials.
- The temperature development in the specimen differs dependent on the position on the specimen. Thermal conduction lead to less temperature increase close to the clamping grips and the highest temperature increase in the middle of the specimen. The positioning on the specimen showed no influence on the YS_{Tmin}. This confirms the correlation of the parameter with the onset of yielding and shows its robustness.
- The applicability and accuracy of the published evaluation method for the additional elasticity parameter YS_0 was further investigated. Despite different behavior of the temperature gradient

for the materials considered, a meaningful evaluation was possible. In addition, it was shown that the method is also applicable for different strain rates. It must be said that the use of an evaluation method always involves a certain user-dependency, which is a clear disadvantage compared to the YS_{Tmin}. But the additional elasticity parameter has great potential for future material models. Efforts continue to improve the evaluation method.

In general, the measurement of the specimen temperature during the tensile test provides valuable additional information related to the mechanical material behavior. It has been shown that with adequate measurement technology, high accuracies and reproducibilities can be achieved. In times of increasingly intelligent material models, such additional material information is very valuable. Based on the results of this paper, a microscopic examination of the assumptions made about YS_0 and YS_{Tmin} is reasonable. Furthermore, these parameters have to be transferred in a suitable way into material models for the FE simulation and their influence has to be investigated numerically. The use of the YS_{Tmin} parameter is particularly suitable for industrial applications, such as incoming material inspection. The sensor is cost-effective and its use is associated with little additional effort. The possibility of directly measuring a parameter for the onset of yielding makes the evaluation less error-prone.

Acknowledgments

The Authors would like to thank the German Research Foundation (DFG) for the financial support under the grant numbers 429432653. Furthermore, the authors thank the company ZwickRoell for their support.

References

[1] K. Roll, T. Lemke, K. Wiegand, American Institute of Physics (2005).
[2] C.E. Bottani, G. Caglioti, Materials Letters 1 (1982) 119–121.
[3] J.M. Dulieu-Barton, Strain 35 (1999) 35–39.
[4] G. Sallat, Theoretische und experimentelle Untersuchungen zum Fliessverhalten von Blechen im Zweiachsigen. Dissertation, Chemnitz, 1988.
[5] W. Weber, Ann. Phys. Chem. 96 (1830) 177–213.
[6] J.P. Joule, W. Thomson, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 4 (1852) 481–492.
[7] W. Thomson, Trans. R. Soc. Edinb. 20 (1853) 261–288.
[8] E. Doege, B.-A. Behrens, Handbuch Umformtechnik: Grundlagen, Technologien, Maschinen, 2nd ed., Springer-Verlag, s.l., 2010.
[9] K.T. Compton, D.B. Webster., Phys. Rev. 5 (1915) 159–166.
[10] A.K. Wong, G.C. Kirby, Engineering Fracture Mechanics 37 (1990) 493–504.
[11] K.N. Pandey, S. Chand, International Journal of Pressure Vessels and Piping 80 (2003) 673–687.
[12] W.N. Sharpe, Springer handbook of experimental solid mechanics, Springer, New York, 2008.
[13] H.-T. Lee, J.-C. Chen, J Mater Sci 26 (1991) 5685–5692.
[14] M.H. Belgen, ISA Trans 6 (1967) 49–53.
[15] Z. Chen, U. Gandhi, J. Lee, R.H. Wagoner, J. Mat. Proc. Techn. 227 (2016) 227–243.
[16] D. Jocham, S. Vitzthum, T. Susumu, W. Annika, V. Wolfram, 9th Forming Technology Forum (2016).
[17] W. Oliferuk, M. Maj, R. Litwinko, L. Urbański, European Journal of Mechanics - A/Solids 35 (2012) 111–118.
[18] R.V. Prakash, T. Pravin, T. Kathirvel, K. Balasubramaniam, Theoretical and Applied Fracture Mechanics 56 (2011) 1–6.

[19] C. Chandraprakash, C.V. Krishnamurthy, K. Balasubramaniam, Trans Indian Inst Met 72 (2019) 2905–2915.
[20] I. Jandrlić, S. Rešković, F. Vodopivec, P. Lava, Met. Mater. Int. 22 (2016) 407–412.
[21] S. Vitzthum, C. Hartmann, M. Eder, W. Volk, Procedia Manufacturing 29 (2019) 490–497.
[22] Deutsches Institut für Normung e.V., Metallic materials - Calibration of extensometer systems used in uniaxial testing: German version EN ISO 9513:2012, 2013.
[23] Deutsches Institut für Normung e.V., Prüfung metallischer Werkstoffe - Zugproben, 50125th ed., Berlin, Beuth Verlag GmbH, 2009.
[24] kloeckner metals, DP Steel: Why is Dual Phase Steel Important to Autos? www.kloecknermetals.com/blog/dp-steel-why-is-dual-phase-steel-important-to-autos/.
[25] W. Volk, P. Hora, Int J Mater Form 4 (2011) 339–346.