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Formability Improvements of DP 1180 Subjected to Continuous-Bending-Under-Tension

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Abstract. There continues to be a desire to incorporate advanced high strength steels (AHSS) into automotive and other applications in order to reduce the overall weight of the final product. However, these materials exhibit limited ductility prior to fracture and require high forming forces. One means to address these concerns, at least in a laboratory setting, is by subjecting the material to continuous-bending-under-tension (CBT). In this procedure, a set of three rollers reciprocate over the gauge length of the specimen while the material is continuously pulled in tension. The adjustable parameters during CBT testing are the roller depth, the crosshead velocity (which applies the continuous, tensile force to the specimen), and the carriage speed for the reciprocating rollers (which is typically set to the highest value possible while maintaining a safe process). The formability improvements obtained through CBT processing are decreased applied force and increased elongation to fracture. The latter is achieved by assuring that during the CBT process the entire gauge length elongates to the maximum possible value before fracture occurs. Past research has shown that the concentrated deformation in the fracture location of a tensile specimen is similar to the deformation over the entire gauge length of a CBT processed specimen. In this paper, a parameter space study of the DP 1180 AHSS is conducted in order to determine the optimal roller depth and crosshead velocity to achieve the maximum formability improvements for this material. The results demonstrate a promising means to improve displacement (approximately four times over that in simple tension) prior to fracture for this AHSS when subjected to CBT processing.

1. Introduction

Federal regulations on vehicle fuel economy stipulate that the current 39.6 mpg CAFE (Corporate Average Fuel Economy) standard will be increased to 46.1 mpg by 2021 and to as high as 55.3 mpg by 2025 [1]. In addition to switching to smaller vehicles, one means to achieve these stringent demands is by significantly reducing the mass of the vehicle body, which accounts for 2/3 of the total weight. Simultaneously, customers demand lower cost and increased comfort and safety for their vehicles. To achieve these lighter, higher performing and more crashworthy structures, new advanced high strength steels (AHSS) such as DP 1180 and Aluminum alloys such as AA6022 are incorporated in designs. However, all of these advanced alloys suffer from limited ductility (often less than 10-15%, [2-6] during sheet metal forming operations. This fuels the research on innovative forming processes such as continuousbending-under-tension (CBT), which achieves strain levels well above those generally observed in conventional forming.

During CBT processing, the material in the gauge length of the specimen is continuously bent and unbent by three rollers. See schematic in Figure 1. This allows the workpiece to be deformed with a lower tensile force as the deformation is primarily achieved through the bending process. Localization of the deformation is prevented through CBT processing, thus elongations significantly beyond what can be achieved during standard uniaxial tension testing are achieved. For example, the percent elongation at fracture for an AISI 1006 steel increased from 22% to 290% [7].



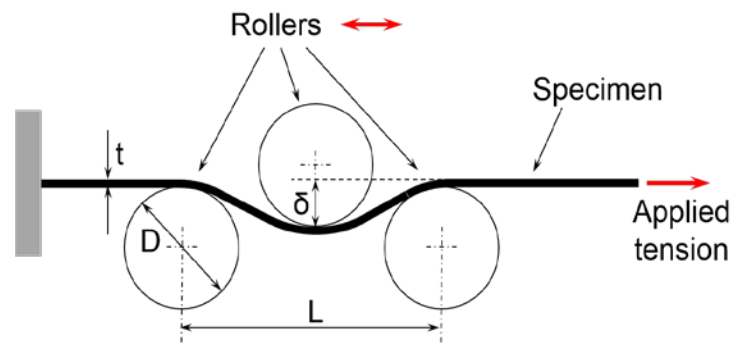


Figure 1. Schematic of the continuous-bending-under-tension (CBT) process and definition of key process parameters.

There are other sheet metal forming processes that produce local deformation, similar to the 3-point bending effects in CBT. For example, in spin forming, a stationary tool contacts a spinning blank to create an axisymmetric component [8-10]. Alternatively, in incremental sheet forming (ISF) a hemispherical tool locally deforms the sheet. In both processes, only a small portion of the sheet is plastically deformed at each instant. Similar to the CBT process, the strains achieved during ISF are well above what is possible in standard sheet forming. One of the hypotheses behind this enhanced necking limit [11-14] is the CBT effect as described in this paper.

In this paper, CBT processing of DP 1180 is investigated through a parametric study. First the material is characterized through uniaxial tension tests, including assessing the anisotropy of the material by performing tests at different angles with respect to the rolling direction. Furthermore, the rate sensitivity of the material is assessed through jump tests. Next, the parameter space for CBT processing is evaluated by varying the normalized bending depth and crosshead velocity, the two main parameters in CBT processing. Results show that the optimum values for these parameters based on the tests conducted are 3.5 and 1.35 mm/s respectively. As is evident from the results, CBT processing is an effective means to increase the elongation to fracture of this less ductile material by approximately 410%.

2. Material Characterization

Due to interests in DP 1180 for automotive applications and the limited ductility of this AHSS, this material is the focus of CBT investigations in this paper. Standard uniaxial tension test specimens, ASTM E8, were produced from 1 mm thick DP 1180 with respect to 0° (rolling direction, RD), 45°, and 90° (transverse direction, TD) to the rolling direction of the sheet material. Figure 2 shows the uniaxial tension test results for both engineering and true stress-strain data. As is evident, the material shows only a small amount of anisotropy in the plane of the sheet. See Table 1 for material parameters determined from these tests. As is evident, the material exhibits high strength, high stiffness, and almost isotropic (unity R-ratio) material behavior, in particular for the 45° and 90° orientations. Uniform ductility of the material is rather small with engineering strain values < 9% at fracture.

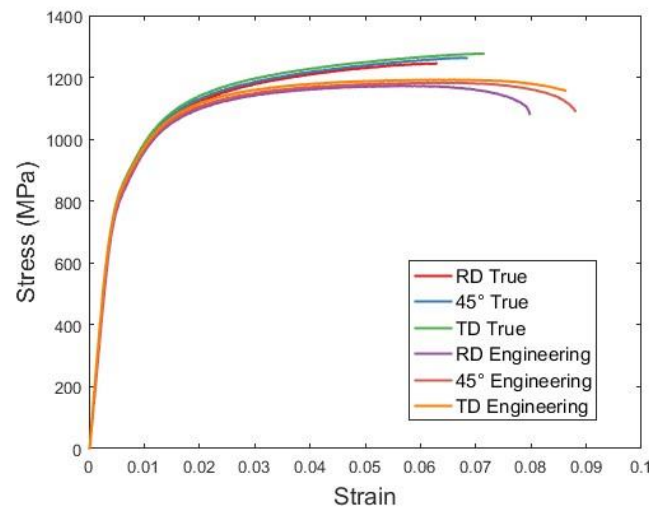


Figure 2. Engineering and true stress- strain curves of DP 1180 along the rolling direction (RD), 45° and transverse direction (TD).

Table 1. Material parameters obtained from uniaxial tension tests [15].

Material Parameter	RD	45°	TD	
Young's Modulus (GPa)	203.4	205.3	214.2	
	840.3	853.8	851.7	Yield Stress (MPa)
	1173.4	1182.9	1192.8	UTS (MPa)
R-ratio	0.84	0.97	0.95	

Due to speed of the material deformation during CBT processing, the strain-rate sensitivity of the material is essential to assess. Thus jump tests, i.e., uniaxial tension tests where the strain-rate was varied when loading the specimen, were conducted [4]. Four strain-rates, 0.0001, 0.001, 0.005, and 0.01 /s, were used. Figure 3 shows the results from a test. Based on the data obtained, the strain-rate sensitivity of the material can be calculated from:

$$m = \frac{\ln \frac{\sigma_2}{\sigma_1}}{\ln \frac{\dot{\epsilon}_2}{\dot{\epsilon}_1}} \quad (1)$$

where 1 and 2 represent stress and strain values before and after, respectively, the strain-rate jump in the test.

The strain-rate sensitivities that were calculated from this test are 0.0082, 0.0055, and 0.008 respectively with the jumps progressing from the lowest to the highest strain-rate. Thus, the DP 1180 used in this research is not considered to be overly strain-rate sensitive. Therefore, the adjustable process parameters such as the crosshead velocity and the carriage speed influencing the rate of deformation are not expected to appreciably influence the recorded load levels during CBT testing.

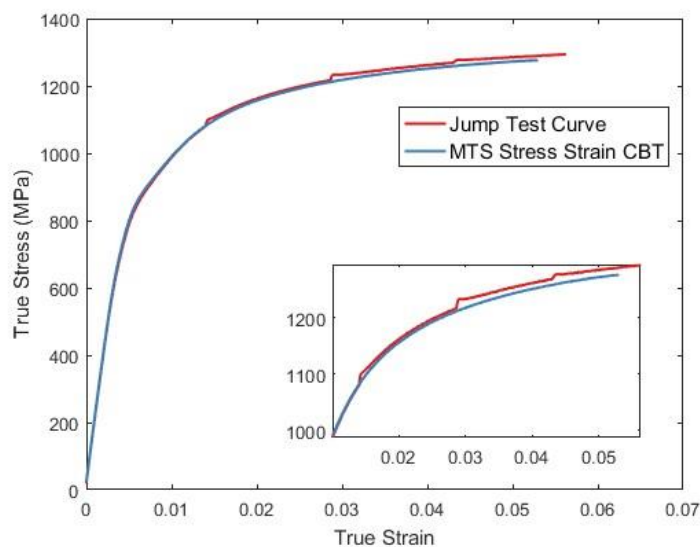
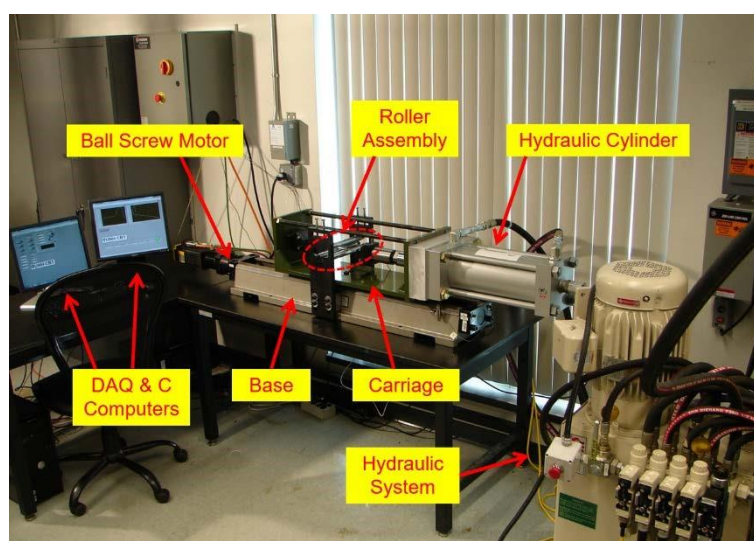


Figure 3. Monotonic true stress-true strain curve along RD for standard tensile test under 0.001 /s strain rate and strain-rate sensitivity test with jumps in strain rate from 0.0001 to 0.001, from 0.001 to 0.005, and from 0.005 to 0.01 /s for DP 1180.

3. Experimental Set-up

The custom experimental apparatus that was created at UNH to conduct CBT research is shown in Figure 4. Advantages to this CBT device over previous ones in the literature [7, 16] is that: 1) the deformation zone is stationary, 2) Digital Image Correlation (DIC) can be used to assess the deformation, and 3) wide sheets, as opposed to simply strips, can be CBT processed. Figure 5 shows a schematic of the CBT specimen with different deformation regions identified. These correspond to how many bending cycles the material in the region undergoes with each CBT cycle. Near the grips, the material only experiences one bend per cycle, while the material in the center of the specimen is bent and unbent three times through the three rollers used in the CBT process. The total gauge length of the specimen is 200 mm.

a)



b)

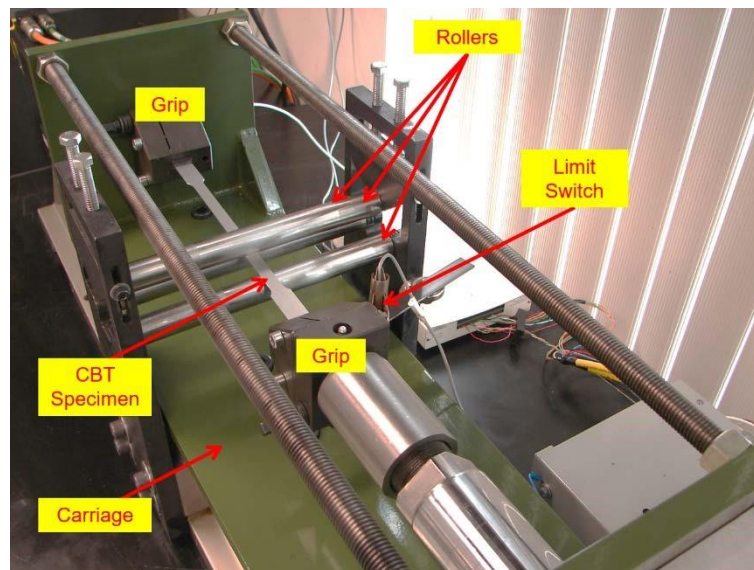


Figure 4. Photographs of the CBT apparatus at UNH: a) overview and b) close-up. Main components are identified.

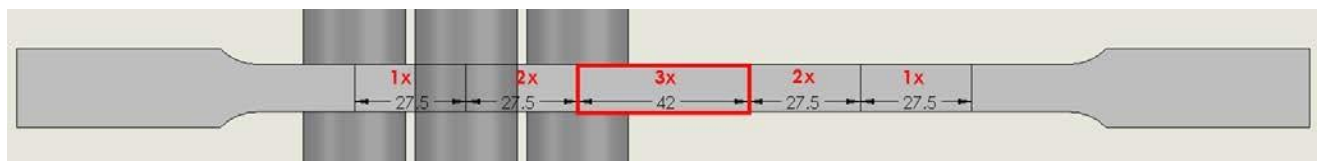


Figure 5. Dimensioned schematic of the CBT specimen, identifying the different deformation regions (units in mm).

4. Experimental Results

Figure 6 shows the force-displacement results recorded during CBT testing along the RD as a function of normalized bend depths to thickness (1 mm), δ/t . Results from a uniaxial tension test is also shown for comparison. As is evident, CBT processing allows significantly more displacement prior to fracture, again due to preventing the localization of deformation from concentrating in a single location as is the case in uniaxial tension tests. Also, evident in Figure 6 is the fact that the normalized bending depth has the effect of lowering the required force to deform the specimen for a specified crosshead velocity (i.e., 1.35 mm/s for results shown in Figure 6). There exists an optimal bending depth where the material is not under- or over-bent, and thus, more displacement is possible. If under-bent, the material is subjected to primarily uniaxial tension and thus fracture occurs at a lower displacement. If over-bent, additional bending strains are induced causing lower displacement values. For this material and other CBT processing parameters, the optimal normalized bending depth is observed to be 3.5.

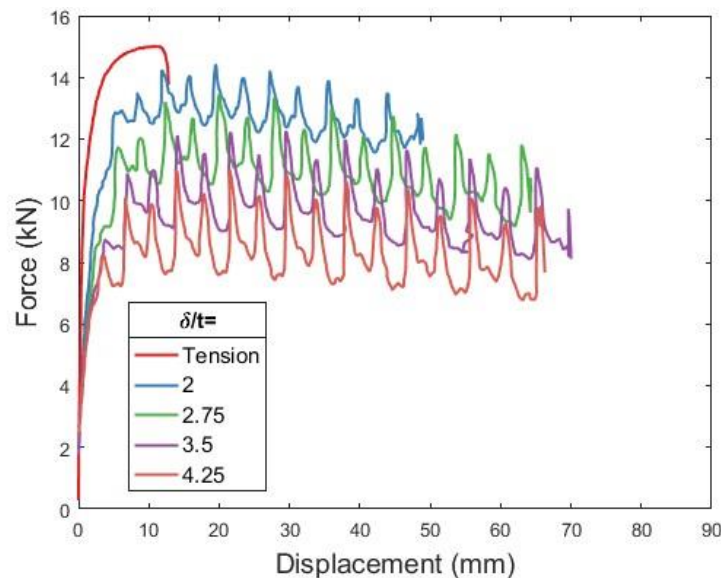


Figure 6. Force-displacement curves for simple tension and CBT testing along RD for a crosshead velocity of 1.35 mm/s and varying normalized bending depths.

Figure 7 shows the effect of cross-head velocity on force-displacement CBT results for varying crosshead velocities for a fixed δ/t value of 3.5. With lower crosshead velocity values, the measured force is less as more of the deformation is caused by bending than uniaxial tension. With higher crosshead velocities, there is more uniaxial deformation which causes higher forces and allows less displacement before fracture. Again, an optimal crosshead velocity, 1.35 mm/s, is observed. Figure 8 summarizes the effect of process parameters on elongation to fracture during CBT testing.

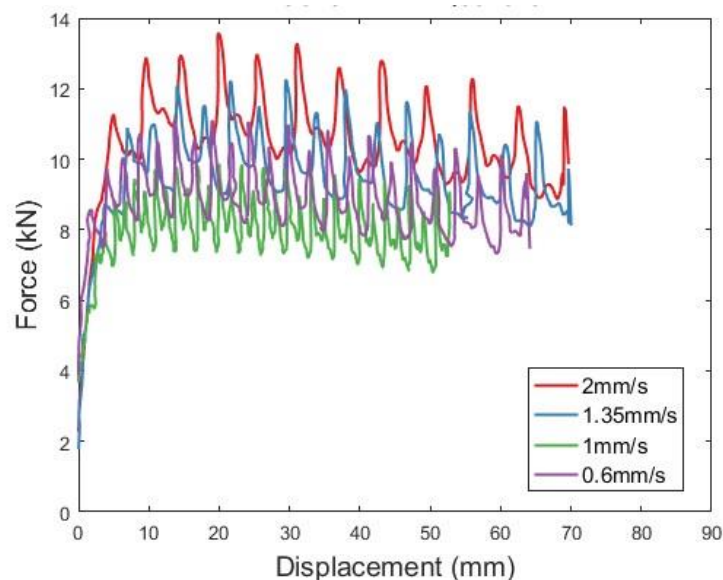


Figure 7. Force-displacement curves for CBT testing along RD for a normalized bending depth of 3.5 and varying crosshead velocities.

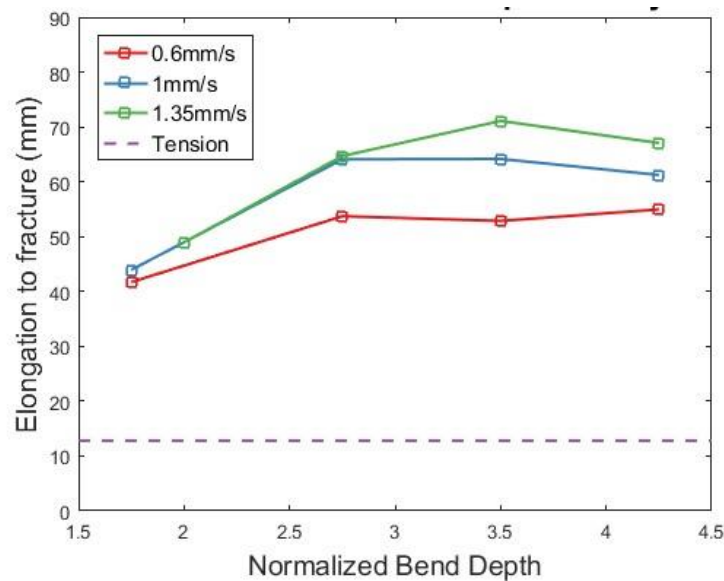


Figure 8. Elongation to fracture in RD during CBT testing. The data for simple tension is also shows as a reference.

5. Discussion

This work presents the main results into the investigation of the effect of process parameters on the elongation to fracture and the CBT axial force levels. The two CBT parameters varied are the bending depth, which determines the extent of specimen wrapping around the rollers and, consequently, the bending strain accumulation per CBT stroke, and the crosshead displacement/velocity of the hydraulic actuator. The work shows that taking advantage of CBT processing can significantly increase elongation to fracture of DP1180. Improvements over four times can be achieved.

To provide better insights into kinematics of the process, i.e., the shape of the curves shown in Figures 6, 7, and 8, Figure 9 is a suitable selected snapshot plot of the force-time and roller velocity-time data in a single graph. At the beginning of each stroke, the carriage accelerates linearly and then attains a constant velocity, which is maintained for the majority of the stroke. It then decelerates linearly until it stops; this profile is repeated during every stroke. The force spikes occur during the deceleration and acceleration phases. This is explained as follows: during these phases, the CBT test is momentarily paused, and the part of the specimen between the rollers and the hydraulic actuator essentially tends towards the tensile condition. Hence the force raises, to meet the force required for plastic flow under tension. However, soon enough the carriage starts moving in the opposite direction, resuming the CBT loading and resulting in a drop in the force. Height of the spikes scales the amount of bending. Between the peaks there is roughly a plateau in the force as the deformation is near steady state. Note that there is a slight difference between the force values for every other plateau. This is caused by the material either moving towards (lower plateau force) or away from (higher plateau force) the load cell.

Future studies will evaluate anisotropy by CBT testing along the TD and 45°. Moreover, the process will be simulated using finite element analysis to obtain better insights into stress-strain fields, as was conducted in [17]. Finally, microstructure evolution for DP 1180 during CBT processing will be investigated.

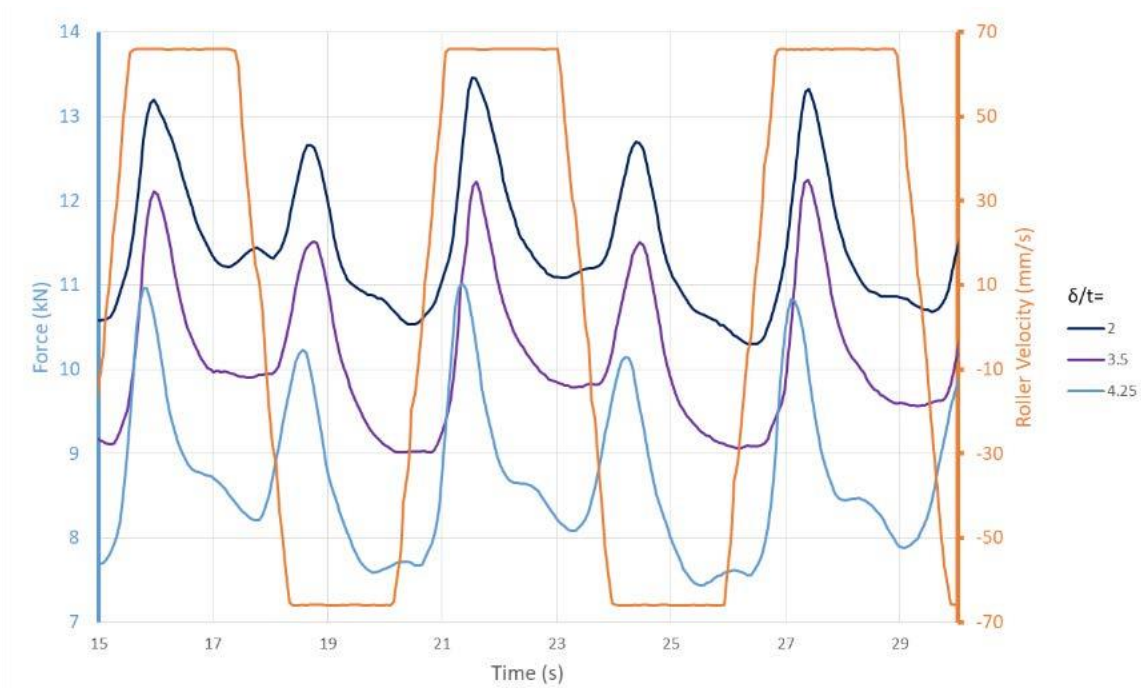


Figure 9. Snapshot of time-evolution of force and velocity during CBT testing for various normalized bending depths.

6. Conclusions

In this paper, the parameter space for optimal CBT processing of DP 1180 is investigated. Significant improvement in the displacement or elongation of the material prior to fracture is demonstrated (410%). Perhaps due to the limited ductility of this material, the improvements obtained are beyond what has been achieved for another material, e.g., AA6022-T6 [18, 19], using the same equipment and methodology and other materials in the literature [7]. In addition to demonstrating a possible means to improve the elongation prior to fracture, the method is being investigated to provide a method of determining the stress-strain behavior of a material beyond what is able to be achieved with a uniaxial tension test. Furthermore, past research has shown that the concentrated deformation in the fracture location of a tensile specimen is similar to the deformation over the entire gauge length of a CBT processed specimen [20]. Additional microstructural analyses will be conducted on DP 1180 samples to assess such effects as well.

Acknowledgements

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