A new design model for welded joints
Experimental investigations of welds on high-strength steels

In the AiF-FOSTA research project P1020 [1], a new design model for welded joints was developed. In this context, a small scale test on flat tensile specimens was designed, with the help of which various influences on the strength and ductility of the welds were investigated. Furthermore, extensive tests were carried out on overlap joints, cruciform joints with double fillet welds as well as partially and fully penetrated butt joints. This was done to calibrate the weld construction factor $a_w$, which takes into account the influence of the type of joint on the load-bearing capacity. In the following article, after a short summary of the current state of research, the design model, and the results from the parameter studies on flat tensile tests are described in more detail in [2–4]. Subsequently, the test program on welded joints and the calibration of the weld construction factor $a_w$ are presented. Finally, the results of the design model and the tests carried out are compared with test results from other research projects and the design model of prEN 1993-1-8 [5].

Keywords: high strength steel; design rules; welded joints; strength of welds; cooling time $t_{cool}$; tensile tests; joint tests; weld construction factor

1 Introduction

The use of high-strength steels offers economic and ecological advantages in many structures in building and plant engineering, but also in mechanical engineering, due to the resource-saving use of materials. In welded structures, these advantages are partly offset by unfavorable design rules for the joints and more difficult execution. Within the framework of the developed AiF-FOSTA research project P1020 [1], basic principles for improving the technical rules for the design and execution of welded joints on high-strength steels were developed.

As the strength of the steels increases, it becomes more difficult to ensure that the mechanical properties of the welded joints correspond to those of the base material. However, in the majority of welded joints in steel structures this is not necessary. Examples are the fillet welds connecting I- and box girders, stiffener connections and all joints where stresses are well below the strength of the high-strength steels. Depending on the steel grade and chemical composition, peak temperature and cooling rate during welding, the properties of the base material change and a more or less pronounced softening can lead to failure outside the weld but within the heat-affected zone.

2 State of research and European standardization

The simplified and directional design method for fillet welds and partially penetrated butt welds according to EN 1993-1-8 [6] subsumes the influences of the base material, filler metal, processing parameters, type of joint and type of stress on the strength of the welds in a single parameter, the correlation coefficient $\beta_w$. The reference value for determining the weld metal strength is the tensile strength of the base material $f_u$ (see Eqs. (1), (2) and EN1993-1-8, 4.5.3.2 [6]). The German National Annex DIN EN 1993-1-12/NA [7] specifies for high-strength steels that only filler metals with a strength equal to or greater than the strength of the base metal are allowed to be used. So-called undermatching, in which the weld seam has a lower strength than the base material, is not permitted. In addition, the correlation coefficient $\beta_w$ which is mainly calibrated on the basis of the longitudinal fillet welds of lap joints is increased from 1.0 to 1.2 in deviation from EN 1993-1-12 [8]. In part 1-12, it is required that for steel grades above S460 to S700 the length of fillet welds in the longitudinal direction of lap joints is a maximum of 50 times the weld thickness $a$, unless the non-uniform stress distribution is taken into account in the design.

$$\sigma_v = \sqrt{\sigma_{\perp}^2 + 3\left(\tau_{\perp}^2 + \tau_{||}^2\right)} \leq \frac{f_u}{\beta_w \cdot \gamma_{M2}}$$  \hspace{1cm} (1)

$$\sigma_{\perp} \leq \frac{0.9 \cdot f_u}{\gamma_{M2}}$$  \hspace{1cm} (2)

with

- $f_{wu}$ characteristic tensile strength of the weld
- $\beta_w$ correlation factor
- $\sigma_v$ equivalent stress (von Mises stress) from the acting stress components
- $\sigma_{\perp}, \tau_{\perp}, \tau_{||}$ stress components, see Fig. 7 and EN1993-1-8, Fig. 4.5 [6]

A number of research projects have recently been carried out to evaluate the load-bearing capacity of welded joints, some of them focusing on joints of high-strength steels. The FOSTA research project P652 – Economical welded...
joints of high-strength structural steels [9] has improved the economic efficiency of welded joints for the scope of DIN EN 1993-1-8/NA [10] through the more favorable correlation coefficients $\beta_w = 0.88$ for steels S420 and $\beta_w = 0.85$ for steels S460. For steels above S460, the unfavorable correlation coefficient $\beta_w = 1.2$ (compared to the recommendation in EN 1993-1-12 $\beta_w = 1.0$) was determined by tests on longitudinal fillet welds on plates made of steel grade S690Q.

In the research project P812 – Load-bearing capacity of fillet weld joints of high-strength steels S690 in steel construction [12] – there were carried out further investigations in addition to the results from P652 on the basis of 63 component tests and 9 tests on tensile specimens from the weld metal. In contrast to the P652 project, in which various steel construction companies under practical conditions produced the welded joints of the test specimens, the execution of the weld seams in P812 was fully mechanized by the Steinbeis Transfer Centre for Joining Technology on Plastics and Metals in Ulm [12]. Under these conditions, the scatter of the test results was lower and the correlation coefficient for the steels S690Q/QL/QL1 could be determined to $\beta_w = 1.1$. 58 of the 63 component tests were carried out on S690Q/QL/QL1 and S700MC steels, 5 tests were carried out on S460 steels. 56 tests were carried out on lap joints with longitudinal fillet welds and seven tests on cruciform joints with transverse fillet welds. The focus of the tests was on the lap joints with matching and overmatching welds under shear stress. On the basis of the investigations carried out and test results from other research projects, a design proposal was developed in which the reference strength results from the tensile strengths of the base material and the filler metal ([9, 12, 13]). The correlation coefficient $\beta_w$ is given depending on the strength of the filler metal. The design proposals are mainly based on tests on fillet weld joints on the steel grades S460 and S690 (Tab. 1).

For the design and execution of welded joints of normal and high-strength steels, in addition to the above-mentioned research projects, other investigations were carried out with different perspectives and objectives, e. g. [13–18]. The main findings are as follows:

The load-bearing capacity of weld seams significantly depends on the direction of loading. To illustrate this, the evaluation in Fig. 1 was carried out. The most unfavorable values result for longitudinal fillet welds, for which the correlation coefficients $\beta_w$ were calibrated [9, 11, 13]. For this purpose, the evaluation for steels above S460 was carried out according to EN 1993-1-12 with $\beta_w = 1.0$, since according to the German National Annex, undermatching is not permitted. Taking into account $\beta_w = 1.2$ according to EN 1993-1-12/NA, the strength values are 17% lower. As design proposals from relevant research projects show, in some cases significantly more favorable values result for transverse fillet welds of lap joints, fillet welds of T- and cruciform joints as well as HY-welds (cf. [11, 14–16]).

With longitudinal fillet welds subjected to shear stress, large differences in elongation occur between the ends and the center of the weld. This requires a higher ductility with increasing weld length in order to activate the entire length for full force transmission. Various Canadian research projects specifically investigated the influence of the different orientation of fillet welds and their combination on the load-bearing capacity of joints ([17, 18]).

3 New design model for welded joints

In order to improve the design rules for welded joints, the verification format according to Eq. (3) was proposed within the framework of the project P1020 and input parameters for this were determined. This design model is based on a separation of the weld strength and the joint-type related demands on strength and ductility.

$$\sigma_v = \sqrt{\frac{\sigma_1^2 + 3(\tau_1^2 + \tau_2^2)}{}} \leq \alpha_w \cdot \frac{f_{\text{w,d}}}{\gamma_{M2}} \tag{3}$$

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Tab. 1 Design proposal for longitudinal and transverse fillet welds according to [11, 12]

| Steel grade | Correlation coefficient $\beta_w$ | Reference strength: Tensile strength base material |
|-------------|----------------------------------|-----------------------------------------------|
|             |                                  | Longitudinal fillet welds Transverse fillet welds |
| S460N/NL/M/ML | 0.85                             | $k_{\text{w,d}} = \frac{f_u}{\sqrt{3} \cdot \gamma_{M2} \cdot \beta_w}$ | $k_{\text{w,d}} = \frac{f_u}{\sqrt{2} \cdot \gamma_{M2} \cdot \beta_w}$ |
| S690Q/QL/QL1 | 1.10                             |                                               |

| Filler metal | Correlation coefficient $\beta_w$ | Reference strength: Tensile strength base material and filler metal |
|-------------|----------------------------------|-----------------------------------------------|
|             |                                  | Longitudinal fillet welds Transverse fillet welds |
| G42/E42     | 0.89                             | $k_{\text{w,d}} = \frac{0.25 \cdot f_u + 0.75 \cdot f_{\text{w,d}}}{\sqrt{3} \cdot \gamma_{M2} \cdot \beta_w}$ | $k_{\text{w,d}} = \frac{0.25 \cdot f_u + 0.75 \cdot f_{\text{w,d}}}{\sqrt{2} \cdot \gamma_{M2} \cdot \beta_w}$ |
| G46/E46/T46 | 0.85                             |                                               |
| G69/T69     | 1.09                             |                                               |
| G89         | 1.19                             |                                               |
The mechanical properties of the welds are significantly influenced by the chemical composition of the filler metals and the process parameters. Due to the type of construction, there are different requirements for the deformation capacity of welded joints in order to activate the strength over the entire area of the fracture surface. For example, lap joints with longitudinal fillet welds have concentration of stress in the weld end areas. The plastic deformation capacity of the welds leads to redistributions within the joint, so that the strength can be better utilized in the integral over the fracture surface. The design format of Eq. (3) requires the determination of the weld strength $f_{\text{wu}}$. A small scale test was developed for this purpose. On the basis of load-bearing tests and parameter studies using structural-mechanical calculations, various joint types were investigated in order to calibrate the factors $\alpha_w$.

The microstructure and the mechanical characteristics of the welds and the heat-affected zone are mainly influenced by the welding process parameters and the resulting energy input. For proper welding processing, the temperature-time curve of the welding process must be within material-specific limits. For unalloyed steels, the concept of $t_{\text{max}}$ times is generally used. The targeted use of undermatching welds enables an extension of the range of permissible process parameters, as the current design guidelines aim for matching or overmatching joints.

The characteristic weld tensile strength was determined using the specimen shown in Fig. 2. This is a comparative test in which the mechanical strength parameters of the weld seam are determined using a flat tensile specimen with a centric hole. The targeted reduction of the cross-section through the hole also leads to a failure in the weld metal in the case of overmatching joints and enables the transferability of the test results to the component level. The authors give a detailed description of the specimen and selected tests in [1–4]. In the series of small scale tests, the influences of the base material and filler metal, the cooling time $t_{8/5}$ between 800°C and 500°C, in the interval of 5 to 20 seconds, the number of layers and the opening angle were investigated. The material combinations used depending on the base material are summarized in Tab. 2.

Welding of the specimens was carried out, among other places, in a fully mechanical test stand consisting of a six-axis welding robot and a synchronized rotary tilting table in which the sheets to be welded were supported in spots. During the welding process, the welding parameters were recorded, and the cooling time $t_{8/5}$ was measured for each weld bead using thermocouples in the molten metal. For reasons of comparability, the electrical power of the individual welds was kept approximately constant. Metal active gas welding (MAG) was carried out in the spray arc area. To achieve the specified cooling times $t_{8/5}$, the welding speed as well as the preheating and interpass temperatures were varied. In addition, test specimens were manufactured in steel construction companies in order to include the results of manually produced welds in the investigations.
heat-affected zone. By varying the peak temperature and cooling times \( t_{8/5} \), the influence of different process parameters during welding on the strength, ductility, hardness values and microstructure of the welds was investigated. Fig. 3 and Tab. 4 give an overview of the test program on joints. At least 4 tests were carried out for each parameter combination, the weld thicknesses were between 3 mm (lap joints) and 20 mm (fully penetrated butt joints). The properties of the investigated base materials and filler metals are documented in [1–4] and the detailed test program for the joints in [1].

The evaluation of 120 test results in [1, 2, 4] shows that the weld tensile strength \( f_{wu} \) is significantly influenced by the filler metal and the cooling time \( t_{8/5} \). A significant influence of the base material, the number of weld layers and the type of production (automated or manual) could not be determined. The statistical evaluation of the tests according to EN 1990 [19] was carried out taking into account and neglecting the influence of the cooling time \( t_{8/5} \). Tab. 3 summarizes the characteristic values of the weld tensile strengths \( f_{wu,k} \) as results of both statistical evaluations.

The test specimens were welded in laboratory and workshop conditions. First, the Chair of Welding Technology at the Technische Universität Chemnitz determined the welding parameters for all test specimens and half of the test specimens of the respective series were fully mechanized welded. Subsequently, the participating industrial partners produced the other half of the test specimens with the same welding parameters under practical conditions under the welding supervision of employees of the
Technische Universität Chemnitz. A summary of the welding parameters used can be found in [1]. All load-bearing tests were carried out at the TU Dresden at room temperature.

### 5.2 Tests on longitudinal fillet welds of lap joints

The tests on longitudinal fillet welds of lap joints were carried out on four different combinations of base materials and filler metals (Tab. 4 and Fig. 5). The ratio of weld length $L_w$ to weld thickness $a$ was varied to 50, 100 and 150 in order to obtain different ductility requirements for the welds. The planned weld thickness was 3 mm. The determination of the shear stress averaged over the weld seam length when the ultimate load $F_{\text{max}}$ was reached was carried out by including the measured fracture surfaces. Fig. 5 gives an overview of the test evaluation with the mean values of the weld construction factors $\alpha_{w,m}$ and the comparison of the experimentally and theoretically determined loads.

On the one hand the test evaluation shows that the weld construction factors $\alpha_{w,m}$ depends primarily on the filler metal. The value becomes smaller as the strength of the filler metals increases. On the other hand, it can be read from the comparison of the values of $L_w/a$ for 50, 100 and 150 for one material combination each that there is no clear dependence of the weld load-bearing capacity on this ratio. For the tested ratios $L_w/a$, there is no significant reduction for longer welds. This is an important finding, as the weld length is limited to $50 \times a$ for welded joints of steels grades greater S460 according to EN 1993-1-12, unless the uneven stress distribution is taken into account in the design. In prEN 1993-1-8 [5], the weld length is limited to $150 \times a$ for steel grades equal to or higher than S460.
The diagram in Fig. 5 shows a comparison of the experimentally and theoretically determined resistances. The evaluation was carried out with the mean values of the weld construction factor $\alpha_{w,m}$ determined for the respective weld filler metal as well as the mean values of the weld seam strength $f_{wu,m}(t_{8/5})$ dependent on the $t_{8/5}$-time. The comparison shows a good agreement between the theoretical and experimental load-bearing capacities and thus a confirmation of the design model according to Eq. (3).

5.3 Tests on transverse fillet welds of cruciform joints

In order to investigate transverse fillet welds, there was carried out a total of 12 tests on cruciform joints made with filler metals G42, G62 and G79 (Fig. 6). The steels S500ML, S690QL, S700MC and S960QL were used as base materials. The target weld thickness was $a = 5$ mm. The average weld length and width of the test specimen was 66 mm. Further details on the base materials, welding consumables and test parameters can be found in [1]. The measured fracture area and mean value of fracture angle of the specimens were taken into account in the evaluation of the test results. Fig. 7 shows the mean values of the weld construction factors $\alpha_{w,m}$ and the comparison of the experimentally and theoretically determined resistance. Also, for the cruciform joints, it was found that the filler metal significantly influences the load-bearing capacity. The weld construction factor $\alpha_{w,m}$ decreases with the strength of the filler metal. While a significant increase in the load-bearing capacity could be observed between filler metals G42 and G62 ($\Delta = 15.5\%$), the difference between filler metals G62 and G79 was small ($\Delta = 4.0\%$). This behavior is consistent with the results from the investigations on longitudinal fillet welds at lap joints and the tests on flat tensile specimens with holes described in [1–4].

5.4 Test on partially and fully penetrated welds of butt joints

The experimental investigations on butt joints were carried out on 20 flat tensile specimens with a thickness of 20 mm and a width of 35 mm (Tab. 4 and Fig. 8). The fully penetrated butt joints were made with an X-seam, the non-penetrated butt joints with a DY-seam with a flank preparation of 4 mm depth on both sides. In both cases, the seam opening angle was 60°. The choice of material combination and weld design had to ensure that failure occurred in the weld and not in the base material. Thus, undermatching welds were chosen for the fully penetrated butt joints, and under- and overmatching welds were chosen for the partially penetrated butt joints (Tab. 4). It was noteworthy during the tests that the fully penetrated welds showed ductile fracture behavior, while the partially penetrated welds showed brittle behavior of the joints with sudden failure.
due to the notch at the weld seam roots (Fig. 8). During the evaluation of the tests, it was particularly difficult to record the penetration of the partially penetrated butt welds, as the depth of penetration varied along the length of the weld due to the pulsating arc. Fig. 9 shows the mean values of the weld construction parameter \( \alpha_{w,m} \) and the comparison of experimental and theoretical resistance. The differences in the \( \alpha_{w,m} \) values between fully and partially penetrated butt welds are comparatively small. While the results for the filler metals G62 and G79 correspond to the expectations, the \( \alpha_{w,m} \) for the filler metal G42 are clearly higher. Subsequent investigations by means of FEM calculations taking into account the base material, filler metal and heat-affected zone made clear the considerable supporting effect of the base material S960 and its heat-affected zone. This effect is evident due to the very strong mismatching ratio of \( f_{eu}/f_u = 0.51 \) so that these results cannot be generalized and transferred to all base materials. Further investigations are necessary.

### 6 Calibration of the design model

The calibration of the design model and the \( \alpha_{w} \) values contained therein was carried out according to EN 1990, Annex D 8.2. A coefficient of variation of the fracture surface of \( V_{Frac} = 0.1 \) was used for the evaluation. Since the cooling time \( t_{8/5} \) was taken into account, the coefficient of variation for the weld tensile strength \( V_{Fwu} = 0.04 \) determined in the research project could be used as a basis. According to the design model for welded joints in EN 1993-1-8, the partial safety factor \( \gamma_{M2} = 1.25 \) was aimed for. Fig. 10 shows the procedure for calibrating the design model on the example of butt welds.

To determine the average connection load-bearing capacities, the \( \alpha_{w,m} \) values were determined on the basis of the tests as a function of the weld filler metal and the connection form (cf. Section 5). The adaptation to the safety level of EN1990 was carried out by introducing the model factor \( \gamma_{Model} \), with which the mean values of the weld construction factors were reduced to characteristic values \( \alpha_{w,k} \) to take into account the scatter of the test results and the reference plane when determining the \( \text{von Mises} \) equivalent stress. The determination of the model factors \( \gamma_{Model} \) was carried out separately depending on the joint type (Fig. 11). For the transverse fillet welds, for example, the fracture angle of 45° used in practice was taken as a basis and the model factor was adapted to this procedure. The determination of the \( \alpha_{w,k} \) values of lap joints was based exclusively on the manual welds carried out by the companies, since some strongly deviating test results arose with the machine welded joints produced in the laboratory due to the device settings, which were not representative. The determined values \( \gamma_{Model} \) and the characteristic values weld construction parameters are compiled in Tab. 5.
Comparison with the results from other research projects

To validate the new design model, among other things, the test results of other research projects were used and various comparisons were made with the design rules from the current and future EN 1993-1-8. Fig. 11, for example, shows a comparison of the test results for longitudinal fillet welds subjected to shear as well as a comparison of the characteristic values and the design values of the weld stresses $t_{w}$ from the new design model (P1020) with those from prEN1993-1-8. Since the influence of the base material is also taken into account to 25% in this standard (Tab. 1), the steel grades S460 and S690 were used as a basis for comparison. In the model according to P1020, the weld strength was used with neglect of the $t_{8/5}$ time (Tab. 3). This leads to lower calculated stress abilities $t_{w}$, only a $t_{8/5}$-time of 20 seconds results in partially even smaller values (Tab. 3). The comparison of the test results with those of other research projects shows predominantly higher values of the achieved shear stresses $t_{w}$ in P1020. This can be explained by the fact that in P1020 the lap joints were welded with very short $t_{8/5}$ times of approx. 3 seconds due to the low fillet weld thicknesses of 3 mm and thus above-average weld strengths developed. This effect is taken into account with the design model in P1020 via the strength $f_{wu,k}(t_{8/5})$ (Fig. 9). Thus, the

Fig. 10 Procedure for calibrating the design model using the model factor $\gamma_{\text{Model}}$ on the example of butt welds

Fig. 11 Determination of the model factors $\gamma_{\text{Model}}$ for the different weld types
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The new design approach leads to an increase in the weld stress depending on the filler metal of 4% to 15% when calibrated weld construction factors are conservatively determined, since longer cooling times $t_{8/5}$ lead to smaller strengths and to higher $a_{w,k}$-values. Despite the conservative comparison, the design model according to P1020 results in higher weld load capacities than the approaches in prEN1993-1-8 (Fig. 11). The difference becomes even clearer when the $t_{8/5}$-times are included (Fig. 12).

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are made with the filler metal used. This also enables to take into account the significant influence of the welding process parameters on the strength. The joint type and ductility of the weld seam is recorded with the weld construction factor $a_{w,k}$. This allows a greater differentiation between the joint types and their ductility requirements. The verification format is kept simple and does not lead to any additional work in the calculation of welded joints.

In conjunction with the design model, a small scale test was developed in the form of a test on a flat tensile specimen with an X-weld. The arrangement of a centric hole ensures that failure occurs within the weld and not in the heat-affected zone or in the base material. This allows the strength and ductility of the weld itself to be determined, even for overmatched joints. The flat tensile test can be

8 Summary

This paper presents a new design model for welded joints. The main difference to the Eurocode-3-model is that the strength of the weld is not determined on the basis of the base metal and, if applicable, the filler metal and subsequent correction. The strength of the weld is determined directly with tests on flat tensile specimens whose welds

**Fig. 14** Comparison of test results on transverse fillet welds from different research projects and the design models of prEN 1993-1-8 and P1020

**Fig. 15** Comparison of the design values of the design stresses $f_{w,d}$ for the weld filler metal G79 of the design models of prEN 1993-1-8 and P1020
used to evaluate new materials and their combinations in a simple way as well as welding processes with their influence on the mechanical weld properties. It can be used for quality assurance and process testing, since the test and measurement requirements were deliberately kept low in the design of the test.

Within the framework of parameter studies using the flat tensile test, the influences of the base metal, the filler metal, the cooling time $t_{8/5}$, the number of weld layers and the weld seam opening angle were investigated. Steels of strength classes S500 to S960 and filler metals G35 to G89 were considered. While the influences from the base materials and the number of weld seam layers were within the usual statistical scatter of the strengths for a weld filler metal with constant process parameters, the significant influence of the cooling time $t_{8/5}$ could be determined. The dependence of tensile strength, yield strength and ductility on $t_{8/5}$-time increases with increasing filler metal strength.

The statistical evaluation of the weld seam strengths was carried out separately according to the strength class of the filler metal and the $t_{8/5}$-time on the one hand, and without differentiation by the cooling time on the other. In the first case, this led to coefficients of variation below 4% and up to 17% higher characteristic strengths compared to the second case, in which coefficients of variation up to about 7% were calculated (cf. [1, 2, 4]). These two evaluation variants allow either to carry out the weld design with predominantly conservative values or to take the cooling time $t_{8/5}$ into account by means of a more differentiated strength assumption and to back this up with the process parameters during production.

The determination of the factors $\omega_{8/5}$ to consider the connection type and ductility of the weld seam was carried out with the use of test series on welded joints of lap, cross and butt joints as well as structural-mechanical calculations using a damage plasticity model. The evaluation of the tests and numerical parameter studies led to the conclusion that, in the case of longitudinal fillet welds of lap joints up to a weld length of 150 - a, no significant reduction of the weld strength due to the joint length is required. For the lap and cruciform joints, failure always occurred in the weld seam. The influence of the base material on the load-bearing capacity can be classified as negligible. For the partially and fully penetration welded butt joints, the test parameters were selected in such a way that failure occurred in the weld seam itself. However, in the joints with strong undermatching, the supporting influence of the base metal could already be clearly detected. Extensive numerical parameter studies confirmed that the base metal must be taken into account when determining the strength of the welded butt joints. In addition to the influence of the support effect, failure of butt joints can also occur as a mixed failure of weld, heat-affected zone and base metal. For this purpose, further investigations are required, which in particular also cover the softening behavior of the high-strength steels.

A comparison of the design model developed with the test results for longitudinal and transverse fillet welds from previous research projects shows a sufficient level of safety. A comparison with the design rules in prEN 1993-1-8 also shows that the new model allows a significantly higher utilization of the welded joints. This is particularly the case for transverse fillet welds. The possibility of taking the cooling time $t_{8/5}$ into account also allows a more differentiated capture of the manufacturing parameters in the design.

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