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Prediction of the fatigue limit of blunt-notched components

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Abstract

A prediction of the fatigue limit of blunt-notched components of a low carbon steel was made on the basis that the fatigue limit of polycrystalline metals represents the critical conditions for the propagation of nucleated cracks. An expression for the material resistance to crack propagation as a function of the crack length is obtained for the first part of the short crack regime, which defines the blunt notch sensitivity to fatigue. The material resistance curve is modeled from a depth d, given by the position of the strongest microstructural barrier to microstructurally short crack propagation, which defines the plain fatigue limit. A microstructural threshold, ΔK_d, is suggested as an intrinsic material resistance to microstructurally short crack propagation, defined by the plain fatigue limit $\Delta\sigma_{e0}$ and the position of the strongest microstructural barrier d. The modeled notch sensitivity fits reasonably well the experimental results for a low carbon steel. © 2001 Published by Elsevier Science Ltd.

Keywords: Fatigue limit; Blunt notches; Notch sensitivity; Microstructural barriers

1. Introduction

The stress fields in the immediate vicinity of the stress concentration produced by notches have a strong bearing on how fatigue cracks nucleate and propagate. There exists now sufficient experimental evidence showing that the fatigue limit of polycrystalline metals represents the critical conditions for the propagation of nucleated cracks, and this holds both for smooth and notched components [1–12]. In "sharp" notches (high stress concentration factor k_t), mechanically small non-propagating cracks exist at the fatigue limit of the notched component (crack length less than that at which crack closure is fully developed [10]), whereas "blunt" notches (small k_t), exhibit microstructurally short non-propagating cracks (crack length of the order of the microstructural dimensions). In both cases the length of the non-propagating cracks increases as k_t increases.

In the case of sharp notches, fatigue strength is given by a mechanical threshold defined by a ΔK criterion, and the development of mechanically small non-propagating cracks is allowed by the existence of a sufficiently high stress gradient and the development of the crack closure effect. In this case, the fatigue strength becomes independent of the stress concentration factor, k_t, and is governed mainly by the notch depth, D, and the fatigue threshold, $\Delta\sigma_{th}$, for physically small or long cracks [4,7,8]. On the other hand, in the case of blunt notches the stress that is sufficient to initiate a crack at the notch root and overcome the strongest microstructural barrier is also sufficient to cause continuous propagation of the crack to failure and the fatigue strength is given by a microstructural threshold determined by a $\Delta\sigma$ criterion [1,6,12].

In a previous work [12], a model for the blunt-notch sensitivity was derived, which characterizes the fatigue notch sensitivity by means of the parameter k_{td} defined as the stress concentration introduced by the notch at a distance d from the notch root surface equal to the distance between microstructural barriers, as follows:

$$k_{td}=\frac{k_t}{\sqrt{1+\frac{4.5d}{\rho}}} \tag{1}$$

where ρ is the notch radius.

Defining d_i as the position of the microstructural barriers i, and $\Delta\sigma_{ed_i}$ as the fatigue limit associated with the same barrier i, the fatigue limit $\Delta\sigma_e$ of the notched component at a given k_t would be given by the greatest $\Delta\sigma_{ed_i}$ at that k_t, as follows:

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$$\Delta\sigma_e|_{k_t}=\max\,\Delta\sigma_{ed_i}|_{k_t}=\max\left[\frac{\Delta\sigma_{e0d_i}\sqrt{1+4.5\frac{d_i}{\rho}}}{k_t}\right]_{k_t} \quad (2)$$

where $\Delta\sigma_{e0d_i}$ is the effective resistance of the barrier i. The concept is shown schematically in Fig. 1 by considering three consecutive microstructural barriers spaced at a distance d_1, d_2 and d_3 from the surface ($d_1<d_2<d_3$), with their effective resistance $\Delta\sigma_{e0d_1}$, $\Delta\sigma_{e0d_2}$ and $\Delta\sigma_{e0d_3}$, respectively. From k_t=1 to k_{t_1} the fatigue limit of the notch component is given by $\Delta\sigma_e=\Delta\sigma_{e0d_1}/k_{td_1}$, from k_{t_1} to k_{t_2} by $\Delta\sigma_e=\Delta\sigma_{e0d_2}/k_{td_2}$, and so on.

2. Material crack growth resistance curve

In order to develop a model for the prediction of the fatigue limit as well as fatigue crack propagation life, it is necessary to obtain an expression for the material resistance to crack propagation as a function of the crack length, including the short crack regime. The model described previously takes into account local crack growth resistances, but it is possible to obtain a continuous crack growth resistance curve by fitting the points defined by the position d_i and the resistance $\Delta\sigma_{e0d_i}$ of those microstructural barriers.

It is also necessary to take into account the development of the crack closure effect. It is well known that in the short crack regime, crack closure develops with an increase in crack length [1–9], and this crack closure reduces the effective range of the applied stress intensity factor. So it can be considered as an extrinsic material resistance. In this way a resistance curve to crack propagation can be defined adding the crack closure component of the stress intensity factor to the intrinsic crack growth resistance of the material. This intrinsic resistance is usually identified equal to the effective components of the stress intensity factor threshold for long cracks, $\Delta K_{eff,th}$ [1,2,6,9]. This effective threshold $\Delta K_{eff,th}$, together with the plain fatigue limit $\Delta\sigma_{e0}$ define an effective intrinsic crack length L_{0eff} that it is usually considered as the position of an intrinsic material barrier to crack propagation. However, the physical significance of the parameter L_0 is not understood, neither is there a correlation between L_0 and any characteristic microstructural dimension.

Another problem that has to be considered is that the extension force for the nucleation and growth of "subcritical" or "microstructuraly short" fatigue cracks comes from both the external load (external crack extension force, given by the applied stress intensity factor range, ΔK), and the elastic energy released from the local region near the crack tip (local crack extension force) [13]. The local energy source is defined as the strain energy stored in the form of internal stress fields generated by cyclic plastic deformation. The accumulation of strain energy in local regions during cyclic deformation, or fatigue, is a consequence of the inhomogeneous deformation and the irreversibility of local shear strain. Examples of this are the formation of persistent slip bands (PSBs). The value of the local crack extension force is initially high and rapidly drops as the energy stored in the short ranged internal stress field is "exhausted" by crack growth. On the other hand, the external crack extension force increases with crack growth.

Related to the development of the local crack extension force is the inherent surface strain concentration phenomenon [14,15]. Favourably orientated grains experience the largest amount of surface deformation and the greatest amount of localized slip. Localized slip allows, for instance, PSBs to develop at the surface of the favourably orientated grains which become then a preferred site of crack initiation. On the other hand, in the interior of the material the grains support each other and as more of this constraint is experienced the local strain decreases with depth into the specimen, eventually approaching the nominal strain range. It was recently also shown that the local extension force influences the microstructurally short crack regime and only the beginning of the mechanical small crack regime [16].

According to the last concepts, it seems to have more physical meaning to use an intrinsic material resistance to crack propagation defined as the stress intensity factor, given by the position of the strongest microstructural barrier d, and the plain fatigue limit, as follows:

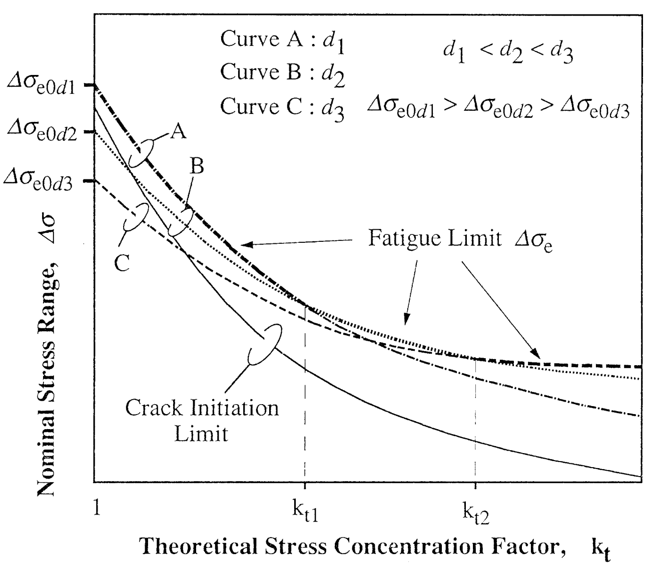

Fig. 1. The fatigue limit $\Delta\sigma_e$ of blunt notches defined as the greatest fatigue limit associated with the effective resistance $\Delta\sigma_{e0d_i}$ and the position from the notch-root surface d_i of the microstructural barriers i (see Eq. (2)).

$$\Delta K_d = \Delta\sigma_{e0}\sqrt{\pi d} \qquad (3)$$

where the plain fatigue limit, $\Delta\sigma_{e0}$, represents the effective resistance to crack propagation of the strongest microstructural barrier, and its position d defines the plain fatigue limit and the notch sensitivity of the material for very blunt notches. Because the plain fatigue limit represents a microstructural threshold to crack propagation, it seems reasonable to define the parameter ΔK_d as a microstructural threshold.

The material-resistance curve, $\Delta\sigma_{th}(a)$, is then obtained by fitting the points defined by the position d_i and the resistance $\Delta\sigma_{e0d_i}$ of the first three or four microstructural barriers. In this way, the material threshold to crack propagation ΔK_{th} can be written as:

$$\Delta K_{th} = \Delta K_d + \Delta K_C[1-e^{-k(a-d)}] = \Delta\sigma_{th}\sqrt{\pi a} \quad a \geq d \qquad (4)$$

where ΔK_C is the crack closure component defined as the difference between the threshold for long cracks (ΔK_{th0}), and the microstructural threshold ΔK_d. The material parameter, k, takes into account the development of the crack closure effect with crack depth.

Then

$$\Delta\sigma_{th} = \frac{\Delta K_d + \Delta K_C[1-e^{-k(a-d)}]}{\sqrt{\pi a}} \quad a \geq d \qquad (5)$$

where $\Delta\sigma_{e0}$ and ΔK_C are functions of the stress ratio R (minimum to maximum stress ratio). Eq. (5) is defined for crack depths equal or greater than d because it is considered here that the crack propagation stage starts at this depth. In this way, the crack initiation period is defined as the number of cycles to nucleate a crack of depth d.

3. Crack driving force and fatigue limit

The stress range available to drive the crack as a function of a can be expressed for plain or blunt notched components as [12]:

$$\Delta\sigma = \frac{k_t \Delta\sigma_n}{\sqrt{1+\frac{4.5a}{\rho}}} \qquad (6)$$

The fatigue limit $\Delta\sigma_e$ at each k_t is then obtained by the following two conditions:

$$\Delta\sigma = \Delta\sigma_{th} \text{ and } \frac{\partial\Delta\sigma}{\partial a} = \frac{\partial\Delta\sigma_{th}}{\partial a} \qquad (7)$$

where $\Delta\sigma_{th}$ is the resistance of the material and can be obtained from expression (5).

In order to apply the concept, the fatigue limit of blunt-notched specimens of a low carbon steel was studied.

4. Material, specimens and testing conditions

A ferrite–pearlite low carbon steel microstructure with an average grain size of 55 μm was analyzed. The chemical composition of the steel was (in wt pct): 0.10 C, 1.52 Cu, 0.81 Mn, 0.04 Ni, 0.029 Al, 0.003 P, 0.002 S, 0.003 N, and balance iron. The mechanical properties of the material were σ_y=387 MPa, σ_u=518 MPa and $\Delta\sigma_{e0}$=500 MPa (smooth fatigue limit at R=−1).

Three different bar tensile specimens were tested (see Fig. 2), one with a plain surface and the other two with blunt notches. According to the results from finite element methods, the values of the theoretical concentration factor k_t in the notched specimens were 1.94 and 2.51. After machining, the notches were mechanically polished with a series of grits down to 1 μm diamond paste. All fatigue test specimens were chemically etched in 3% Nital before being tested. The specimens were analyzed after testing using a scanning electron microscope.

Constant stress amplitude tests under axial loading with zero mean stress and 30 Hz frequency were carried out in an Instron fatigue test machine. All tests were performed at room temperature in laboratory air. The fatigue limit $\Delta\sigma_e$ was defined as the maximum nominal stress under which a specimen endured more than 10^7 cycles. The crack initiation limit $\Delta\sigma_i$ was defined as the limiting nominal stress required to develop a microstructurally short crack. Stress level was kept constant for each specimen. The fatigue limit $\Delta\sigma_e$ was then determined by testing different specimens at different stress lev-

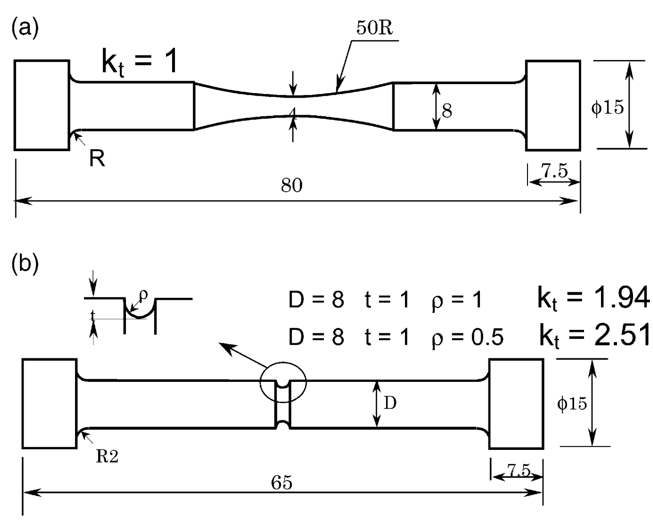

Fig. 2. Specimens, dimensions are in mm. (a) Smooth round bar specimen (k_t=1). (b) Notched round bar specimen: k_t=1.94 and k_t=2.51.

els. Stress increment between two consecutive stress levels was chosen equal to 10 MPa.

5. Results and discussion

Fig. 3 shows the stress distributions ahead of the notch root corresponding to the notches analyzed, for nominal stress ranges at and below the fatigue limit and above the initiation limit of the microstructures. Stress distributions were obtained by using finite element models of the specimens. The dark oval drawings represent the microstructural barriers, and their relative positions in depth are defined by the average grain size of the material. The upper point of the oval drawing gives the effective resistance of the barrier for crack propagation, and was estimated as follows: the elastic stress distributions were drawn only to the depth given by the length of the longest arrested crack obtained at a given nominal stress level, and then the barriers were placed by moving them vertically and considering that they cannot be crossed by the stress distributions. It is worth noting that, for the sake of clarity, only a few stress distributions were drawn, but two consecutive stress distributions were separated by a stress level given by a nominal stress range of 10 MPa and the corresponding k_t. See Refs. 12 and 17 for more details about the procedure and examples of photos of microstructurally short non-propagating cracks obtained in the same steel and similar or other microestructures.

Cracks usually initiate along persistent slip bands (PSBs) proceeding in ferrite grains or along grain boundaries. In any case the grain boundaries are considered as microstructural barriers and the position given by the average size of the ferritic grains (about 55 μm), is considered as the distance between two consecutive barriers. Pearlite is also a barrier to crack propagation, but the amount is small and it is usually placed in grain boundaries. Following the above procedure we get d_1=0.055 mm, d_2=0.11 mm, d_3=0.165 mm, and so on. The effective resistances of the first three barriers were estimated to be $\Delta\sigma_{e0d_1}$=500 MPa, $\Delta\sigma_{e0d_2}$=480 MPa, and $\Delta\sigma_{e0d_3}$=425 MPa.

Fig. 4 shows a plot of the fatigue limit versus the stress concentration factor k_t obtained experimentally. The maximum length of the non-propagating cracks observed at several stress levels below the fatigue limit is specified. The bold line corresponds to crack initiation (Eq. (1) with k_{td}=k_t, or d=0), and the dotted lines correspond to Eq. (2) for the first two important microstructural barriers. Experimental results are also shown.

The material resistance curve, $\Delta\sigma_R(a)$, is obtained by fitting the points defined by the position d_i and the resistance $\Delta\sigma_{e0d_i}$ of the first three or four microstructural barriers (see Fig. 5). For the steel analyzed, k and ΔK_C were found to be 9.3 and 6.3 MPa m$^{1/2}$, respectively. Then, using expressions (5) and (6) and applying the conditions (7) we can get the fatigue limit as a function of the stress concentration factor k_t, as shown in Fig. 6. It can be seen that the predicted fatigue limit fits the experimental data reasonably well.

It is worth noting that the intrinsic crack growth resistance defined by $\Delta\sigma_{e0}$ and d is equal to 6.57 MPa m$^{1/2}$. This value is greater than the effective crack growth threshold for low carbon steels with ferrite microstructure, which is usually between 2 and 5 MPa m$^{1/2}$ [18]. Taking the value of 3.5 MPa m$^{1/2}$ as an estimated effec-

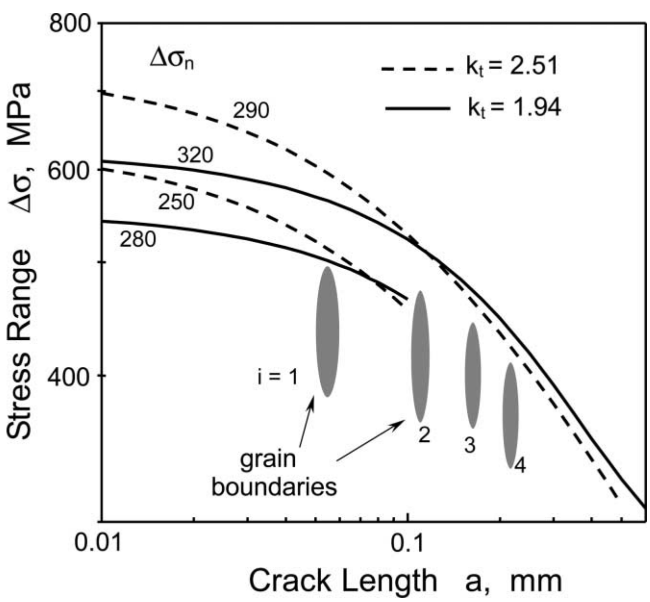

Fig. 3. Stress distributions ahead of the notch root for different nominal applied stress ranges and two stress concentration factors k_t. Dark oval drawings represent the position and the effective resistance of the microstructural barriers (grain boundaries).

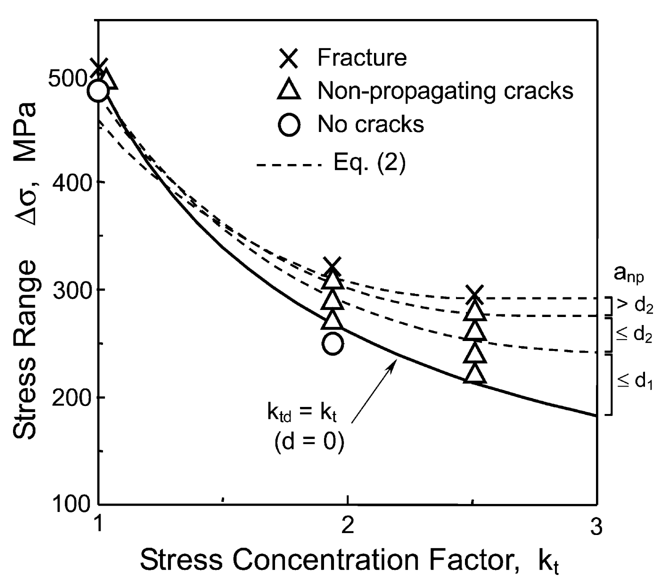

Fig. 4. Fatigue strength against theoretical stress concentration factor: ○, No cracks; △, non-propagating cracks; X, fracture.

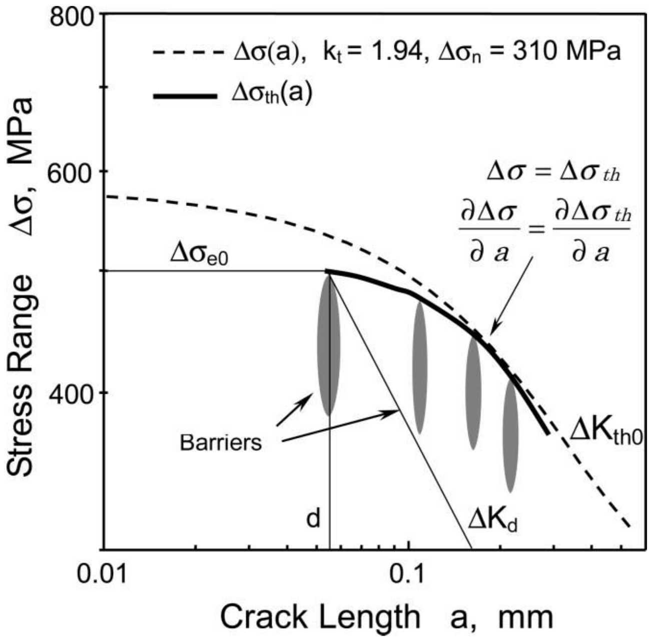

Fig. 5. Material fatigue resistance curve, $\Delta\sigma_{th}(a)$, obtained by fitting the points defined by the position d_i and the resistance $\Delta\sigma_{e0d_i}$ of the first three or four microstructural barriers.

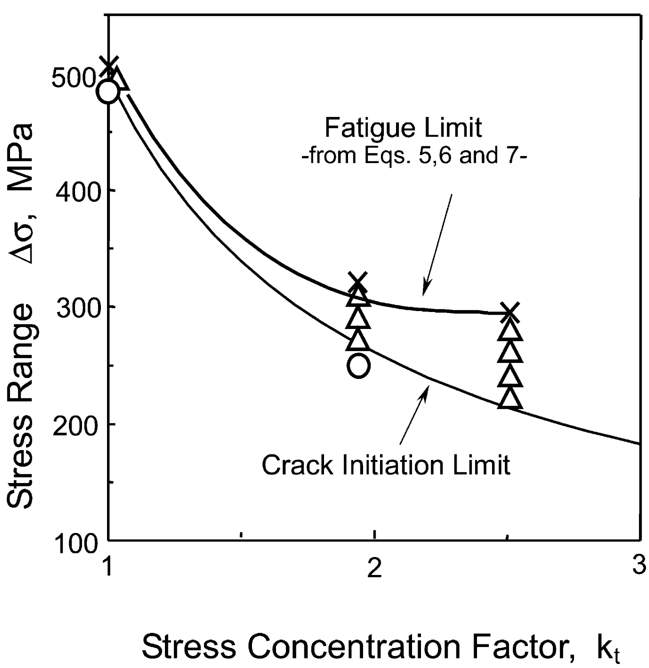

Fig. 6. Estimated fatigue strength against theoretical stress concentration factor k_t. Experimental results are also shown. ○, No cracks; △, non-propagating cracks; ×, fracture.

tive crack growth threshold, this is about half the value of ΔK_d. A factor of 2 in difference in the intrinsic resistance give a factor of 4 in difference for the position of the strongest microstructural barrier, and this gives a difference in the fatigue limit associated with that barrier of 17% (35 MPa for k_t=2.5). The difference can be greater if we consider that for higher k_t deeper barriers define the fatigue limit. Even though it can be addressed that the estimation given by models that use the parameter L_{0eff} are conservatively good, it seems that the parameter d not only has better physical meaning (as the intrinsic crack length related with the microstructural resistance defining the plain fatigue limit), but gives also a better estimation.

If it is possible to find an expression for the crack closure development, the defined material resistance curve can be extended to deeper crack depths in order to include both physically small and long crack regimes. An estimation of this curve could be then done with the plain fatigue limit $\Delta\sigma_{e0}$, the position of the strongest microstructural barrier d, the mechanical threshold for long crack ΔK_{th0}, and some material parameter to take into account the crack closure development (k). The main aim would be to use only mechanical, geometric and microstructural parameters which can be obtained through standardized mechanical tests and simple microstructural, geometrical and mechanical analyses.

6. Conclusions

A material resistance curve is defined and modeled from a depth d, given by the position of the strongest microstructural barrier to microstructurally short crack propagation, which defines the plain fatigue limit. A microstructural threshold ΔK_d is suggested as an intrinsic material resistance to crack propagation, defined by the plain fatigue limit $\Delta\sigma_{e0}$ and the position of the microstructural strongest barrier d.

It is shown that with the material resistance and the driving force to crack propagation (both as a function of the crack depth), it is possible to obtain a condition to crack arrest that defines the fatigue limit for a blunt notched component. Using this concept, fatigue experimental results of a low carbon steel were fitted reasonably well.

Finally, it is suggested that a material resistance curve including physically small and long crack regimes could be estimated using only mechanical, geometric and microstructural parameters which can be obtained through standardized mechanical tests and simple microstructural, geometrical and mechanical analysis.

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